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BACKGROUND PAPERS FOR INNOVATIVE BIOLOGICAL TECHNOLOGIES FOR LESSER DEVELOPED COUNTRIES

An Office of Technology Assessment Workshop November 24–25, 1980

REPORT

PREPARED FOR THE

COMMITTEE ON FOREIGN AFFAIRS
U.S. HOUSE OF REPRESENTATIVES

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FOREWORD

This report on innovative biological technologies was prepared by the Food and Renewable Resources staff of the Office of Technology Assessment at the request of the Committee on Foreign Affairs. In view of the committee's oversight responsibilities for programs of the Agency for International Development, it was deemed necessary to seek additional information on the potential of biological technologies to help developing countries to enhance soil productivity and increase food supplies while minimizing reliance on expensive chemical fertilizers.

The workshop on this subject organized by OTA covered many aspects of this subject and produced a broad ranging series of papers on specific technologies with potential application in developing countries. In the interest of stimulating further discussion and action on the use of these technologies, the committee is publishing both the summary and the complete papers presented at the workshop.

The findings and views expressed in this document are those of the Office of Technology Assessment or the individual authors and do not necessarily reflect the views of the Committee on Foreign Affairs or any of its members.

CLEMENT J. ZABLOCKI,
Chairman, Committee on Foreign Affairs.

LETTER OF TRANSMITTAL

CONGRESS OF THE UNITED STATES,
OFFICE OF TECHNOLOGY ASSESSMENT,
Washington, D.C., August 6, 1981.

Hon. CLEMENT J. ZABLOCKI,
Chairman, Committee on Foreign Affairs,
U.S. House of Representatives, Washington, D.C.

DEAR MR. CHAIRMAN: The enclosed workshop report was prepared in response to your request for OTA to review innovative biological technologies that have potential for enhancing soil productivity and food production in the lesser developed countries (LDC's).

OTA assembled some 40 scientists, AID representatives, and congressional staff for a 2-day workshop on November 24 and 25, 1980, to examine a range of innovative ways that LDC's might reduce their need for expensive chemical fertilizers and to discuss how AID might more fully use such technologies in its programs and projects. As preparation for the workshop, OTA commissioned 10 papers from recognized leaders in appropriate fields of science and technology.

The workshop report describes the LDC food/energy problem, summarizes the 10 technical papers, and summarizes the workshop discussions regarding current and potential use of such innovative technologies in LDC's. Also enclosed are the background papers, which represent only a sampling of the innovative technologies being tried around the world. They illustrate some of the more promising areas being pursued but should not be considered an exhaustive list.

The question of developing sustainable, productive agroecosystems is important to the United States as well as to LDC's because both could benefit from opportunities for economic diversification, reducing soil degradation, and bolstering production while lowering capital costs.

We will be glad to discuss any aspect of the workshop report with you or your staff at any time.

Sincerely,

JOHN H. GIBBONS.

Enclosures.

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INTRODUCTION AND SUMMARY

SUSTAINABLE LDC AGRICULTURE: INNOVATIVE BIOLOGICAL TECHNOLOGIES TO ENHANCE SOIL FERTILITY AND FOOD PRODUCTION

In view of its oversight responsibilities for the Agency for International Development (AID), the House Committee on Foreign Affairs, under Chairman Clement Zablocki, requested the Food and Renewable Resources Program of the congressional Office of Technology Assessment (OTA) to review innovative biological technologies that AID could use to assist lesser developed countries (LDCs) to enhance the productivity of their soils, reduce their need for expensive chemical fertilizers, and increase food supplies.

The workshop hosted by OTA in response to the committee's request brought together some 40 leading scientists, AID representatives, and congressional and executive branch staff for 2 days of presentations and discussions on November 24 and 25, 1980 (see list of attendees). The first day of the workshop was organized to allow each non-AID scientist to present a paper about innovative biological technologies and to respond to questions. The second day was devoted specifically to discussing AID and its role in using, promoting, or developing innovative technologies.

Background

Fertile soil is the key to productive agriculture, whether for an Illinois corn farmer or a subsistence farmer in Ghana, Haiti, India, or other LDC. The farmers know this; they know their soil must have good tilth, hold water, and be rich with the necessary nutrients and minerals. They learn these principles through education or, more likely, through tradition and experience. But for most LDC farmers, the old ways of maintaining soil quality may no longer be adequate. Population pressures and rising expectations force them to demand more from the land, to reduce the traditional fallow periods, and to open marginal lands that past generations avoided. The farmers may turn to modern agricultural methods--for instance, commercial fertilizers--only to find that rising input costs take away even this option. This predicament is common throughout LDCs.

Most LDCs, with their growing populations, are concentrated in a belt roughly 30 degrees north and south of the equator. These tropical and subtropical lands contain diverse ecosystems--mountains, rainforests, semiarid regions, and deserts--and house some 45 percent of the earth's people.

The concentration of LDCs in the tropics is not a coincidence but stems in large part from inherent physical limitations caused by climatic and soil constraints. As populations of these nations have grown, many LDCs have come to face a myriad of severe resource problems: degraded soil fertility, deforestation, soil erosion, water

pollution, and land-use conflicts. Concomitant social problems --including malnutrition, poverty, and political instability--are common as well. Woven through the history of many LDCs is the effect of their being colonies of various other countries of temperate regions. Agricultural systems imposed on the LDCs were appropriate for temperate regions but not for the tropics. As a result, soil fertility in many of these ex-colonies has been severely damaged.

The humid tropical regions have some of the earth's most productive ecosystems, lush forests that are the result of eons of long growing seasons, warm temperatures, and abundant rainfall. But this apparent fertility is often superficial. Tropical forests have been called "deserts covered by trees." In fact, natural soil fertility in the wet tropical latitudes is extremely low, most mineral nutrients having been leached away by ages of rain and weathering. Most of the necessary plant nutrients are trapped in the vegetation itself; as the greenery dies and decays on the forest floor, the nutrients are released, then quickly absorbed back into new growth.

Arid and semiarid regions face different problems. Lack of water limits the type and amount of crops that can be grown. Wind erosion, salinization, and temperature extremes all work to limit the land's productivity.

Agriculture in tropical latitudes must contend with these and

other physical dictates. And it must work within increasingly severe economic constraints, too, as the costs of energy, water, equipment, and various other agricultural inputs, from seed to fertilizer, continue to rise.

Conventional agricultural methods, many of which were developed for use in temperate areas, are not wholly suitable for tropical conditions. It is not that conventional agriculture cannot work in the tropics; it can in the short run. But without continuous commercial fertilizer inputs, poor tropical soils cannot sustain temperate farming methods. Also, in arid and semiarid regions temperate farming technologies require expensive irrigation systems. Thus with the increasing cost of irrigation development and fertilizers derived from natural gas, it seems inevitable that LDC farmers will look for new ways to sustain soil fertility and to ensure continued agricultural productivity.

AID is one mechanism by which the U.S. can assist LDCs in meeting development and resource challenges. AID has been commended for many of its programs, but it also has been cited for its reluctance to change and for its lack of innovative vision at a time when innovation seems most necessary.

Innovative Biological Technologies

The innovative biological technologies chosen for discussion in

the workshop represent only a sample of the diverse and adaptable approaches being studied by scientists here and abroad. The workshop examined the following:

--Promoting underexploited plant species, especially native species already adapted to local climates and conditions. Nature is a storehouse of genetic possibilities including plants with underexploited potential as food, fodder, oil seeds, and export goods. Native plants can be integrated into cropping systems, reducing the need for fertilizer and water and enhancing resistance to pests and disease. There is also promise in plant breeding efforts and tissue culture, where native stocks are used to adapt crops to less-than-ideal environments, thereby reducing the need to alter the environment with fertilizer, irrigation, and other expensive inputs.

--Developing multiple-cropping and intercropping systems suitable for specific tropical environments so as to maximize land productivity. Multiple cropping is intensive agriculture--growing two or more crops that share space and resources--and can produce more per unit of land than monoculture. Proper design of the cropping pattern--using legumes, for example--ensures and enhances soil quality while providing farmers with a range of products.

--Reducing the need for commercial nitrogen fertilizer by inoculating suitable crops with beneficial soil

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bacteria--rhizobia--that biologically take nitrogen from the air and convert it to a usable form for the plant. Legume rotations, of course, were fundamental to agriculture before the development of commercial fertilizers. Legume inoculants of certain strains of bacteria are used commercially in U.S. agriculture, and suitable strains are being developed for LDC environments.

--Increasing a plant's capacity to absorb nutrients by encouraging the growth of beneficial microorganisms--mycorrhizal fungi--that live in association with some plants. The mycorrhizae significantly increase the root's surface area, the part of the plant that assimilates nutrients from the soil.

--Developing integrated agricultural systems that take advantage of the special benefits provided by leguminous trees. Various species of nitrogen-fixing trees (e.g., *Prosopis* and *Acacia*) could be used to revegetate deforested landscapes while providing food, fodder, cash crops, fuelwood, and increased soil fertility. Unlike legumes used in temperate agriculture (e.g., alfalfa), many of these tree species can fix nitrogen under arid conditions.

--Cultivating "green" fertilizer for rice production. Azolla, a small aquatic fern native to Asia, Africa, and the Americas, shows great promise as a green manure for flooded crops. The fern provides nutrients and a protective leaf cavity for a strain of blue-green

algae, which in turn convert atmospheric nitrogen into a usable form. The nitrogen-rich azolla is grown in rice paddies, either before or along with the rice crop. It also can be harvested and transported to upland fields.

--Using underexploited animal species to meet local needs for high-protein food as well as to provide local populations with innovative cash crops. For instance, in Peru, guinea pigs are being produced as an unconventional, but tasty and prolific, protein source for local diets. And in Papua New Guinea, villagers are supplementing farm income by tending an additional garden crop--exotic butterflies for export.

--Exploring the use of natural mineral soil amendments, such as zeolite minerals, that improve soil properties and extend fertilizer efficiency. Because of their structure, zeolites have unique properties. They are used today primarily as molecular sieves in industrial processes, but they show promise in agriculture. They seem able to help maintain nitrogen availability in soils and help plants resist water stress. More immediate benefits may show in animal agriculture, where zeolites can serve as feed additives and as decontaminants for feedlot wastes. Zeolite deposits are thought to be widespread in many LDCs.

The workshop participants shared a general feeling that a range of promising, innovative technologies exists, in various stages of development, that can help LDCs sustain soil fertility with reduced

fertilizer inputs. However, most of these technologies are underused and many important ones are being ignored by the development community. Many of the innovative approaches discussed are "technologies" in the broadest sense; they are new management systems, not new pieces of hardware. Commonly, research on such innovative techniques is underfunded, perhaps because of technological complexity, human reluctance to stray too far from the norm, or well-intentioned skepticism about radically new and unproven approaches to agriculture. Thus it is all the more difficult to document their worth. Most of the technologies, while promising, need pilot-scale testing in appropriate environments to determine potential problems or necessary alterations before they can be promoted on a wide scale. Also, the workshop participants thought that much of the development of innovative technologies occurs outside of, and perhaps in spite of, the national and international institutions normally considered responsible for maintaining natural resources and for dealing with problems of land quality and productivity. A particularly interesting facet of these new technologies is that many of them could benefit not only LDC agriculture but also U.S. agriculture by providing opportunities for economic diversification, reducing soil degradation, and bolstering production while lowering capital costs.

No new technology, of course, can be a panacea. The importance of innovation lies in the fact that each new approach increases the number of options available to deal with problems. More choices thus provide increased adaptability to changing social, economic, and physical conditions.

Day 1. Innovative Biological Technologies (Highlights of Workshop Papers)

During "day one" of the workshop, a wide range of papers was presented by non-AID scientists on specific innovative biological technologies. Assembled below are highlights of the workshop papers as they relate to broad technological themes.

This planet is believed to house some 80,000 species of edible plants. Man, at one time or another, has used 3,000 of those for food Only about 150 plants have been cultivated on a large scale, and less than 20 crops currently provide almost 90 percent of the world's food.[1,2]

It is clear that mankind could exploit more fully the range of botanical diversity found on earth. In developing countries, especially, various innovative uses of plant resources hold great promise in helping to enhance land productivity and increase food supplies. First, it is possible to expand the range of crops grown by using underexploited plant species, especially certain native

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[1]Myers, N., 1979, The Sinking Ark, Pergamon Press, N.Y., pp. 57-58.

[2]National Academy of Sciences, 1975, Underexploited Tropical Plants with Promising Economic Value, p. 1.

species already adapted to local climates and conditions. Second, special attention could be devoted to the potential of leguminous species, including leguminous trees, that are capable of converting atmospheric nitrogen into a usable form and thus enhancing soil fertility while reducing reliance on expensive commercial fertilizers. Finally, innovative and conventional crops could be used together in multiple-cropping or intercropping systems designed for specific tropical environments so as to maximize efficient resource use and land productivity.

Underexploited plant resources

Every culture, of course, has indigenous species that have been used traditionally for food, fuel, livestock feed, construction, fiber, medicine, and other purposes, either gathered from the wild or cultivated in various small farming systems. But until recently, these traditional crops in LDCs had been lost in the shadow of the Green Revolution and westernized farming techniques.

Now, however, there is renewed optimism about the agricultural potential of many of these plant resources. Native plants can be innovative sources of a wide range of goods--food for people and livestock, fuelwood for cooking

and warmth, materials for homes and clothing, even oil seeds and other exports. The benefits provided in these many uses are compounded by the fact that native plants can require fewer total man-made inputs of fertilizer, herbicides, insecticides, energy, and in some cases water. This is because native species are adapted to local environmental conditions--soil type and quality, climate, and terrain. Indigenous species commonly are more resilient to stress, as well; they have evolved defenses for local disease and pest organisms and evolved to be efficient users of available resources, whether water, soil nitrogen, or other necessary nutrients. The native plant concept is a reversal of the old philosophy of using inputs to change the soil to suit the crop. Here the crop is chosen to suit the soil.

Examples:

Winged bean (*Psophocarpus tetragonolobus*): Generally identified as a "poor people's crop" in developing countries, the winged bean's nutritional potential has been vastly underrated. Actually, this plant, sometimes called a "supermarket on a stalk," has at least six edible parts. The leaves are used like spinach as a vegetable or salad; the flowers are edible, tasting somewhat like mushrooms; the pods, similar to green beans, are nutritious and palatable;

the seeds are similar to soybeans and are composed of 17 percent oil and 42 percent protein; the tendrils are also edible and taste like asparagus; and the below-ground tubers contain four times the protein content of potatoes.

Amaranth (Amaranthus hypochondriacus): Once the mainstay of certain ancient South American cultures, Amaranth is a fast-growing, cereal-like crop that produces high-protein grains in large sorghum-like seed heads. The grain is also exceptionally high in lysine--one of the critical amino acids usually deficient in plant protein. Amaranth grain is usually parched and milled to be used for pancakes, cooked for gruel, or blended with other flours. Its leaves can be eaten as a spinach substitute.

Leucaena (Leucaena leucocephala): Of all tropical legumes, leucaena probably offers the widest assortment of uses. It is a fast-growing tree which produces good, dense firewood; it fixes nitrogen in the soil; and its leaves make nutritious cattle forage. The leguminous tree is especially valuable in reforestation efforts.

Any change in agriculture's use of fertilizer, pesticides, irrigation, or machinery would depend entirely on the nature of the native plant chosen for cultivation,

whether the particular plant could be used on an intensive or extensive basis, the degree to which the plant is susceptible to pests, and many other variables. Fertilizer use, however, could be affected three ways by a switch to native plant crops:

- Farming leguminous (nitrogen-fixing) native plant species would produce crops with minimal fertilizer requirements (such species would still require phosphorus, sulfur, and micronutrients). The nitrogen produced is available to both the legume and to companion and follow-on crops.

- Some native species may require reduced fertilizer inputs because they are adapted to low-nutrient environments. Under such conditions, plant growth and production may be correspondingly low, although it will be higher than production from nonadapted plants.

- Some nonlegume native species may require optimal soil and water conditions and so require substantial amounts of fertilizer to achieve optimal production levels, thus proving no more attractive than conventional crops.

Water needs also vary with the specific species chosen for cultivation. Species adapted to tropical soils and moist

climates should not require irrigation if adequate rainfall occurs during the critical stages of plant development. In regions of less-than-optimal precipitation, farmers can choose native plants with low water requirements such as jojoba, atriplex, guayule, buffalo gourd, guar, cassia, and acacia species. It is also possible to enhance the effectiveness of water use through management (alternate fallow periods, spaced planting, etc.), water harvesting, and drip irrigation. Where land is not the limiting factor, enhanced water harvesting is showing high potential for fostering plant production under desert conditions. The most suitable plants for these technologies are deep-rooted tree crops, drought-adapted species, and biomass plantings.

Some native species also offer hope for intensive agriculture as certain plants could be developed for large-scale operations. If a low-value crop can be replaced with a high-value new crop, even irrigation may be justified. Close plantings, tillage, pest control, and fertilization may then be needed to optimize production and under certain circumstances might be economically viable. Grain amaranth, winged bean, and guar are only a few possible species for intensive development.

Equipment and labor needs also vary depending on the

specific native plant in question. Some species (e.g., guar or guayule) are amenable to mechanical harvesting. Many others, however, require manual labor, which could be an advantage where excessive unemployment exists.

To develop the potential of native plant resources, more effort should be devoted to identifying valuable species and adapting them to modern needs. Once identified, researchers need to look for opportunities to expand the plant's use into similar environments elsewhere in the world. Along with an improved understanding of the plant diversity available worldwide, there needs to be more openness to innovation and acceptance that folkways are often valid and could be incorporated into a productive compromise between old and new customs.

Multiple Cropping

Multiple cropping is intensive agriculture where two or more crops share space and resources, enhancing both land-use efficiency and long-term productivity. It is not a new technology but rather is at its roots an ancient technique that mimics the diversity of natural ecosystems. Today's multiple-cropping systems vary greatly depending on the character of the site being farmed. In general,

multiple-cropping systems are managed so that total crop production from a unit of land is achieved by growing single crops in close sequence, growing several crops simultaneously, or combining single and mixed crops in some sequence. Both "sequential cropping," which is growing two or more crops in sequence on the same land, and "intercropping," which refers to various ways of growing two or more crops simultaneously on the land, are included in the broader term "multiple cropping."

Generally, productivity on multiple-cropped land is more stable and constant in the long run than in monocultures (Gliessman, pp. 5,6). Although each crop in the mixture may yield slightly less than in monoculture, combined production per unit area can be greater with multiple-cropped fields. The overall increased yields result because the component crops differ enough in their growth requirements so that overlapping demands--whether for sunlight, water, or nutrients--are minimal. Multiple cropping, in effect, broadens the land's productive capacity by more fully exploiting the dimensions of time and space.

It is important to point out that certain crop mixtures will not produce improved yields when multiple-cropped. Certain combinations make better overall use of available

resources and will be more successful; these crops are considered "complementary." One of the main ways to achieve such complementarity is by varying the crop components temporally--that is, using sequential planting to achieve a multiple-cropping system that avoids antagonistic interactions between the components. Such systems require special management: timely harvesting, the use of proper varieties, alteration of standard planting distances, special selection of herbicides so as not to create antagonisms or residual effects, etc.

Another way of complementing crop components is through intercropping based on relay planting. Direct competition is avoided by planting a second crop after the first one has completed the major part of its development, but before harvest. Research on relay cropping in Mexico and Latin America shows definite yield advantages, especially for corn and beans (Gleissman). The success of relay intercropping depends on the correct combinations of timing and other variables so as to avoid shading, nutrient competition, or inhibition brought about by toxicity produced by the decomposition of previous crop residues. Research in these areas is inadequate.

Finally, farmers can get maximum complementarity in

systems where two or more compatible crops are grown simultaneously, either in rows, strips, or mixed fields. For example, traditional corn, bean, and squash systems grown in Mexico show how three species can benefit from multiple cropping. All three crops are planted simultaneously but mature at different rates. The beans, which begin to mature first, use the young corn stalks for support. The squash matures last. As the corn matures, it grows to occupy the upper canopy. The beans occupy the middle space and the squash covers the ground. Research shows that the system achieves better weed and insect control than where the crops are grown separately. And while the beans and squash suffer a distinct yield reduction, corn yields are significantly higher than in comparable monocultures. It is still uncertain whether the higher yields are the result of more efficient resource use or if some mutally beneficial interaction is occurring among the crop components.

Agroforestry, as it sounds, is a multiple-cropping management technology that combines tree crops with food crops, animal agriculture, or both. Like other multiple-cropping systems, its goal is to optimize land productivity while maintaining long-term yields (Gleissman, p. 31). In the past, small-scale traditional agriculture

commonly included trees as part of the farm design, but interest in agroforestry's place in modern agriculture is just beginning. Agroforestry systems can be used to bring marginal lands into production--lands with steep slopes, poor soils, or widely fluctuating rainfall. But tree-crop combinations can also be used on prime agricultural or grazing land to further increase productivity. The main limitations to widespread use of agroforestry practices at present is lack of knowledge and expertise and unwillingness in the agricultural establishment to accept the idea of long-term, diversified yields.

The key to multiple cropping's benefits is the intensity of the cropping pattern--drawing as much as possible from the land resource. Despite the intense demands, such systems need not abuse the land; through proper design and operation, multiple-cropping management can sustain and actually enhance soil fertility. Depending on the multiple-cropping system used, advantages can include:

- More efficient use of vertical space and time, imitating natural ecological patterns, permitting a more efficient capture of solar energy and nutrients;

- More biomass (organic matter) available to return

to the soil system;

- More efficient circulation of nutrients, including "pumping" them from deeper soil profiles when deep-rooted species are used;

- Possible reduced wind erosion because of surface protection;

- Promise for marginal areas, as it can take better advantage of variable soil types, topography, and steeper slopes;

- Reduced susceptibility to climatic variation (especially precipitation, wind, and temperature);

- Reduced evaporation from soil surface;

- Increased microbial activity in the soil;

- Improved efficiency of fertilizer use through the more diverse and deeper root structure in the system;

- Improved soil structure, less likelihood to form "hardpan," and better aeration and infiltration;

- Reduced fertilizer needs because legumes fix atmospheric nitrogen for themselves and associated

nonlegumes;

- Improved weed control from heavier mulch cover;

- Improved opportunities for biological control of insects and diseases because of increased plant diversity;

- Potential benefits from mutualisms and beneficial interactions between organisms in crop mixture systems.

But as previously mentioned, certain crop combinations do not lend themselves to successful multiple cropping, and some forms of multiple cropping are not necessarily good for the land. Sequential cropping, for instance, of two or three crops can actually mine the land of nutrients and minerals if little thought is given to legume rotations, green manures, animal manures, or other fertility-building activities. And in light of the biological and physical aspects of the agroecosystem, other disadvantages in multiple cropping might include:

- Competition for light, soil nutrients, or water;

- Possibility for allelopathic influences between different crop plants caused by plant-produced toxins;

- Potential to harm one crop component when

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harvesting other components;

- Difficulty building a fallow period into multiple-cropping systems, especially when long-lived tree species are included;

- Difficulties in mechanizing various operations (tillage, planting, harvest, etc.);

- Increases in evapotranspiration caused by greater root volume and increased leaf surface areas;

- Possible overextraction of nutrients, followed by their subsequent loss from the agroecosystem if they are exported as agricultural or forest products;

- Damage to shorter plants from leaf, branch, fruit, or water-drop from taller plants;

- Higher relative humidity in the air that can favor disease outbreak, especially of fungi;

- Possible proliferation of harmful animals (especially rodents and insects) in certain types of systems.

Even though it seems that the biological and physical advantages of multiple cropping outweigh the disadvantages, there also is a range of social and economic factors that

would influence the acceptance and use of multiple-cropping technologies in various cultures. In terms of social stability, multiple cropping is advantageous because it leads to a diverse agricultural system. Such a system is less susceptible to damage from climatic variation, environmental stress, and pest outbreaks. It is also less vulnerable to swings in crop prices and markets. Multiple cropping also demands more constant use of local labor and provides a more constant output of harvested goods over the course of the year. And because such systems are highly adaptable, they can be melded into many different types of cultures without undue stress on existing local customs. Multiple cropping also provides farmers with a large variety of useful products, depending on the type and complexity of their systems. And, of course, multiple-cropping systems can reduce the need for fertilizers and other energy imports, thus giving LDC farmers improved economic stability and self-sufficiency.

Reported lower yields, complexity of activities and management, higher labor demands, and difficulty in mechanizing operations that discourage modern farmers from multiple cropping. Conventional agriculture is looking for short-term profits rather than at maintaining constant income

over the long term, although it seems that the economics of farming may be changing to favor such innovative systems, especially in LDCs.

Although the tangible disadvantage of potentially lower yields exists, most disadvantages involved in multiple cropping are derived from our lack of experience and knowledge about the workings of complicated agroecosystems.

Biological Nitrogen Fixation

One of the most promising multiple-cropping strategies is the increased use of leguminous plants for the multiple purposes of food, livestock fodder, and wood while concurrently improving soil fertility. Leguminous plants--for example, temperate species such as alfalfa, soybeans, and clover--have the capacity to provide their own nitrogenous fertilizer through bacteria (Rhizobia) that live in nodules on their roots. The bacteria chemically convert atmospheric nitrogen into a form that the plant can absorb and use. The nitrogen also is available in the root zone for nonleguminous companion or follow-on crops to use.

Legume use is not a new technology; generations of farmers relied on rotations of legume plants to restore nitrogen in the soil long before the advent of cheap

commercial fertilizers. Now, as energy costs skyrocket and fertilizer costs become economically prohibitive in many developing countries, legume use--green manure--may be the best remaining option for maintaining soil fertility and agricultural productivity.

Leguminous species could not only help protect LDCs from burgeoning energy costs but could also improve local nutrition. Nutritionally, legume seeds (beans or pulses) are two to three times richer in protein than cereal grains. Many have protein contents between 20 and 40 percent; a few even range up to 60 percent. This is particularly important because there is chronic protein deficiency in virtually every developing country.[1]

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[1]National Academy of Sciences, 1979, Tropical Legumes: Resources for the Future.

Biological Nitrogen Fixation (BNF) Inoculant Technologies: Nitrogen can be converted into forms usable by plants through industrial processes, but only at great cost, especially as energy prices escalate. But BNF by symbiotic associations of plants with microorganisms may be an economically and environmentally sound approach to sustainable agriculture (Halliday).

Farmers can capitalize in two ways on certain plants' innate ability to fix nitrogen biologically. First, of course, they can use legumes in their cropping systems and benefit from the nitrogen produced as have past generations of agriculturalists. But recent innovations also can help farmers maximize nitrogen fixation through inoculant technology. With this technique, selected legumes can be inoculated with specific strains of rhizobium, the soil bacterium that associates with certain legume roots and fixes nitrogen. This way farmers can more fully exploit the plant's fertilizing capabilities.

Most soils harbor various native rhizobial populations and these strains will associate with sprouting legumes. But because these strains differ greatly in their symbiotic effectiveness, it can be to the farmer's advantage to plant legume seeds that have been inoculated with proven strains of

rhizobium. The objective of inoculation technologies is to introduce sufficiently high numbers of preselected strains of rhizobia into the vicinity of the emerging root so that they have a competitive advantage over any indigenous soil strains of lesser N-fixing ability.

Commercial scale inoculant use is common in the U.S. and Australia. Brazil, Uruguay, Argentina, India, and Egypt also produce inoculants. But while demand for inoculants is growing in many countries, it is not enough to simply import U.S. or other inoculants because they may not be suitably adapted to the LDC's climate, soils, and farming systems. BNF can be improved by selecting effective rhizobium strains from the local environment and culturing them. In fact, the only major scientific constraint on developing BNF technologies at present is our inadequate understanding of the interactions among specific host legumes, rhizobial strains, and various environments, resulting in an inability to predict whether a given legume will respond to inoculation in a particular region. A lack of trained personnel in tropical regions also acts to limit research and development efforts. And because inoculant development and use requires some technical training, it may not be an easy technology for LDCs to adopt widely. But while legume use holds potential

in all segments of agriculture, inoculant technology at present should only be advocated when there is a known need to inoculate.

Most legumes in the tropics fix about 100 kg/ha/yr of nitrogen, although nitrogen fixation of the forage tree Leucaena can fix as much as 350 kg/ha/yr and some other species can fix as much as 800 kg/ha/yr. However, the benefit to nonlegumes, because of the inclusion of legumes in a cropping system, is small compared to the level of nitrogenous fertilizer used in the intensive cereal production systems of the developed world. It is unrealistic to think that biologically fixed nitrogen will replace commercial fertilization of cereal and root crops, as these crops are known to respond to levels of nitrogen far in excess of those that could currently be supplied through legume BNF. Thus it would be profitable to determine ways to increase the contribution of legume BNF as a complement to nitrogen fertilizers rather than as an alternative.

Although legumes seem unlikely to replace commercial fertilizers, fertilizer savings through the use of legumes could represent a significant savings in foreign exchange, reduce dependence on energy-rich nations, and lend increased stability and diversity to LDC agriculture.

Leguminous plants: A great variety of leguminous plants--both food crops and species useful for fuelwood, fodder, and other needs--exists that could be cultivated in moist and arid/semiarid tropical climates. (For a more detailed discussion of many of the moist climate species, see the NAS report Tropical Legumes: Resources for the Future.) Winged bean, as mentioned, is one particularly valuable leguminous species. Tarwi, tepary bean, and yam beans are also nitrogen-fixing species with potential in moist tropical environments.

Some leguminous species can thrive where water is scarce. Adapted plant species thus could be used in arid and semiarid regions, serving not only to enhance land productivity but also to stimulate depressed economies.

For example, leguminous trees such as Acacia, Leucaena, and Prosopis could be important, fast-growing fuelwood sources. Because 80 percent of the wood consumed in the Third World is used as fuel and wood shortages are of crisis proportions in some areas, the potential of agroforestry seems good.

In arid/semiarid regions, of course, water availability is a key factor in agricultural productivity. But problems

are compounded in some dry environments where soils also have low fertility. In these areas, drought-adapted, deep-rooted, nitrogen-fixing tree species (such as Acacia albida and Prosopis cineraria), perennial arid-adapted herbaceous legumes (such as Zornia and Tephrosia), and shrubby legumes (such as Palea species) could increase soil fertility and triple or quadruple water use efficiencies. By bolstering soil fertility with tree species, it is possible to create a system where production of food staples is water-limited rather than fertility-limited. And intercropping traditional, annual food staples such as millet, sorghum, groundnuts, and cowpeas with leguminous trees can actually stimulate crop yields (Felker, p. 7).

Livestock fodder and cash crops can be obtained from arid species. Arid-adapted, salt-tolerant shrubs (such as saltbush--Atriplex species), the pods of leguminous trees (such as Acacia tortilis, Acacia albida, and Prosopis species), and even cactus (Opuntia and Cereus) can expand the amount of forage available for local livestock while improving soil quality and enhancing the stability of the grazed ecosystems. LDC farmers also could benefit from growing perennial, arid-adapted plants as cash crops. The species jojoba is under development in southern California,

Arizona, Mexico, and various of the semiarid LDCs, and produces seed that contains a rancidity-resistant, nonallergenic, liquid wax with lubricating properties equivalent to oil from the endangered sperm whale (Felker, p. 12). Another desert plant, guayule, contains latex and could become a major semiarid crop for rubber production. Other potential lies with various species of drought-adapted leguminous trees that might be useful for the gums they exude, cacti that produce table-quality fruits, and a number of other innovative plant resources.

Surprisingly, relatively little work is being done to further current knowledge about some of these highly promising plant resources. But as energy, fertilizer, irrigation, and other costs escalate, it seems inevitable that farmers in arid and semiarid regions will look more to adapted crops.

Optimal water use efficiency in an arid/semiarid agroecosystem demands a mix of nitrogen-fixers and water-to-dry-matter-conversion specialist plants. For instance, cacti are a better supplier of the energy portion of livestock feed than legumes because they have a fivefold greater efficiency converting water to dry matter (Felker, p. 20). However, legume-leaf litter is important to create good

soil fertility in order for the cactus to achieve its maximum water use efficiency--so a mix of the plants is needed. And because livestock need energy and protein, both energy- and protein-producing plants are required.

Similarly, appropriate use of arid-adapted legumes can increase fertilizer use efficiency. Adapted legumes do not require nitrogen themselves, and when properly incorporated into a diversified agroecosystem they will reduce nitrogen needs for nonlegumes as well. Many arid-adapted plants, both legumes and nonlegumes, have deep root systems--an advantage in that they are thus capable of extracting nutrients and minerals from deep subsurface soil layers. Also, the deeper rooted species should capture a higher portion of any fertilizers applied because the nutrients are not as likely to leach beyond the root zone. As an added benefit, wind and perhaps water erosion might be reduced, as many of these plants are perennials and thus keep the soil more adequately protected.

There are no major scientific constraints to using arid-adapted plant resources in LDC agriculture, but there is great need for expanded research and development efforts. And the potential paybacks could be great. Environmental impacts, too, are overwhelmingly positive, including the

potential to halt desertification in arid regions.

Political and social constraints exist, however, that might limit the use of innovative plants. Cultural traditions, for instance, are not easily changed and innovation must blend into existing values systems and local behavior. If, as in Sahelian Africa, free-roaming goats devour young tree seedlings because tradition allows the goats to forage unrestrained, reforestation attempts must take this into account and devise goat-proof protection for the young trees.

Other social influences, too, can make the acceptance and use of innovation difficult. This is especially clear in research centers run by scientists either from or trained in developed countries; consciously or not, they sometimes strive to promote their own cultural values and ignore the methods and effectiveness of native farming systems. As was the case with Acacia albida, the scientists may not be broadly trained--the agronomists failing to see the tree's food potential and the foresters underestimating its uses because it does not grow in forests and hence is not part of standard sylviculture concepts. It is not lack of concern that causes this problem but rather that some agricultural scientists tend to be overspecialized and limited in their

experience. Also, administrative structures sometimes thwart attempts to develop integrated, innovative programs.

In practical terms, such innovative biological technologies offer real hope for LDC farmers. And the scale need not be so big. A farmer, for instance, could plant 1 hectare with 200 Prosopis trees at 15 cents each for a total cost of $30. Land, a shovel, and buckets for watering the seedlings are the only prerequisites. With protein and nitrogen contents of 12.5 percent and 2.0 percent, respectively, pods from the trees could in 2 or 3 years produce 60 kg of nitrogen and return the $30 initial investment.

Many of the innovative systems now receiving attention from various segments of the scientific community are actually widely used by subsistence farmers in developing countries. However, the plants under cultivation mostly are of unselected genetic stock. It is comparable, in fact, to the use of unselected races of maize and wheat that were in use in the late 1800s in the U.S. and Europe. So, subjecting the innovative species to a rigorous research and development effort could be expected to produce yield increases--perhaps twofold and threefold in 15 years--and other beneficial refinements of considerable value to people of the Third

World. And yield increases in tree legume production, fuelwood production, cash crop production, soil fertility, and ensuing staple food production would have repercussions throughout the economy: more income; greater demands for goods; a larger tax base to support roads, schools, and health services; and increased employment. But working within the bounds of the ecosystems, innovative plant resources can help agrarian societies ensure sustainable and stable agriculture.

Mycorrhizal Fungi

Nitrogen is one of the nutrients essential to plant growth. Thus another approach to enhancing LDC agriculture without inputs of commercial fertilizers is to find ways to increase the effectiveness of the plant's use of soil nutrients.

Selective plant breeding, of course, still holds great potential for developing varieties of innovative and traditional crops with improved resistance to environmental stress. Geneticists have made extraordinary strides in breeding varieties that respond to commercial fertilizer inputs; similar efforts could help locate and develop plants that would grow and prosper under less-than-ideal conditions--marginal lands, variable climates, or nutrient-poor soils. This potential amplifies the importance of preserving native plant resources, both in seed storage facilities and in their natural habitats, because geneticists necessarily turn to hardy, native stocks as sources of genetic material to improve or strengthen cropped varieties.

There is another "biotic fertilizer" that might aid LDCs in their quest for sustainable agroecosystems. Mycorrhizal fungi are beneficial soil fungi that live symbiotically with

a vast range of plants. Mycorrhizae are the structures formed--part plant, part fungus--by the symbiosis. These structures can extend up to 8 cm from the root into the surrounding soil, providing a bridge to transport nutrients back to the roots. The host plant obtains nutrients via the mycorrhizal fungi, while the fungus obtains sugars or other foods from the plant. The assocation results in a marked increase in the host plant's growth.

There are many species of mycorrhizal fungi that form mycorrhizae and can enhance plant growth. These fungi are so common, in fact, that literally any field soil sample from the Arctic to the tropics will contain some (Menge). The most common type, vesicular-arbusula (VA) mycorrhizae, occur on liverworts, ferns, some conifers, and most broad-leaved plants including agronomically important species such as wheat, potatoes, beans, corn, alfalfa, grapes, date palms, sugar cane, cassava, and dryland rice. Only 14 plant families are considered primarily nonmycorrhizal.

The fungi essentially increase the surface area of the plant's roots for absorbing nutrients. They actually can increase the plant's absorptive area by as much as ten times (Menge). The fungi also extend the host plant's range of uptake; nutrient ions that do not readily diffuse through the

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soil--such as phosphorus, zinc, and copper--can be tapped from beyond the normal root zone by the fungi. Absorption of normally immobile elements can be increased by as much as 60 times by the plant-fungi symbiosis (Menge, p. 9). Perhaps the most important benefit provided by mycorrhizal fungi is increased phosphorus uptake. They also stimulate plant absorption of zinc, calcium, copper, magnesium, and manganese. Plant uptake of mobile soil nutrients such as nitrogen and potassium is rarely improved because normal soil diffusion typically supplies adequate amounts of these regardless of root size.

Mycorrizal fungi also can assist plants by their ability to enhance water transport, prevent water stress under some conditions, enhance salt tolerance, and act to increase modulation by symbiotic nitrogen-fixing bacteria such as rhizobium (Menge).

However, limitations exist for using mycorrhizal fungi as biotic fertilizers. Mycorrhizal fungi already occur in most soils and thus already grow in association with most agronomic crop plants. Because these fungi are so widespread, immediate needs for inoculation are limited. The inoculants available are for use on disturbed sites (strip-mined areas where indigenous mycorrhizal populations

have been destroyed), on fumigated soils (any forest, crop nursery, or plot that has been treated to remove soil-borne pests), and in greenhouses (because sterile soils lack mycorrhizal fungi). In these situations, inoculation with mycorrhizal fungi has proven beneficial--for example, in fumigated sand or soil, VA mycorrhizal fungi will increase the growth of citrus by as much as 1,600 percent, grapes by 4,900 percent, soybeans by 122 percent, pine by 323 percent, and peaches by 80 percent (Menge). Growth improvements also show in cotton, tomatoes, corn, wheat, clover, barley, potatoes, and many other crops.

But even though large-scale field inoculations with mycorrhizal fungi are rare because of adequate indigenous populations and because of limited inoculum availability, it seems likely that such applications might be much more valuable if, for instance, scientists develop mycorrhizal fungi inoculants that are superior to native populations. Because many indigenous mycorrhizae are relatively inefficient symbionts, improved strains of fungi could enhance plant growth, even in nonsterile soils. And because huge expanses of tropical soils (such as the Brazilian Cerrado) are either deficient in phosphorus or immobilize added phosphorus fertilizers, mycorrhizal fungi could improve

the productivity of the marginal lands if fungi having the ability to extract small quantities of phosphorus were developed and added to the soil. Ultimately though, even with mycorrhizae present, the soil's phophorus supply could be depleted and phosphorus would have to be added to maintain plant growth.

Even though mycorrhizal fungi inoculants are used commercially in some circumstances, their importance is limited and many questions about their effectiveness remain unanswered. For instance, fumigating fields with methyl bromide, a biocide that is extremely toxic to mycorrhizal fungi, often is followed by stunted growth in following crops. Yet little work has been done to determine the feasibility of field-scale application of inoculants even though it seems that such inoculations should be economically possible (Menge, p. 17). And even in nursery crops grown on sterile, nonmycorrhizal soils, inoculations receive limited use in part because detailed information regarding their value is lacking. For tree crops, however, some of the answers may be soon in coming; the U.S. Forest Service has undertaken a massive testing program using commercial inoculum on tree nursery sites throughout the country. When the tests are complete (within 4 years) they should indicate

the commercial feasibility of producing and using mycorrhizal inoculum in fumigated tree nurseries.

Three major obstacles hinder further development of this biotic fertilizer. First, no large-scale field experiments using mycorrhizal fungi under normal agricultural conditions have been conducted, yet such work is a necessary forerunner to actual use of the fungi. Second, cost-benefit analysis is warranted to determine the economics of mycorrhizal applications. And, finally, agriculture itself must shake loose of some conventionality; it seems locked to practices for increasing soil fertility that only involve use of commercial chemical fertilizers.

Because mycorrhizal fungi increase the efficiency of fertilizer use, they can be thought of as biotic fertilizers and could indeed be substituted for substantial amounts of some fertilizer components (Menge, p. 12). Considering estimates that 75 percent of all the phosphorus applied to crops is not used within the first year and thus reverts to forms unavailable to plants, especially in tropical soils, it seems that further work on improving mycorrhizal fungi effectiveness could aid LDCs in developing sustainable agricultural systems.

Azolla/Algae Symbiosis

Rice--one of the most important staple crops in the world--demands rich, fertile soil. But traditional legume crops do not make good green manures for rice farmers; they are reluctant to devote part of the valuable growing season to a relatively slow-growing legume crop, and most legume crops cannot grow or fix nitrogen in flooded or waterlogged soils. But both these disadvantages can be avoided. Through the use of azolla, a small aquatic fern native to Asia, Africa, and the Americas, rice farmers can have access to a fast-growing green manure that thrives in paddy-like conditions.

Azolla is a genus of small ferns that live naturally in lakes, swamps, streams, and other bodies of freshwater. Its important agricultural potential lies in the fact that azolla lives in a symbiotic relationship with a nitrogen-fixing blue-green algae, Anabaena. The delicate azolla fern provides nutrients and a protective leaf cavity for the Anabaena. In turn, the algae produce enough nitrogen to meet the needs of both plants and then some. Under the right conditions, the fern/algae combination can actually double in weight every 3 to 5 days and fix nitrogen at a higher rate than most legume/Rhizobium symbionts. In 25 to 35 days,

azolla can easily fix enough nitrogen for a 4 to 6 ton/ha rice crop during the rainy season or a 5 to 8 ton/ha crop under irrigation during the dry season. The nitrogen fixed by the fern/algae combination becomes available to the rice after the azolla mat is incorporated into the soil and its nitrogen is gradually released as the plants decay.

Azolla's value as a green manure for flooded crops has been known for centuries by the people of the People's Republic of China (PRC) and Vietnam. But its use was relatively limited; few families knew the intricate techniques needed to overwinter and oversummer the sensitive fern successfully, and these families controlled the distribution of starter-stocks in the spring. After the recent revolutions in the PRC and Vietnam, the new governments eventually recognized the value of azolla and began promoting its use officially, but their efforts were minimal and progress was slow. It is only recently that worldwide attention has focused on the plant and that continued serious efforts havebeen made to search for hardier varieties for widespread use.

Azolla's ability to enhance soil fertility occurs both because it is an input of nitrogen and of organic matter. Nitrogen, of course, is a necessary plant nutrient. Humus,

the rich organic material formed through plant decomposition, increases the water-holding capacity of the soil and promotes better aeration and drainage. Organic matter also can bind soil particles together, thereby improving the soil structure and its productivity.

Azolla also is important in the cycling of nutrients. While it is growing, the plant not only fixes nitrogen but absorbs nutrients out of the water, nutrients that otherwise might be washed away. Some nitrogen and other nutrients, then, are stored in the living plant matter until the fern/algae mat is incorporated into the soil and begins to decompose. Because it has a rather high lignin content, azolla decomposes relatively slowly--6 weeks or more before all the nutrients are released. This natural slow-release is ideal for the developing rice crop.

In addition, it seems that azolla suppresses the growth of certain aquatic weeds--in part because the thick azolla mat deprives young weeds of sunlight and in part because the interlocking mat physically inhibits weed emergence. Rice seedlings are not harmed because, when transplanted, they stand above the azolla mat.

Using any green manure crop requires some adjustments in

a farmer's crop management scheme. Depending on the local environments, azolla can be grown as a monocrop, intercrop, or both. If the fern is grown as a monocrop, it is grown and incorporated into the soil before the rice is harvested or it is grown and transported for use on upland crops. Azolla is often intercropped in areas where there is too short of a growing season for successful monocropping. One method grows two rows of rice planted about 4 inches apart with the azolla growing in larger, two-foot spaces on either side of the double rows. The azolla will be incorporated by hand or with a rotary rice weeder. Combining monocropped and intercropped azolla provides nitrogen before transplanting and throughout the growing season. At present, azolla's primary role is as a spring green manure and its secondary role is as a fall manure. It is highly susceptible to pests and temperature extremes and generally is not grown in summer.

To be successful, azolla requires phosphorus fertilizer (0.5-1.0 kg P/ha/week), but this is not necessarily an increase over the fertilizer needed to produce a rice crop. Rice, too, requires phosphorus; so, rather than applying it directly to the rice, the fertilizer can be given to the azolla first in small weekly doses. Once the azolla is incorporated into the soil and begins to decompose, the

phosphorus becomes available to the rice crop. Other inputs that enhance azolla growth in certain soils (e.g., potassium) are usually also applied for a high-yielding rice crop and so can be cycled in a similar way.

Water is the primary environmental constraint on azolla cultivation. As a free-floating, aquatic fern, azolla can only grow in areas with abundant, stable water supplies. Although it can last for months under refrigeration, the plant cannot survive for more than a few hours on a dry soil surface under direct summer sun. And the azolla varieties now available are not very tolerant of stress; azolla cannot live in water outside a 0°-to-40°C range, and for adequate growth the daytime temperature should stay within 15° to 35°C. Humidity and pH also are variable in azolla growth.

Because the technology to grow azolla from seeds (spores) does not exist, some plants (1 to 10 percent of the inoculation requirements) must be maintained throughout the year. Because of azolla's sensitivity to temperature stress, the overwintering and oversummering periods are critical. The plant is also susceptible to a number of insect and disease pests. The pests are especially destructive during the summer and must be controlled carefully. In fact, the primary reason why azolla is not cultivated during the summer

is because of the destruction caused by rampant insects.

There are also cultural and economic constraints on azolla cultivation. As with any innovation, it can be difficult for people to accept an idea that is foreign to their traditions. The idea of growing an aquatic legume is fundamentally different from most farming societies' norms, and in many hungry countries, the idea of growing a crop just to plow it under seems utterly impractical. Azolla cultivation may be slow in gaining acceptance, too, because it demands a year-round commitment not usually required of rice farmers. And because azolla cultivation is not applicable in areas where rice is broadcast-sown, it is not a viable technology for those regions that do not plant rice in rows.

Finally, social and political factors can work both for and against azolla's use. In some regions, especially where there are unfavorable land ownership patterns, low prices, or other strong disincentives, farmers may not be willing to shift from their immediate-subsistence, s times-haphazard, plant-and-harvest approach because they may not see long-term benefits as to their advantage. Political systems, too, can have an effect. The successful azolla programs in China (PRC) and Vietnam depend heavily on specially trained "azolla

teams" made possible by the structure and discipline of their farming communes and cooperatives. Societies less centrally organized could have difficulty adopting and transferring azolla cultivation techniques as readily.

One of the major constraints on the development of azolla technologies is simply lack of information. Although it is an ancient agricultural system, its use has always been limited in extent and it has not received much scientific attention. Research efforts are disorganized, scattered, and often repetitious. There has not been an international discussion of azolla research priorities. And once again, traditional segmented research approaches have proven inadequate as many of the problems that remain to be solved require a multidisciplinary approach. It is within the power of current funding agencies to provide some of the needed direction.

At present, azolla is cultivated as a green manure on about 2 percent of the harvested rice area of China (PRC) and about 5 percent of the spring rice crop. In Vietnam, azolla grows as a winter green manure for 8 to 12 percent of the total harvested area, and about 40 to 60 percent of the irrigated spring rice in the Red River delta. But these two countries are only two of many that might tap azolla's

potential. With research, strains could be found that are less sensitive to summer insects and temperature. Cultivation could increase substantially. In essence, using azolla in rice production exchanges labor for nitrogen fertilizer. In countries with a shortage of cash but plentiful labor, azolla technology could be a needed step toward sustainable agricultural productivity.

Animals

Those interested in having developing countries improve their standards of living tend to promote resources and technologies with which they have already had experience or for which they already have respect. One hears much, for example, of how genetic engineering can be expected to make such conventional crops as wheat and corn into nitrogen fixers. While understandable, an exclusive preoccupation with increasing the productivity of "mainstream" species overlooks the potential of others indigenous to developing countries that have the further advantage of being relevant to the customs and values of their citizens.

If, as discussed elsewhere, there are unfamiliar plants ripe for development as sources of food, feed, fiber, and fuel, so are there unfamiliar animal species at least as promising. Man has traditionally relied for meat and hides primarily on animals that have been domesticated since prehistoric times. Domestication of some creatures not usually raised in captivity could pay dividends. In some countries, in fact, it already has.

Small animals, for instance, are particularly suited to domestication in many developing countries because they

require little space, fit well into village or urban life, and require no refrigeration, since they can be eaten in one meal.

Moreover, many of these species withstand the climates of developing countries better than do sheep, cattle, and pigs, and they thrive on readily available diets that larger species could not tolerate. Thus snail farming in Nigeria, giant toad farming in Chile, and guinea pig farming in Peru are being developed to supply native people who otherwise get little meat or fish, with much-needed high-quality protein at affordable costs.

In addition, the experience to date is that at least some of these ventures can become the basis of new industries. Thanks to the efforts of researchers at the La Serena campus of the University of Chile, for example, intensive methods have been developed that furnish grocery stores, restaurants, and canneries with 10 to 15 tons of giant toad legs a year. Because the meat has an attractive white color and tastes like a blend of chicken and lobster, it could prove to be a lucrative export as well.

Making this more likely is that the giant toads are reportedly easy and inexpensive to rear. Once put in

isolated ponds (so that they will not cannabilize other aquatic life) and supplied with insects attracted to their homes by flowers, shrubs, and rotten fruit, they require little attention and reach their market weight of about half a pound in 2 years.

The domestication of exotic species is, in fact, already producing foreign exchange for at least one poor country--Papua New Guinea. There, people who used to hunt crocodiles in the wild are now more profitably rearing hatchlings in captivity for the world skin market. And in remote jungle villages butterflies are being raised on "farms without walls" to meet the rising international demand from museums, entomologists, private collectors, ordinary citizens, and the decorator trade.

The upshot is that two crocodile species, once headed for extinction, are now flourishing and that the number of butterflies is not diminishing because the program relies on healthy wild populations to keep the "farms without walls" stocked. Both projects demonstrate that development and the conservation of natural resources can go hand in hand.

They also demonstrate something else: that to succeed, such projects need not only a concern for development but

also a sensitivity to local environmental conditions and knowledgable inputs of science and sociology.

In Papua, New Guinea, for instance, the introduction of western-style cattle-ranching or crop-farming could threaten the fragile tropical forest ecosystem, and natives would have to master unfamiliar imported technologies. By contrast, crocodile and butterfly farming that can be based on sound ecological principles would make it advantageous for the natives to use indigenous renewable resources wisely.

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Zeolites

Zeolites are natural, three-dimensional, fine-grained minerals about 1/1,000 mm in diameter containing silica, alumina, water and alkalai, and alkaline earths. Zeolites can lose and gain water and gases reversibly, and readily exchange some of their constituent elements without major changes in their structure. They contain open spaces in their structure, and as a result certain other compounds having the proper size can move into these spaces, but larger molecules cannot. This property gives rise to the name of this category of minerals--"molecular sieves." Nearly 50 natural species have been identified; over 100 other forms have been synthesized in the laboratory and are now the mainstay of the multimillion-dollar molecular sieve businesses that have been developed for a variety of industrial purposes by U.S. and foreign chemical and petrochemical firms.

The widespread dispersion of natural zeolite sediments of volcanic origin and their special properties should make them of interest to countries wishing to rely less on expensive imported chemical inputs to produce food. More specifically, they seem promising as a means to improve certain aspects of animal husbandry, fish production, and

crop yields. Although their existence has been known to scientists for at least 200 years and they have been used since antiquity as building materials, their potential agricultural and aquacultural applications were virtually ignored until about 20 years ago. Even now this technology must be said to be suffering from neglect.

Zeolites, when added to animal feed, can inhibit development of mold during storage as well as increase the growth rates of swine, rabbits, poultry, beef, and dairy cattle. Moreover, animals raised on zeolite-enriched rations tend to be free of diarrhea or other ills. Consequently, zeolites are a possible alternative to the controversial use of antibiotics for promotion of livestock well-being and growth.

Besides thriving on zeolite-supplemented diets, animals fed these minerals produce excrement that is almost odorless and an exceptionally good fertilizer. This is because zeolites capture the ammonia ion from the feces and hold it in open spaces inside the zeolite crystals. Thus direct zeolite treatment of manure to reduce odor and improve its efficacy as fertilizer is feasible. And the absorption properties of natural zeolites can be used to obtain pure methane for energy purposes from animal or other organic

wastes.

In summary, the application of zeolites to animal husbandry appears promising from the perspectives of livestock production, pollution control, crop yields, and cheap alternatives to conventional fossil fuels on individual farms or in small communities.

Zeolite technology also has potential for commercial breeding and raising of fish that is fast becoming a major business in the United States and elsewhere. For one thing, the rations now fed to fish in such enterprises are quite expensive. Because the nutritional requirements of fish are similar to those of poultry, the indications are that zeolite supplements could be expected to reduce feeding costs.

For another, many fish species are raised in closed or recirculating water systems where the accumulation of nitrogen from their droppings and the decay of uneaten food commonly results in fish sterility, stunted growth, and high mortality. Although various means already are used to deal with these problems, zeolite regulation of the nitrogen content of fish ponds has been reported to be cheaper and, under low temperature conditions, more reliable.

Similarly, the affinity of zeolites for nitrogen can

probably be brought to bear on ponds and small lakes where eutrophication results in an oxygen-poor environment detrimental to fish life. Tests suggest that the ability of these minerals to introduce free oxygen into stagnant water should increase the number of fish that can be raised or transported in a given volume of water.

The properties of zeolites seem to improve the performance of some chemical fertilizers and herbicides and to serve as an effective carrier of these and of pesticides and fungicides. For example, zeolite-treated soils retain the nutrients supplied by chemical fertilizers longer than soils treated with the fertilizers alone, and the presence of zeolites as soil conditioners (also known as soil amendments) has also been found to pace the release of critical nutrients from fertilizers for uptake by plants. Improved yields of wheat, apples, eggplant, carrots, sorghum, radishes, chrysanthemums, and sugar beets have been reported as a result of zeolite-treated soils. Zeolites also can remove toxic heavy metals from the soil, thus preventing the metals from moving up the food chain from plants to animals and, ultimately, to man. Consequently, zeolites may play an important role in agriculture in the safe use of sewage containing heavy metals.

Nonetheless, the commercial use of zeolites in agriculture generally has been small-scale and limited mostly to Japan and other parts of the Far East. Even though a number of domestic companies have undertaken zeolite studies, little information is available on the long-term benefits or adverse impacts of these minerals on food production or the environment. And much of this information is proprietary. Though the desire of the private sector to keep its data confidential is understandable, this cannot help but lead to duplication of effort and slow progress in this field. Some researchers suggest that Federal, State, and perhaps international agencies provide sustained funding to underwrite large-scale field tests of zeolite technology, with some field trials being carried out in developing countries.

Cooperative ventures might be arranged whereby the United States would contribute sustained geological and agricultural assistance in zeolite technology to a developing country, and the LDC might cooperate by exploring for zeolite deposits in its own country and undertaking long-term or large-scale testing projects under field conditions.

Day 2. Agency for International Development

Agricultural Activities

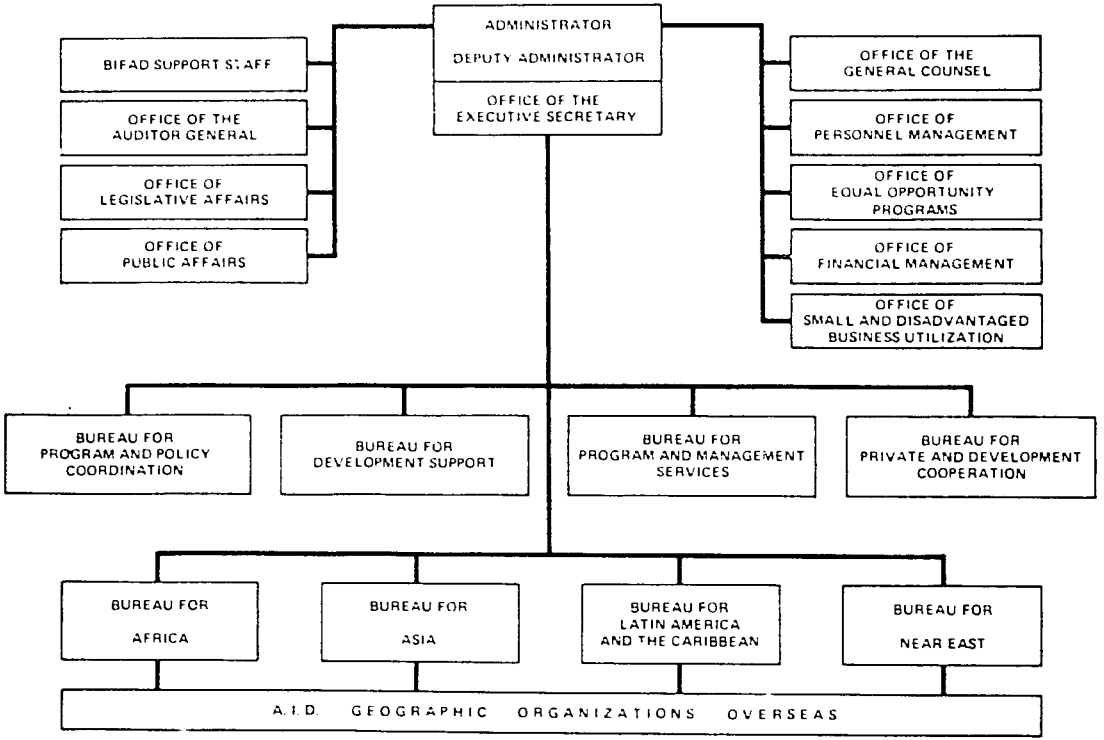
During the second day of the workshop, AID staff reviewed AID's agricultural development activities and the various constraints under which AID operates when carrying out its agricultural mandates. Their discussions were candid and are summarized in the following text. (The organizational chart in effect for AID in November 1980 also follows.)

Budget and Goals

In fiscal year 1980 AID carried out about $600 million of agricultural projects and research related to solving agricultural problems and developing agricultural opportunities in LDCs. Further, AID spent an additional $43 million to transfer fertilizer, much of it going to Sri Lanka, Zambia, and Bangladesh.[1] During the first quarter of FY '81, fertilizer transfers to India, Kenya, Zambia, and Bangladesh were $105 million. AID's main thrust in agriculture is to assist LDCs to increase agricultural productivity, especially the productivity of the locally accepted basic food crops. By doing so, AID's goal is to assist LDCs to improve their economy, nutrition, and the general well being of their people.

[1] AID's financed fertilizer purchases for FY '80 were at the lowest level since 1965.

AGENCY FOR INTERNATIONAL DEVELOPMENT



Effective Date May 27, 1980

But for AID to step beyond traditional approaches and promote innovative technologies to solve LDC food and agricultural problems is risky. AID is not a research agency; its goal is development. Therefore, AID commonly supports research that holds promise of high immediate payoff and tends to avoid research that may have long-run payoffs. Similarly, AID feels that its development projects should focus on the short term, have high visibility, and show positive results quickly. It is not surprising that some AID agriculturalists believe that "when you only have $2 to bet you don't go for long shots." To compound the problem, AID's small budget for innovative activities is often one of the first targets during budget cuts.

The U.S., on the basis of its gross national product (GNP), now ranks 14th of those countries that provide development assistance to LDCs. For example, Sweden contributes 1.0 percent of its GNP whereas the U.S. contributes 0.19 per cent.

AID's budget dilemma is complicated further by a growing list of competing development needs such as forestry, women-in-development, and environmental concerns. AID has been many things to many people but it has not been perceived by Congress as a technical transfer agency. AID stressed that there remains a lack of understanding among the public and the Congress about how science and technology relate to economic development.

Current Innovative Biological Activities of AID

AID participants presented a brief overview of some of their current activities involving various innovative biological technologies. Examples included biological nitrogen fixation, tissue culture, and applied soybean research. In addition, through a collaborative effort, AID, the Joint Research Committee (JRC), the Board on International Food and Agricultural Development (BIFAD), and 30 land-grant colleges and universities have developed three Collaborative Research Support Programs (CRSP) to study small ruminants, sorghum and millet, and bean/cow pea production systems. These activities involve 30 U.S. universities, six international agricultural research centers, and one foundation. Work is carried out at 28 LDC sites with collaboration of the local LDC institution. Two new CRSPs are being developed in nutrition and soils. These activities will expand the number of participating U.S. universities by eight and LDC sites by ten.

CRSPs are viewed as long-term research endeavors, at least 5 years in duration. AID funds up to 75 percent of the CRSP and the collaborating U.S. colleges and universities contribute from 25 to 50 percent. At least 50 percent of

AID's CRSP budget is spent in participating countries. AID's minimum budget for FY '82 CRSP activities is $11 million. AID plans to invest a minimum of $88.3 million in CRSP activities from FY '82 through FY '87.

Biological nitrogen fixation (BNF) is not a new technology; it was recognized in Biblical times that when certain legumes were grown in alternate years, the yield of the following year's crop was improved. After 5 years of research, AID recognizes that BNF technology still could be improved. Because it can provide nitrogen to plants in a usable form without adding expensive commercial nitrogen fertilizers it has important potentials for LDCs and developed countries alike. Further, BNF is a simple technology to deal with from the point of view of the farmer but does require faith.

Rhizobia, the nitrogen-fixing bacteria that live in nodules associated with the roots of certain plants, can be used in some instances to inoculate the roots of plants to enhance nitrogen production. No infallible technique to inoculate seeds is known but this is an area of research AID is addressing. (The information on BNF summarized elsewhere in this report is based on research at the University of Hawaii sponsored in part by AID). BNF in tropical grasses

also is being studied. AID is working on in-country testing of BNF technology, building inoculation production and distribution systems, developing profitable BNF cropping systems, and providing continued help in improving BNF technology for LDC use.

AID believes that commercial fertilizers play an important role in LDC agriculture but also believes that BNF technology can help LDCs reduce their need for commercial nitrogen fertilizers. Considering that commercial nitrogen fertilizer may cost as much as $1 a pound by the year 2000, BNF, which ultimately may be able to reduce the need for commercial nitrogen fertilizers in LDCs by 25 percent, could help LDCs tremendously.

AID is supporting some research on tissue culture to supplement its traditional research on standard crop-breeding practices. AID believes tissue culture to be an inexpensive technology and one that has good potential for use in LDC agriculture.

In the past, agriculturalists selected plants for reproduction by handpicking those few individual plants having certain desirable characteristics out of many thousands of the less desirable specimens. Space and time

severely limit the number of plants screened this way. With tissue culture, desirable plants can be selected and propagated quickly and easily. For example, an agriculturally desirable plant can be used as a cell source for a desired special characteristic such as salt tolerance needed for growth in irrigated areas. A tiny slice of the plant can be used to grow large clusters of cells that can be separated in the laboratory and screened to find the cells having the required characteristics. These cells in turn can be grown to full plants that themselves can be used for seed sources. Current research has demonstrated that the new plants will survive the particular soil stresses for which they were screened. This technique enhances our ability to design plants for the especially harsh environments in LDCs and holds real promise for improving LDC agriculture.

AID provides support for the International Soybean Program (INTSOY) as part of its effort to support innovative biological technologies. INTSOY works to improve and adapt soybeans for tropical developing countries through germ plasm selection. Some of their applied research deals with finding improved ways to store seed for extended times in LDCs and improving soybean processing using simple technologies. INTSOY also is studying the role of soybeans in the LDC farming economies and in the national economy as well.

Possible AID Approaches to Applying Innovative Biological Technologies to LDC Agricultural Problems

Two sharply different approaches to applying innovative biological technologies to LDC agricultural problems, particularly the problem of rising fertilizer costs, surfaced during the workshop's discussions. The first might be called an "agroecosystem approach" and was stressed by most non-AID participants. The second reflected a "conventional production approach" and was mainly an AID viewpoint.

The "agroecosystem approach" focuses on applying biological technologies that are tailored to fit the biological, physical, and social limitations of the local environment so that sustainable agriculture can exist within the constraints of the natural resource base. This approach includes a concern for energy conservation and a desire for truly interdisciplinary research and development.

The "agroecosystem approach" to LDC requirements for food, fodder, and fuel focuses on developing new agricultural systems and on accepting rediscovered, and perhaps improved, agricultural systems. A wide spectrum of agricultural crops is considered including a number that might be viewed as nontraditional. This approach emphasizes restoring,

maintaining, and improving the natural resource base while offering the LDC farmers a reasonable chance for economic betterment.

In comparison, the "conventional production approach" stresses production and increased yields. It tends to focus on a limited number of crops for which a market already exists. The ecosystem is adjusted to provide high production of these crops by using intensive inputs in the form of commercial fertilizers, pesticides, pumped water, and petroleum-powered farm equipment. Some such systems commonly are categorized as "green revolution" technologies. Major efforts have been devoted to mainstay crops such as rice, corn, sorghum, and soybeans, and production increases generally have been outstanding.

The variety of crops dealt with in this approach is more limited than in the "agroecosystem approach" and monocultures often are economically advantageous. Production efforts typically are aimed at fostering crop growth by overcoming local environmental constraints such as infertile soils and water scarcity. In many cases the technologies promoted are adaptations of technologies that have been used successfully in developed countries and temperate climates.

There are, of course, instances where the two approaches overlap but these are exceptions. Proponents of both approaches are trying to assist LDCs to improve the well-being of the populace--their methods, however, include quite different agricultural styles and practices. The workshop also focused on the opportunities shown by each of the systems for helping LDCs reduce their need for expensive commercial fertilizers while enhancing soil productivity.

Participants agreed that agricultural research and its appropriate implementation in lesser developed countries is an AID/LDC cooperative venture and that good communication is essential for success. They discussed the inherent difficulties involved in using U.S. expertise in LDC projects because many U.S. experts lack the special training that is appropriate to the physical and biological environment. Many U.S. technical experts used by AID are drawn from U.S. land-grant universities and consulting firms where familiarity and experience with LDCs are slim. And because the U.S. historically has little experience in LDC--i.e., tropical--agriculture, AID has difficulty finding contractors who are able to grasp LDC agricultural problems quickly and to recognize the appropriateness or inappropriateness of temperate region agricultural solutions. AID has provided

grants and other support to numerous U.S. universities to help them develop their teaching/research expertise so that it can be tapped to help solve LDC agricultural problems. Many of these universities have set aside land for use in agricultural research and teaching, but again agricultural research results commonly are not readily transferable from region to region. Further, because pilot studies commonly are cumbersome to conduct, take considerable time, and lack significant recognition, few university scientists are eager to devote effort to projects relevant to LDC agriculture, even though certain aspects may also hold promise for improving U.S. agriculture.

Pilot projects, demonstrations, and field experiments carried out in LDCs by U.S. and host-country interdisciplinary teams on innovative biological technologies are essential first steps before new technologies are used widely in LDCs. Section 103A of the Foreign Assistance Act directs AID to carry out pilot studies. Further, workshop participants agreed that the private sector, whether U.S. or LDC, should be encouraged to participate in biological technology development and its transfer to potential users. Only where new technologies can be shown to be economically profitable is there the likelihood of their being pursued and

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adopted by the private sector. For example, Thailand recently established several innovative programs in alcohol production from cassava through direct links between the private sector and Thai research institutions. It was also pointed out that in many DCs and LDCs, farmers learn new agricultural techniques from salesmen.

AID believes that during the 1980s it will emphasize technology transfer but hopes to sponsor increased adaptive field-oriented research and assist cooperative research with LDC scientists. The Agency sees the need for multitiered development efforts but recognizes the difficulty in coordinating them. There is an acute need for LDCs to establish their own national research priorities rather than having the donor community do so or rather than conducting research based on the current scientific activities in more developed countries.

Pilot-scale activities that receive partial support from AID do exist at the international agricultural centers. But whether or not all such institutions strongly emphasize the "agroecosystem approach," especially agricultural techniques that are aimed at enhancing soil fertility and reducing reliance on expensive commercial fertilizers, was debated. AID believes that much of the work carried out at the

international centers is innovative, but many of the non-AID participants felt that these centers pay little attention to low fertilizer, low-energy agricultural systems.

Further, AID was criticized for currently spending $43 million of its $650 million agricultural efforts on the transfer of expensive commercial fertilizers to LDCs without providing incentives to try new agricultural methods that minimize their use. LDCs must develop the resources to continue appropriate fertilizer use, but along with this should go development of efficient new agriculture systems that largely use biological processes to complement soil nutrient availability. The use of mycorrhizal technologies (see section on Innovative Biological Technologies) seems to hold great promise for reducing fertilizer needs, but AID is not working with this technology. Although AID agricultural professionals in the Development Support Bureau have tried to initiate mycorrhizal research, it has failed to place high enough on their priority list to warrant funding in each of the last 2 years. AID interest in biological technologies has expanded, but the Agency staff feels funds remain the limiting factor. They feel their involvement in biotechnology research might help speed transfer and implementation of its results.

Workshop participants encouraged AID to place agricultural scientists from nonconventional fields of study on AID peer review panels of field projects and research activities. Because AID seemed committed to conventional agriculture, the other workshop participants believe that AID needs fresh ideas to help their agricultural professionals move away from conventional paths and into new areas having potential for high agricultural payoff for LDCs. AID's current peer review was likened to "an old boy system," one in which acceptance of new ideas was slow. Non-AID members also viewed the U.S. Department of Agriculture (USDA) dimly in the field of innovative biological research because they felt that USDA, too, primarily is committed to conventionality. Some participants thought USDA was not helping AID with the question of how to maintain productive soils in LDCs while reducing the input of expensive commercial fertilizers.

In the view of "agroecosystem" proponents, AID and some international agricultural centers place the greater part of their efforts on a few traditional food crops but do little to develop underexploited, nutritionally important new food crops. AID was viewed as having no interest in these "odd-ball" crops even though such foods contribute

significantly to LDC diets. Proponents of the "agroecosystem approach" proposed looking into any food crops that fit into the local ecological system. Therefore, the resulting mix of crops might be radically different from the crop mix recommended by the "production approach," but one that could be sustained with lower fertilizer inputs.

An agroforestry system might be instituted that would integrate, for example, tree crops for food, fodder, firewood, and erosion control; native food crops; microbiological systems such as mycorrhiza and rhizobium; and local mineral resources such as zeolites into a low-energy-consuming system. Participants encouraged AID to set aside a certain percentage of its appropriations each year to look for new, low-energy agricultural systems. The Agency could continue to back its efforts in "bread and butter" crops--corn, rice, etc.--but should be willing to commit some of its resources to nonconventional approaches. All participants agreed that AID should be encouraged to take some risks and not merely to back "winner" crops such as soybeans. Soybeans were innovative crops in the U.S. 30 to 40 years ago, but remain innovative in much of Africa and tropical South America.

Most non-AID participants, as well as some AID members,

believed that the Agency needs a more flexible mechanism to provide funding for small-scale innovative activities. Currently, AID seems unable to transfer small amounts of money quickly or easily for such projects or experimental activities. The Agency claims that processing a small amount of money is as time-consuming as processing large grants or projects. Pressure within AID to obligate program dollars rapidly makes dealing with small projects bothersome. Though AID's agricultural professionals in the Development Support Bureau, for example, may wish to support certain inexpensive innovative activities, they are discouraged by internal AID procedures and the program office's strong control. Consequently, scientists outside of AID who have special useful knowledge and who wish to participate in solving LDC agricultural problems feel that AID is neither open nor interested in outside assistance. Yet most participants felt that many aspects of both the "conventional production approach" and "agroecosystem approach" could be integrated with positive results.

The non-AID scientists elaborated on how it is generally difficult for them to obtain needed support for innovative approaches to low-energy agricultural systems. The picture was similar for the varied researchers. First, there seems

to be little support for funding the broad range of innovative biological technologies that may be of assistance to improving LDC agricultural systems. This is particularly true at most U.S. universities because the universities find it difficult to support activities that seem remote to the sources of university funds. Then, too, researchers who rely on the university for their salary commonly do not want to jeopardize their security by conducting nonmainline research.

Some of the non-AID researchers admitted that to carry out their chosen areas of LDC-related research they sometimes resort to using small amounts of money from other projects that are not LDC-related ("bootlegging"). Other common small funding sources for LDC-related research include a variety of Federal agencies other than AID, although AID does provide significant support for the biological nitrogen fixation work at the University of Hawaii. An AID grant provides partial support for azolla/algae research. Because Federal support for LDC-related research has the habit of vanishing suddenly, non-AID researchers face constant doubt about the continuity of their funding. The National Science Foundation, some United Nations institutions, small university grants, and private industry and institutions sometimes are funding sources as well. Private industry support seemed lacking for

applied research in these fields.

Underlying all of the above problems was the strong need for a significant increase in the number of technically trained professionals in agriculture and natural resource areas in AID and its missions overseas. Existing technical professionals need to spend increased time on the substance of their projects and less dealing with bureaucratic constraints. Without such an environment, AID may find it increasingly difficult to maintain or expand technical competence within its Washington offices or missions in LDCs. A need for improved communication between scientists and the Congress was restated several times during the workshop, and activities similar to this workshop were cited as a step in the right direction.

Perceived Constraints

AID's major efforts in innovative agricultural research are directed primarily to the 13 international agricultural research centers to which AID contributes financial support. Much of the AID activity, however, depends upon the work of the AID missions and the ability of the professional staff to relate to the scientific community at large and to the missions and regional or geographic bureaus. A number of problems in these areas were identified by the workshop participants.

Mission Agricultural Activities

AID missions largely are removed from current science and technology developments in the academic and private sectors. Consequently, AID faces a difficult task in channeling new science and technology to field activities in most LDCs. In addition, AID workshop participants explained that many missions feel that adequate technology already exists and that new science and technology are not needed. The missions want AID technical people to solve the problems that the missions identify, using established technologies. This approach frustrates AID professional staff, including staff in the Agriculture Office.

CGIAR

AID considers its contribution to the Consultative Group on International Agricultural Research (CGIAR) valuable and feels that the nonbureaucratic institution functions very well in addressing agricultural development problems and in implementing research results. AID sees Korea as a model of successful development where effective technology transfer has occurred, and feels that the Korea example should be used as a model for development activities by other LDCs.

Agricultural Staff

AID agricultural professionals attempt to maintain close contact with agricultural experts in the scientific community both within and outside of USDA. But the number agricultural scientists in AID is so small that maintaining regular contact with their scientific colleagues can be difficult. AID employs about 4,000 individuals yet its Development Support Bureau (DSB), the bureau that provides technical support to all of AID's regional or geographic bureaus, has only about 25 agricultural professionals. These 25 people managed about $70 million in agricultural projects in FY '80. Further, only about 10 percent of AID mission personnel worldwide are agricultural officers even though

some 50 percent of AID's development programs are agriculturally oriented. Because AID commonly reassigns its agricultural professionals to new missions or back to the U.S. about every 3 to 4 years, many agricultural programs suffer from the lack of continuity. AID's workshop participants felt personnel rotations occur too frequently.

AID workshop participants felt that the Agency's emphasis on natural resource management should be increased but that this area is not receiving much Agency attention. Natural resource management requires an interdisciplinary approach, but because AID is segmented into numerous administrative compartments it is extremely difficult to conduct interdisciplinary activities. For example, agroforestry activities were to be transferred recently to DSB's Office of Forestry, Environment, and Natural Resources, the successor to the Office of Science and Technology (OST). Agroforestry, by definition, combines aspects both of agriculture and forestry, yet in the new arrangement, agroforestry is separated from agriculture.

The mandate to identify and test innovative and/or emerging science and technology and to transfer promising ideas to AID's Mission and Regional Bureaus belonged to the recently disbanded Office of Science and Technology. This

office served as AID's "window" to the science and technology community and gave AID the opportunity to tap a broad array of innovative science and technology to help solve LDC problems.[1]

A problem that AID workshop participants highlighted again and again was that of the expanded role of AID program officers in decisionmaking and priority-setting for agriculture projects and research. Program officers commonly are generalists having little or no technical agricultural training. Organizationally, they sit between top bureau administrators and agriculturalists and other professionals and exert a strong influence on AID's agricultural efforts. AID agricultural professionals feel that they are continually second-guessed by program office generalists and that the technical content of proposed agricultural projects and research many times is adversely affected by the action of the program office.

Program officers commonly evaluate project or research activities. But AID's evaluation process seems to foster a strong desire to have evaluations that show positive results.

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[1]As of May 1981, a new Bureau for Science and Technology was formed. (See section on recent AID organization changes.)

Without positive evaluations, the difficulty of moving subsequent projects through the AID system and, therefore, through the program office may increase. This perception, whether true or not, discourages some technical professionals from pursuing innovative opportunities in science and technology because the element of risk in innovative activities generally is higher than in traditional approaches. The overall effect of having an inordinately strong program office is that agricultural professionals introduce fewer innovative technologies into AID agricultural programs.

Summary of Workshop Suggestions

Summarized below are a variety of suggestions generated by the 40 workshop participants during the course of their 2 days of discussion. Some of these topics received considerable attention and others much less. The participants were encouraged to express their points of view freely on any issues they felt were relevant. By doing so, the participants touched upon a variety of topics, many of which deserved more detailed examination than could be accomplished in 2 days. The issues that surfaced, however, should assist the House Committee on Foreign Affairs in their oversight responsibilities of the Agency for International Development and in determining the role that innovative biological technologies could have in enhancing soil fertility and improving food production in lesser developed countries while reducing the countries' need for expensive commercial fertilizers.

* AID should greatly increase the number of in-house agricultural professionals in Washington and in the missions, especially in decisionmaking positions.

* AID should increase substantially the number of mission directors who are agricultural professionals.

Similarly, effort should be made to encourage the selection of an increased number of people with professional agricultural training as ambassadors for LDCs.

* AID should encourage the U.S. and LDC private sector to participate in pilot-scale projects testing and developing innovative biological technologies.

* AID should appoint some outside experts in nonconventional agricultural technologies to its advisory committees and to its peer review panels.

* AID should broaden its inventory of scientists who might assist AID to expand its efforts into nonconventional agricultural practices.

* AID should streamline its procedures to encourage increased outside participation by U.S. scientists and technologists in small-scale innovative agricultural activities.

* AID should set aside a certain percentage of each agricultural project to integrate some new, innovative biological technology into the project.

* AID should fund some small-scale, pilot-type projects on the kinds of innovative biological technologies presented

at this workshop and encourage the participation of outside scientists to work on the project as members of interdisciplinary teams. The need for pilot testing of a wide variety of innovative biological technologies by AID was stressed heavily and the need for risk-taking was encouraged.

* AID should increase its activities in agroforestry systems. These activities should be expanded to include both humid, tropical regions and arid/semiarid regions. Pilot testing of the arid/semiarid systems should be carried out in the Southwest U.S. and LDCs.

* An expanded inventory of innovative biological technologies that could help LDCs reduce their need for expensive commercial fertilizers should be prepared, and institutions and individuals who have the skills for these technologies should be identified.

* OTA should conduct a full assessment of a broad range of innovative biological technologies that could help LDCs reduce the need for their use of expensive commercial fertilizers.

* AID should emphasize the transfer of technical information to LDCs and to AID mission agriculturalists, particularly on innovative biological technologies that might help LDCs reduce their need for expensive commercial fertilizers.

Recent AID Organizational Changes

The Administrator for the Agency for International Development (AID) on May 21, 1981 announced a reorganization for the structure of AID (see following chart). One major change was the formation of a new Bureau for Technology and Science to replace the old Bureau for Development Support. Structurally, this change gives greater prominence to the role of science and technology in AID than has existed previously. About one month later the new bureau was renamed the Bureau for Science and Technology. Unlike the other AID bureaus which are headed by Assistant Administrators, the Bureau for Science and Technology is headed by a Senior Assistant Administrator, thus giving added strength to science and technology in AID.

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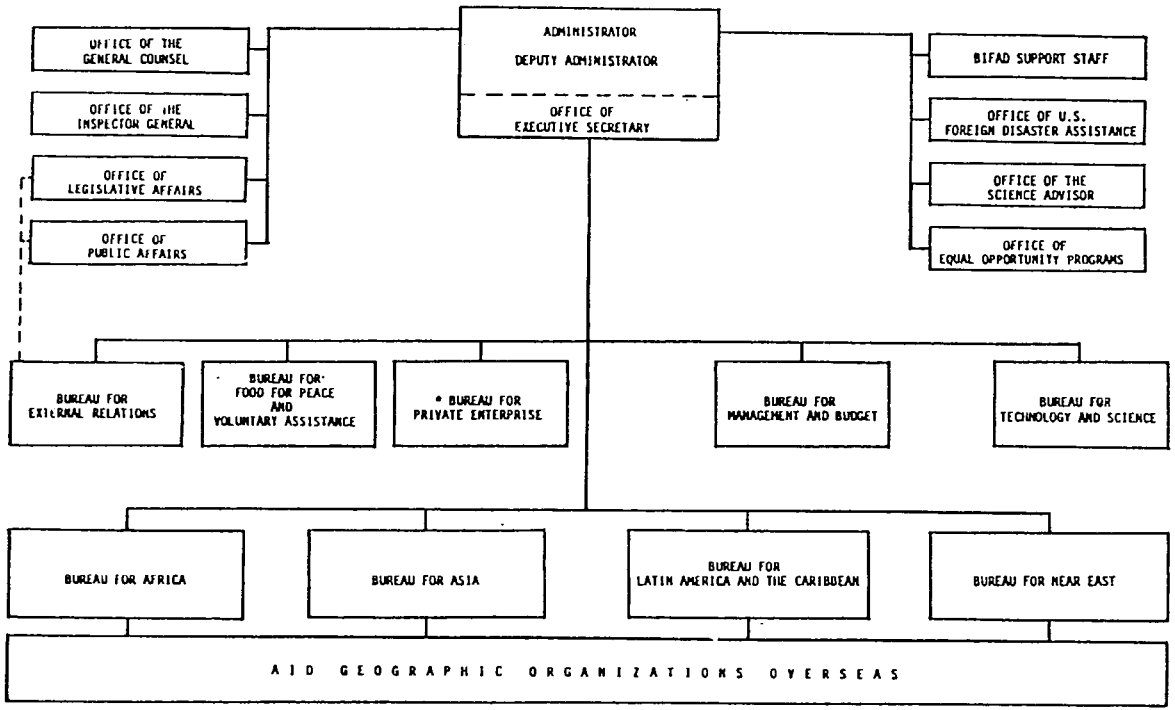
Agency for International Development



* The Director, SDB, also reports to the Office of the Administrator on those functions which by law require that relationship.

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PAPER NO. 1. THE GENE REVOLUTION[1] (MAXIMIZING YIELDS IN THE TROPICAL MOIST FOREST BIOME)

(By J. A. Duke, USDA, Econo-nic Botany Laboratory, Beltsville, Md.)

It is the skills of plant geneticists, rather than large amounts of artificial additives such as pesticides and fertilizers, that have led to one record after another in crop yields in ... both temperate and tropical zones. (Norman Meyers, The Sinking Ark, 1980)

Summary:

Should there be a Gene Revolution, based on low-input multiuse extensive agroecosystems, to supplant the Green Revolution, based on high input intensive agriculture? Genes best adapted to the marginal environments of the humid tropics should be pooled, combined and recombined to produce moderate-yielding well-adapted multipurpose native or introduced species. These combinations and recombinations of genes should be tested, not for their yields in monocultural situations, but in well-planned multi-tiered intercropped agroecosystems. The search for appropriate genes can be scientifically directed by a computerized catalog of the varieties, cultivars, and species of potentially economic native and introduced species. Species from the various tiers of the multiple intercropped community should further be tested, not for conventional mono-use yields, but for multiple yields. Technologies required to make such a multiple-use agroecosystem include small scale biomass- or alcohol-fueled or solar plant-extraction equipment, as well as fermentation and distilling apparatus, designed to be run on some of the products of the agroecosystem. In summary, the Gene

[1] Talk to be delivered at OTA (Office of Technology and Assessment) workshop, November 24, 1980. Due to short lead time, this paper has not been cleared by USDA and reflects the personal views of the author.

Revolution should be directed toward a multi-tiered, multiuse polygenic low-input agroecosystem, fueled and fertilized from within. The Gene Revolution should pull together the five major ingredients which have long been advocated for marginal environments (1) tolerant germplasm (2) multiple and intercropping scenarios (3) organic gardening (return of animal and plant residues) (4) biological control of pests (including allelopathy) and (5) whole plant fractionation and utilization for such integrated agroecosystems. Such systems should be developed from existing farms, not from the forests.

Introduction

"... Plant germplasm can be selected and superior cultivars developed on the basis of their adaptation to problem soils. Although we have moved slowly to capitalize on this information, it offers great promise in reducing energy inputs and improving the reliability of crop yields in both developed and developing countries." (A. A. Hanson, 1976)

The highly weathered soils of the humid tropics will rarely support conventional crops for long periods of time without a high level of inputs, a level barely, if at all affordable by many developing tropical countries. If these countries cannot afford the inputs required for high-level production of conventional food crops, perhaps their targets should be instead a moderate production of non-conventional crops with moderate inputs. The green revolution, which called for maximum inputs, has pretty well run its course, maximizing productivity where high inputs are possible. It's time for the Gene Revolution, to tailor existing plant cvs, vars and their hybrids to maximize output with minimal input. The genes still exist in nature, but they are disappearing fast. It is up to the Gene Revolutionists to get the genes together in the most meaningful manner, to maximize productivity under various low input scenarios.

With the end of the cheap energy era, developed and developing countries must reassess their imports and exports, their agricultural inputs and outputs, and their needs, often with a view toward substituting botanochemical fibers, fuels and pharmaceuticals for those derived from petrochemical feedstocks. The complexity of such issues is such that a systems approach might be needed for rationalized options.

Energy-hungry developing countries should closely watch developments at Peoria (Northern Regional Research Laboratory). If the botanochemical approach is practical today or tomorrow in an energy-rich country like the U.S., then it is at least twice as practical in energy-poor countries of the humid tropics.

1. Natural (and agricultural) productivity per unit area are higher in tropical than in temperate zones, other things being equal. Hence, there should be much more biomass for a total-utilization scheme. The Gene Revolutionist is charged with finding the best genes and combining them in the best plants for maximizing output in the marginal low-input farm scenario.

2. The diversity of useful species upon which to draw for our total-utilization concept is perhaps ten times as high in the tropics as in the temperate zone. Hence, the array of combinations for the recommended intercropping approach is staggeringly complex. The multitiered intercropping agroecosystem being studied seems to be one of the most highly productive terrestrial agroecosystems, competing with the highly productive aquatic ecosystems of the tropics. Yields of either of these systems can be improved vastly by the addition of ameliorated sewage sludge or other natural fertilizers in lieu of artificial fertilizer inputs. However, sewage sludge is recommended for biomass and chemurgic crops, not food crops.

Today I will try to respond to the central issue, the highly weathered soils of the hot, wet tropics -- i.e. those soils rich in aluminum, silica, and iron, and poor in the common plant nutrients. What could EBL do to improve "biological productivity of such soils without using much or any chemical fertilizer?" That is the charge put to me by Dr. Parham. Let's analyze that a bit before proceeding. Is it rare that we can improve on natural biological productivity? Nature has done a good job of maximizing biological productivity under nature's constraints. If I contrasted productivity, I would only be contrasting useable with total productivity. And if we are talking about the Maximum Useability Concept, then we are not talking conventional agriculture at all.

Before laying out my plans for any country, I would analyze their import-tables, especially the energy columns. Then I would plan the multi-tiered agroecosystem that would maximize benefits to the countries import-export situation, seeking out the best genes to maximize output for a modicum of inputs, under the ecological conditions prevailing. Geneticists could maximize the yields while American technology can serve to maximize the extraction of useful products from the total yield.

Humid tropics has been variously defined. Most of my examples relate to what is called the Tropical Moist Forest, where annual biotemperatures are greater than 24°C and annual rainfall is between 2000 and 4000 mm. I have spent years in the Tropical Moist Forests of Latin America, and am still awed by the diversity of economic products endemic to the area. There are even more exogenous economic species from similar ecological zones outside Latin America. Unlike Dr. McKell, I do not stress using the native species, but I share his beliefs that we should not introduce exotics that are ill-adapted to the area. ESL's computer system helps find the right germplasm for a given tropical ecosystem. Drawing on these other tropical gene pools, the Gene Revolutionist has perhaps more than 75% of the world's species to consider, perhaps 2[illegible],000 species, each a unique chemical factory, manufacturing biomass which we may need to draw upon as a source of energy, if there are no breakthroughs. The preface of a recent NRC book (Conversion of Tropical Moist Forests) begins "The tropical moist forest biome is biologically the richest, and least well known portion of the earth's surface" (NRC, 1980).

Unfortunately, much of TMF is underlain by ferralsols (strongly weathered soils of tropical regions, consisting mainly of kaolinite, quartz, and hydrated oxides, and having a low base exchange capacity). Dudal (1976) summarizes the mineral stress phenomena in such soils.

1. Deficiency in bases (Ca, Mg, K) and incapability to retain bases applied as fertilizers or amendments.
2. Presence (pH <5.2) of exchangeable Al, toxic to many species and active in binding phosphates.
3. Presence (acid soils) of free Mn, also toxic.
4. Fixation of phosphate
5. Deficiency of Molybdenum, especially for legumes.
6. Fe and Mn toxicity shown by paddy rice.

Such soils are said to occupy more than a billion hectares, more than 8% of the world's soil. Could we get 25 billion barrels of oil from these soils?

There are those who say that conversion of TMF to agriculture will lead only to the so-called "red desert". Ewel (1980) says, however, "The red desert view of mature tropical ecosystem destruction is incorrect. Nature abhors a vacuum, so sites laid bare by human activity are quickly covered by some kind of community, although not usually the original one. We must face the fact that successional communities are going to be the dominant tropical ecosystems of the future."

Economic Botany Laboratory

Still awed by the diversity of the Tropical Moist Forest that embraced three of the best years of my life, the Economic Botany Laboratory (EBL) has begun to try to sort out the information pertinent to the Tropical Moist Forest. There is already so much information that we are dependent on computers to assimilate the information. We are primarily concerned with the medicinal plants of the world, especially those with anticancer activity, and secondly concerned with cataloging agronomic, ecological, geographical and utilitarian information on economic plants of any description. From his studies alone, Schultes (1980) compiled a list of more than 1,300 species employed by natives of the northwest Amazon alone as medicines, poisons, or narcotics. Our computer files already contain entries on more than 4000 folk medicinal species, some of which double as food plants, fiber plants, dye plants, etc. We have yield data on some of these, under various ecological regimes in the Tropical Moist Forest. With careful expansion such a data base could catalog the data on ecology, utility, and yields of all economic plants, to guide the Gene Revolutionists in their search for the right genes or germplasm. Details of some strategies that should be employed in the quest of tolerant germplasm are explored in Duke (1978). Ecological data on more than 500 species suitable for exploitation in the Tropical Moist Forest are tabulated. I will not relate all those data here, but will pull out a few examples for the tables that conclude this paper.

We know the conventional yield figures for only a fraction of tropical crops. Biomass or residue figures are even rarer, although such numbers are necessary for systems analysis of the yield potential of a multiuse agro-ecosystem. According to Westlake (1963), conversion factors range from 1.3-4.0 for estimating aerial biomass from conventional yield units. I called all the experts I could find, in vain, in my search for the biomass figures for the

temperate lentil. Who would I call for such figures on the myriads of tropical products. Repeating, the numbers do not exist. "The accuracy of productivity measurements is the lowest in tropical areas. The key to future refinement of our understanding the global productivity capacity lies, therefore, in the study of tropical primary productivity." (Lieth, 1978) If biomass is a viable competitor in the energy field, it is time pertinent numbers were generated by baseline research programs.

If I were Secretary of State, determining what strings were tied to AID funds overseas, I would see to it that funds went to carefully distributed research plots in developing countries. These plots would be funded to generate the numbers needed for Maximum Utilization Concepts. How much biomass can we grow and harvest under various scenarios? Which scenario gives us the greatest net useable returns? I would fund no studies that did not give biomass yields related to climatic and edaphic data, and I would fund no country that did not make a commitment to preserve their current forests, and concentrate on increasing the productivity of current croplands. Having said this, I must admit that it is difficult for me to convince a republican that the remaining forests should not be converted into agroecosystems. Thousands of undescribed species will be lost forever before they have been named. Thousands others will disappear with no studies of their economic potential. It is difficult to put a price on their heads. One in ten species studied has shown anticancer activity; still only about 15 of the first 30,000 species studied in our anticancer program are of sufficient interest to have reached preclinical testing and only one of those has resulted in thousands of remissions in cancer. The superstar, Catharanthus roseus, the Madagascar periwinkle, is now a pantropical ornamental and folk medicine in Tropical Moist and Dry Forests. There are probably nine more superstars awaiting discovery (if they do not fall victim to the tropical axe). Can we afford to extinguish them?

The Quest for Tolerant Germplasm

Elsewhere (Duke, 1978), I have advocated and outlined measures for seeking out the genes we need for marginal environments in the tropics. Spain (1976), having worked with the CIAT screening program at Carimagua (pH 4.5, 80% Al saturation) summarizes "There are very wide differences between species and among cultivars in the same species as to tolerance to soil acidity". In the same volume Foy (1976) notes "The correction of Al and Mn toxicities by liming is not always economically feasible, especially Al toxicity in strongly acid subsoils. However, plant species and varieties with species differ widely in their tolerance to both factors, and some of these differences are genetically controlled". It is such differences we hope to capitalize on in the EBL Quest for Tolerant Germplasm. It is cheaper to increase the yields by finding the tolerant cv that will tolerate the acidity, and its complications, than to increase the yields by importing six tons of lime per acre. This is just the first step in the Gene Revolution. Incorporating the appropriate genetically tailored species, varieties, races, and cultivars in a multitiered multiple cropping system requires even further genetic selection, manipulation and experimentation.

Intercropping

Work on multitiered agroecosystems is proceeding most rapidly in Asia, but temperate systems are familiar to us all, at least two-tiered systems, with hay, legume or cereal crops alternating or intercropped with rows of fruit or nut trees. Potty et al (1979) describe just one of the thousands of possible combinations possible in a tropical three-tiered system. Pineapple was planted as the ground crop, cocoa as the first story, and pepper as the second story. Total harvestable crops and residues from such systems usually exceed significantly the expected crops of the individual species, had they been planted in monoculture. Advocating agroecosystems that simulate the natural ecosystem it replaces Hart (1980) says: "The replacement of weeds by analogous crops and an increase in crop diversity will usually reduce the amount of energy used by weeds and pests."

Those systems of tropical forestry and agriculture that have been successfully employed for the longest periods are those which favor the maintanence of large mycorrhizal fungus population ... Traditional shifting agriculture in small forest-enclosed plots probably attains mycorrhizal homeostasis. Mycorrhizae seem to minimize the expense to the host of seeking-out minerals. Cultivation of annual crops may lead to increased prominence of non-mycorrhizal species and grasses in weed communities. Soil sterilization can eliminate mycorrhizal fungi, and fungicides used against pathogens may adversely affect mycorrhizal fungi as well. Monocultures of crops that are probably non-mycorrhizal, such as grain amaranths and chenopods,might markedly lower mycorrhizal fungus populations and jeopardize subsequent mycotrophic crops. (Janos, 1980)

Legumes

Even the nitrogen fixed by legumes is not free. Under conventional farming, there is a price to pay for the nitrogen contribution of the legume. In an unpublished paper, I pulled, at random, biomass yields for pure stands of C-4 grasses, C-3 grasses and legumes. Though relatively higher in nitrogen and protein, the legumes yielded only half as much total biomass as the C-3 grasses, which in turn yielded only about half as much total biomass as the C-4 grasses. These are the biological costs (1) for nitrogen fixation and 2) excessive photorespiration. Although no one seems to have accepted my simple 1:2:4 ratio, I believe it. So called super yield targets in the U.S. are for 100 bushels of soybeans; but 400 bushels of corn.

Appropriate combinations of legumes and grasses seem to give the best yields for forage or hay, and probably for maximum utilizable biomass under renewable situations where water is not the limiting factor. The C-4 grass might give highest yields for a while, but it seems doubtful that such yields would be sustainable without the help of added N, be it from legume, crop residues, manure (green or brown), or sewage sludge. For high quality leaf protein, the legume seems indispensable for most scenarios (without the sewage increment) whether the protein is for animal food, human food, or chemurgic utilization.

The amount of N fixed by legumes varies of course, but some of our economic legumes play a larger role than making beans and fixing nitrogen. According to Nigmator et al (1978), the cultivation of the legume licorice (Glycyrrhiza glabra) showed a marked ameliorative effect on saline soil in Uzbekistan, Russia. The licorice, in pure stands, did not form a complete soil cover during the first one to two years, but this was achieved by sowing it in mixture with sudan grass, cowpea, and lablab. The mixture decreased the evaporation and the rise of salts

to the upper soil layers. Haines et al (1978) reported that undersowing sycamore (Platanus occidentalis) with clovers and vetch in a disc-cultivated two-year old plantation suppressed weed growth to the point where height and volume increments of the young trees were significantly increased.

According to Felker (1979) "Leguminous trees have a unique advantage over annual legumes in dealing with the inhibitory effect of drought stress on nitrogen fixation because the deep-rooted leguminous trees may reach moisture, and thus relieve the plant of water stress for a longer time in the year than is possible with annuals... An illustration of the ability of leguminous trees in semi-arid climates to increase the soil fertility more than annual legumes can be found in West Africa where yields of peanuts are increased if grown beneath Acacia albida trees.

The work on "teaching the grasses to fix nitrogen" goes on but does not generate as many headlines as it used to. Nitrogen-fixation is being reported in more and more non-legumes. Just this month, I noted an abstract dealing with nitrogen fixation in blackberries. Becking (1979) assayed nitrogenase activity by acetylene reduction in detached Rubus ellipticus root nodules. It was similar to that in several non-legume N2 fixing nodules. The endophyte was an actinomycete.

Fertilizer

Legumes are one source of fertilizer for our multitiered agroforestry units, tropical azollas might be another. Returning spent residues from which various extractives have been removed can often be a rich source of mineral fertilizer. The oriental night-jar has much to be said for it. Without drinking beer, my urine volume is more than a metric ton per year. Of that volume, approximately 0.002% is Nitrogen, good for humid tropical soils.

Chinese are known to add night soil to their rice paddies. The human excrement is then ingested by fish which are in turn ingested by humans. While not advocating this unsanitary short cut in the food chain, I am impressed by such natural fertilization. Clark (1980), reviewing the Azolla approach in China, notes that Azolla "seed" are started in basins ca 15 m square and 1 decimeter deep. The seed ferns are introduced directly into rice paddies. In some areas, two rows of rice are planted ca 10 dm apart with the Azolla growing in larger 6 dm rows on either side of the double rice rows. Yields of 15 MT/ha of rice and 150 MT of Azolla have been reported for this simultaneous cultivation method. Rice grown with conventional fertilizers averages only 10 MT/ha (Clark, 1980). No mention is made of fish biomass harvested from such ecosystems. Could they also harvest 15 MT/ha catfish as have been reported from well-aerated Louisiana fishponds (fed 22.5 MT but not feces) (Plemmons and Avault, 1980). Grass carp (Ctenopharyngodon idella) and Tilapia mossambica are said to relish Azolla, which has also been fed to cattle, chickens, ducks, and has even been suggested for human consumption. Yields of grass carp are nearly ten times as high in the tropics (1500 kg/ha) as in the temperate zone (164 kg/ha).

Unfortunately, we do not know that Clark's 150 MT of Azolla is dry weight or wet weight; if dry weight, we have our fertilizer factory producing biomass equivalent to some of the highest reported, while increasing the yields of the rice crop, almost incredible. Here let me point out serious conflicts of interest facing USDA officials, there are potent advocates and opponents of the introduction of many of the biomass wonders of the world, Acacia, Azolla, Leucaena, Prosopis, etc., the opponents hoping that the advocates are willing to foot the bill should these midnight wonders become the major weed of the 21st century.

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Azolla

I mention Azolla first because it is being championed as a free fertilizer, one producing 150 MT of biomass, while increasing the yield of rice by 1-1/2 times. These are the "facts" hailed by the advocates. Azolla pinnata can double its biomass in three to five days, maybe five to ten days in the field. Some claim that Azolla will suppress other weeds in rice, if not the rice itself. Other reports indicate the Azolla can either prevent mosquitoes from laying their eggs of their larvae from surfacing. Some say it releases N while alive, others only after death. Vietnam reports 1 MT/ha N fixed per year, China 0.7-1.8 MT N. (LeRoy Holmes, pers. comm. 1980)

But there is a weed potential lurking there. Weeds cost the U.S. $16 billion last year, if my memory serves me correctly. Would Azolla introduced to the U.S. increase yields of the few aquatic crops we grow, or would it clutter up more ponds than it helps. Responsible weed scientists as loudly and justly proclaim their fears as responsible forward-lookers champion this "free" fertilizer. There is no cut and dry answer to the cutting question: would the introduction of new biotypes of Azolla help or hurt American Agriculture, American Ecosystems, or the American Economy.

On the negative side of the Azolla equation:

In Japan, complaints about Azolla covering the rice seedlings.

In Philippines, Moomaw calls it a weed in rice.

In New Jersey, has completely clogged up water channels to boat traffic.

In S. Africa, farmers claim it killed fish, prevented cattle from drinking the water, pipes were clogged.

Holmes' notes say 1 ha Azolla requires 360-500 kg P_2O_5, 3-5 MT ash, 5-7 liters insecticide. Unlike the 150 MT/ha reported by Clark, Holmes found 2.8 MT/ha dry weight in India, 1-2.5 in U.S., 3 in Denmark, 8-10 in S.E. Asia.

Unlike the 150% yield increase reported by Clark found 114, 117, 122, & 140 in Australia, 112 to 216 in U.S., 106-138 in India, 100-160 in China. (Holmes, pers. comm.)

Heat or Meat

Unlike temperate U.S., the tropics may not face the heat or meat decision that temperate countries will face if there re no energy breakhroughs soon. According to some estimates, more than 90% of U.S. cereals and legumes are destined for animal food. If Americans went vegetarian tomorrow, and quit exporting grain, more than 95% of our agricultural biomass could go into ethanol production here in the U.S. Some of us (50% of my family e.g.) would rather be warm and do without meat, than be cold and eat meat regularly; others find vegetarianism repulsive. According to Meyers (1979), much TMF biomass goes into cheap hamburger for the U.S. Would it be better converted to fuel for the TMF?

I have been a human guinea pig on three human nutrition studies at USDA, all involving high fiber and/or vegetarian diets. In one, 20 male subjects, none vegetarian or particularly sympathetic with vegetarianism, were fed soy protein in lieu of meat protein. None suffered adversely from the soy as opposed to meat. On the contrary, there were no significant changes in the health of the subjects, at least by the standards investigated. From 40 to 50% of the human subjects preferred each soy analog to its meat counterpart.

Thanks to coal America need not face the heat or meat crisis immediately. Thanks to the temperature of the humid tropics, the TMF might not face that choice either. But they might need to decide whether their biomass residues go into animal production or fuels for their machinery.

Best Available Document

Wood

Even today in the U.S., wood is said to provide more energy than hydroelectric or nuclear approaches. Wood is a valuable byproduct of the multitiered agroecosystem, and the Gene Revolutionist should remember that in tailoring species for TMF.

"The growth rate of tropical weed trees characteristic of the humid lowlands are quite remarkable. I have measured naturally regenerated Trema micrantha in Costa Rica's OSA Peninsula, which were 9 m tall at one year, and more than 30 m tall at 8 years. It is these fast-growing, low-density trees which will constitute the wood resource of the future as mature tropical forests are felled and regenerate," (Ewell, 1980). Ewel's figures for 13-month old regrowth in various life zones are TWF, 12 MT/ha; TDF, 10 MT/ha; SWF, 6 MT/ha; SDF, 5 MT/ha; and Tropical Montane Rain Forest, 1 MT/ha.

I do not advocate replacement of wood as a source of energy for cooking and heat in the TMF. I do advocate the production of cheap wood-burning devices for distribution to the poor. Most of the timbers of the tropics go up in smoke, mostly wasted. With energy-conserving wood stoves, there would be more biomass available for the production and distillation of alcohol.

Liquid fuels for use in cars, trucks and vehicles should be produced by all but the smallest farms in cheap mass-produced stills provided by the technologically well-off.

Sewage

There is justifiable concern that maximum utilization will strip the soils of organic matter. If we only utilize the above-ground biomass, we leave the below-ground biomass. (For example, Westlake [1963] reports that root biomass represents 2% of total biomass in Hordeum, 73% in Secale.) According to Van Dyne et al (1976) "Belowground production is more than twice aboveground in annual grasslands, but standing crops of biomass belowground may be five to ten times as much as aboveground standing crops."

The humid tropics do not need the water like the arid tropics, but they do need organic fertilizers, if continuously harvested. Here I take the opportunity to introduce into the tropical scenario, an idea that I think shou'd be exploited in the U.S.: piping sewage sludge out of the cities of the world and into the energy farm areas of the world. The pipeline routes could parallel proposed coal-slurry lines, natural gaslines, or petroleum pipelines. Oil shale mines, strip mines, any type of old mine site coold be partially or totally reclaimed or improved with sludge-planted areas. The highest biomass yield reports I find are from The Wealth of India, where such yields as 160 MT/ha for Pennisetum purpureum are reported for fields irrigated with sewage. Westlake (1963) reports unusually high yields even in the temperate zone. With sewage irrigation and intercropping, he reported DM yields of mixed alfalfa-orchardgrass at 26-39 MT/ha, at least five times greater than the expected yield of alfalfa alone, without sewage irrigation. This compares with 40 MT for Phragmites australis, which Westlake describes as the most productive temperate community.

City planners should adopt the Design With Nature Concept, building above the productive alluvial plains, clearly the most productive lands in any biome, with nothing but natural inputs. Alluvial plains and energy sumps should occupy

the fertile lowlands, while no more building on the floodplains should be permitted. These most fertile lands are being gobbled-up by suburban creep, here and elsewhere.

I decry the cancellation of plans to barge sludge to Haiti, because I believe sewage sludge could play a big role in the greening of Haiti or the Sonoran or Negev deserts for that matter. We could concomitantly alleviate the shortage of water and organic matter in the desert scenario, with its low-real-estate values, while alleviating the waste disposal problem in the cities, with their high-real-estate values. If we can ship coal slurry east from the desert of the U.S., we can ship sludge west via the same or parallel conduits.

Water to the humid tropics is like coal to Newcastle, but water-borne sludge could prove a boon to the humid tropics. If sewage sludge can double yields in the humid tropics, the reverse pipeline could be shipping ethanol out, still leaving a positive balance in organic matter in the humid tropics. Once the pipelines were established, the sludge could be a free input, doubling outputs. Hence, I see this untried concept as one way to double the productivity of the humid tropics, or treble the productivity of the arid tropics, with a free input. The excess yields could be devoted to production of alcohol, for internal or external energy utilization.

Such an area might appropriately be called an energy sump, and would not be an attractive place to live, but the products of the energy sump could make jobs there, and a higher standard of living elsewhere.

Here, as much as anywhere, the talents of the Gene Revolutionists will be called into play. The genes for maximizing productivity in the energy sump will be very different from those for maximizing productivity in the unaltered humid tropics. Planting, cultivating, weeding and harvesting technologies, even the recommended varieties, if not species, will be different for the two scenarios.

Oil Seeds

Back in April, 1977, I suggested that palm oil might someday be competitive with petroleum. Today, foreign palm oil in New York is still higher than domestic petroleum at the pump, but at the rate the gap has closed since my paper of 1977, palm oil will be as cheap by the year 2000.

Oil palm is one of many species with varieties tolerant of the allic soils of the humid tropics. Oil palm is currently grown in countries that show deficits in both edible oils and energy. It has already been shown that simply growing legumes between the oil palms can increase oil yields by 2 MT/ha/yr (Broughton, 1977) or the equivalent of six barrels of oil per hectare, simply by the selection of proper legume for intercropping. These legumes (Centrosema pubescens, Pueraria phaseoloides), in addition to increasing our energy budget, at little or no cost following planting, can provide food, conventional or unconventional. I am sure, based on temperate figures, that more protein per hectare will be produced if the whole aerial biomass of the legume is harvested, thrown into our energy vat, the leaf protein extracted for human consumption, the carbohydrates for ethanol production, the residues for return to the soil in other than energy-sump scenarios.

We have spoken only of the oil yields of the oil palm. There is still a lot of unused biomass, which could go, depending on the outcomes of our systems analysis, into ethanol production, internal or external combustion devices and/or soil amendments.

Not all, but most palms, survive or thrive in the humid tropics. Like the oil palm, they are multiple-use plants, prime candidates for the upper or intermediate stories in the multitiered agroecosystem for the humid tropics. Could we not multiply the yields of these unstudied palms by 10 as we have done with the Hevea rubber plant. Let's look briefly at one mentioned by Amazonian expert R. E. Shultes (1980):

Orbignya martiana: "One palm may produce a ton of nuts a year, 198 pounds of which is kernel ... with up to 72% of an almost colorless oil very similar in composition in use to coconut oil. The seed cake remaining, containing 27% protein, is an excellent animal feed. I read this as a ton of biomass per year, more than 100 pounds of which is oil. I don't know that these figures are more or less reliable than those with which Calvin derived 50 barrels of diesel per acre. Conservatively, it would take 4 of these productive palms to produce one barrel of oil per year, or 200 trees to produce 50 barrels. From my experience in Latin America, I would pin my 50 barrels/acre hope on the palm before I would Calvin's Diesel Tree. Calvin figured at least 100 trees per acre, but his trees were 1 m in diameter. I don't know any palms that big. Thin canopied palms would permit intercropping of food crops, which I speculate would be impossible in the shade of "diesel trees".

Note that with our hypothetical Orbignya with no genetic research, we are getting 50 barrels of palmoil per acre, with a residue of 1900 pounds per tree. We have assumed a tree producing 2000 pounds of fruits, 100 pounds of which is oil (3,300 pounds are reported, with an oil yield in excess of 200 pounds oil per tree). Assume 300-350 pounds per barrel of oil. We can further assume after the extraction of our 100 pounds of oil, we have 1900 pounds of biomass in the pot, 900 pounds of which might, conservatively, be water. Of the remaining 1000 pounds, perhaps there is another 100 pounds of protein, per tree, and 900 pounds of carbohydrate, etc., 400 pounds of which might give us another barrel of ethanol per hectare. So, hypothetically we have 100 pounds of protein and two barrels of ethanol as byproduct from our one barrel of palm oil.

The technology needed for this oilpalm scenario:

1. oil extraction (available for oil palm)
2. carbohydrate fermentation and distillation
3. protein purification and sanitation, for human or animal production.

There are palms for the arid tropics, for the humid tropics, for bracish swamps, for freshwater swamp situations, and for our sewage sump, all potentially intercroppable with other food/energy/chemurgic crops. But the Gene Revolutionist has not started to tailor these species to specific environments and to increase their yields. And we have not even talked about the waxes, steroids, leaf-proteins and ethanol that could produced by the leaves. Some palms will disappear before we have studied their potential.

Production of conventional palm oil (from Elaeis) was expected to total ca. 4.3 million MT in 1979-80, compared to 3.9 million MT in 1978-79 (Chemical Marketing Reporter, Nov. 12, 1979, "Prices for the oil will always follow the lead of the soybean oil market." [28.5¢/lb, Nov. 12, 1979]). Whether or not these are viewed as petroleum alternatives, many oilseeds are handled in the U.S. market. Residues could be used for alcohol or methane generation, or as a soil amendment.

Some prices quoted in the Chemical Marketing Reporter for various tropical oilseeds during 1979 are avocado ($3.13/lb), stor oil (0.40/lb), coconut (0.57/lb), corn (0.50/lb), cottonseed (0.18/lb), oiticica (0.60/lb), palm (0.33/lb), palm kernel (0.42/lb), and soybean (0.48/lb). The newly generated market for jojoba "oil" has a cult of followers, but this so-called oil is a liquid wax, unique to the jojoba among plants. Soy oil, peanut oil and sunflower oil have been used as diesel substitutes.

Allelopathy

To the author's knowledge, allelopathy has not yet been developed to be an alternative to herbicides. But if different chemurgic species are selectively herbicidal, as one gathers from reading the allelopathic literature, then all these relative herbicidal activities should be cataloged. Residues of the allelopathic species might then be returned to that portion of the intercropped agroecosystem where the divergence between its negative effects on the weed species and the crop is greatest, i.e. where its herbicidal effects will do the most good and least harm. One can even suggest how coumarin-containing residues (Melilotus, Trigonella, etc.) can be used to stimulate rooting in the soft-wood cuttings used for propagation in our tropical agroecosystem (Lipecki & Selway 1977). Steenhagen and Zimdahl (1979) show that the hydrocarbon-producing Euphorbia esula reduces the frequency of quackgrass and ragweed, but also reduces the growth rate of tomato seedlings. Dry leaves of the medicinal species, Parthenium hysterophorus, inhibit growth and nodulation in legumes, branching in tomato and plant height in ragi (Eleusine coracana) and reduce the yield of bean, tomato, and ragi. On the other hand, the leaves stimulate the growth of Pennisetum americanum (Kanchan and Jayachandra, 1979). Such data are being generated rapidly, but there seems to be no computerized catalog to enable us to evaluate and utilize these data effectively in planning our multiuse agroecosystem.

Drug Crops

EBL specializes in medicinal plants; there are often huge residues of biomass following drug extraction. It takes 1-1/2 MT of dry stem and bark of Maytenus to yield a gram of maytansine, one of the anticancer superstars of the last decade.

Bruceine, cassia, caffeine, cocaine, heliotropin, ipecac, papain, pilocarpine, quinine, quinidine, reserpine, rutin, steroids, and theophylline; these are a few drugs that can be harvested in the humid tropics. Many of these are million dollar items which could be extracted on-site as income producers, leaving behind 99% of the biomass for food and/or fuel production. Some of our drugs might be byproducts from conventional foods, e.g. caffeine from coffee and tea, theophylline from tea, steroids from legumes, rutin from buckwheats. The steroids once derived from tropical dioscoreas ("barbasco") are now largely derived as byproducts of legumes and agaves.

Essential Oil

Currently the U.S. imports nearly 10,000 MT of essential oils at close to $100 million per annum. This probably represents the distillation somewhere or one million MT of biomass, 99% of which could have been funnelled into food and fuel production as byproducts. By no means all of these essential oils are humid tropical species, but I list a few reported to me from the humid tropics:

Trees: bay, bergamot, camphor, cassia, cinnamon, clove, copaiba, grapefruit, guaiac, lemon, lime, lignaloe, nutmeg, petitgrain, ylang-ylang

Forbs: cardamon, citronella, ginger, lemongrass, palmarosa, patchouli, vetiver.

The trees might be considered as alternating trees or strata with other trees, like palms, in the upper strata of our multi-tiered agroecosystem. The forbs might be considered for the ground layer. Our Gene Revolutionists should already be looking for tolerance to shade and root competition in our lower tier, and tolerance to root competition in candidates for the upper tier.

Fiber Crops

On the last day of October, 1980, an official called from the Strategic Materials Department to ask where in our 50 states we could grow several strategic matrials. Among them were two tropical fibers, abaca and sisal, the former adapted more to the humid tropics, the latter more to the arid tropics. With sisal, fiber yields are only 3% of the leaves. From the remaining 97% biomass, I am certain that steroids, waxes, leaf protein and alcohol, even tequila, could be produced. Many natural fibers can be produced in the humid tropics, among them abaca, baobob, coir, cotton, ensete, hemp, henequen, jute, kenaf, ramie, roselle, sisal, snakeplant, sunn hemp, etc. As the cost of petrochemicals rise, some economists predict a return to natural fibers instead of synthetics.

Gums, Resins, and Balsams

Some chemicals in this group approach the classical petrochemical or "neo-classical" botanochemicals. Swedish and Finnish firms are reported to have developed an efficient turpentine car engine which runs on turpentine produced from the oleoresin of scotch pine. High road mileage is claimed for turpentine (Noble, 1979). Presumably, yields of tropical pines in the Philippines, e.g., may be higher than the temperate pines being viewed as energy sources. The Gene Revolutionist would be charged with increasing both the nut (pinyon) and turpentine for specified intercropping stratagems under specified ecological conditions.

The copaiba oil listed in CMR as trading at over $2.00 per kilo may or may not be the same as the oil from Melvin Calvin's tropical "diesel tree" Copaifera langsdorffii (CBC News for Television, September 11, 1979). According to Dr. Calvin (personal communication, September 17, 1979) 1-1/2 in. holes are drilled halfway through large trees about two feet above the ground. Such holes are reported to yield about 20 liters of "diesel" (mostly 2 or 3 main C-15 sesquiterpenes and 30 or 40 minor C-15 sesquiterpenes) in two hours. The holes are bunged and retapped again in about six months, and said to yield another 20 liters of diesel, or 40 liters of diesel per year per tree. This is exactly the same yield reported in Grieve's Modern Herbal, 1931. Dr. Calvin, perhaps optimistically, calculates that we can get 25 barrels of diesel per acre per year on a sustainable basis from the copaiba tree (Maugh, 1979). Unfortunately, the tree seems to be intolerant of frost. I will be getting resin from an equally productive timber species of Copaifera during my next trip to Panama.

Gum arabic, guar, karaya, locust, myrrh, olibanum, and tragacanth are among some of the vegetable gums whose trading is listed in CMR. With problems in Iran, a major producer of tragacanth, prices of tragacanth have risen considerably lately. In April 1979, 56,900 pounds of tragacanth were imported with a value of $608,346. More than 23,000,000 pounds of guar gum were imported in that same month. Acacia, Tamarindus and Sterculia are major tropical sources of gums which can provide renewable harvests in intercropping stratagems.

Rubber

As Schultes notes, the first Hevea plantation set out in the Far East yielded about 450 pounds dry rubber per acre, while currently available clones yield about 3,000 lbs/a (<10 barrels). New chemical treatments applicable during tapping can increase the figure to ca 6,000 lbs. an improvement of 13.3 times. These yields are available while leaving the biomass intact. Other options might be to grow whole plants for rubber extraction between our upper story palms in the humid tropics. The Petroleum Plant from which Calvin once projected 50 barrels per acre could be grown in the humid tropics as well as the arid tropics. Detractors from Calvin say yields would be closer to two barrels than 50 barrels from the "Petroleum Plant". More recently (Solar Times, October 1980), Calvin's plant has received new headlines, under the name of gopherweed (Euphorbia lathyris). "Melvin Calvin, Nobel Laureate in Chemistry, believes that the U.S. could produce more than 2 million barrels a day of gopher-oil by 1995. The Department of Energy has granted Calvin $250,000 to continue his research. Marvin Bagby, head of the Agriculture Departments hydrocarbon-plant research project, thinks that gopherweed is the leader among fortyfive hydrocarbon-bearing plants that have commercial promise." "Diamond Shamrock, starting a pilot plant in Arizona, hopes to get 25 barrels of oil per acre, costing from $20-60 per barrel." I think they may be optimistic, but I hope they are right. Other species of Euphorbiaceae are better adapted to and more productive in TMF than the headliners Calvin promoted. The latex of milkweeds could more appropriately be funnelled into rubber production. Be it spurge or milkweed as hydrocarbon sources, the whole plant would be thrown into the extraction vat, with waxes, drugs, rubber, leaf-protein and ethanol as feasible by-products, all grown between our upper-story palm trees. Whether Calvin gets 2, 10, 25, or 50 barrels/acre of petroleum or rubber from the "petroleum plant", "gopherweed", or "diesel plants", I maintain that the ethanol potential from the residues has more energy content than what he milks from the plants.

Wax Crops

Waxes tend to be more frequently derived from arid land plants than humid tropical species. But if the wax be taken as a byproduct, like ethanol, following extraction of edible leaf protein, humid tropical waxes might become export money-makers. In the Chemical Marketing Report, one finds such waxes as the temperate bayberry way (ca $3.00/kg), the arid lands candelilla wax (ca $3.00/kg), and the subtropical carnauba wax (ca $4.00/kg). Yields rarely exceed 1% of the plant, leaving 99% of the biomass as waste, or better as leaf-protein or energy stock. One second-growth "weed" Calathea lutea, of the humid tropics, could serve as source for food, wax, and biomass, as could many members of the banana family. According to Schultes (1980), the Calathea is easily propagated with as many as 30,000 plants per hectare, yielding up to 70 pounds of wax per acre. I project that would leave at least 29,700 pounds dry weight of biomass in the vat for leaf protein and ethanol production. This leaves untapped, the underground roots. Aerial biomass yields of 18 MT/ha might complement the edible-rooted Calathea allouia (12 MT root/ha). Here, as with the winged bean, we must remember that increases in the below-ground yields will usually be compensated for by losses in above-ground yields. As with banana, Calathea and other tropical plants, now all but unexploited, can yield food, fiber, fuel, and residue for the energy farm of the humid tropics.

Weeds

Neither the Weed Science Society of America (WSSA), nor the Oil Interests have loudly advocated the use of biomass as an energy alternative in the past. I find it interesting that there were five items in the October Newsletter of the WSSA hinting at plants as a source of energy. Not necessarily believing the figures, myself, I summarize the estimates from that WSSA newsletter.

Euphorbia	50-125 bbls/ha
Salsola	Arizona grant to make fuel from the Russian thistle, a serious weed.
Asclepias	Improved variety of milkweed could be source of biomass for synthetic fuels and chemical feedstocks and a source of fat, protein, oil and fiber ... Lab estimate of 60 bbls/ha crude oil
Parthenium	Guayule provides a latex which can be used for fuel, petrochemicals and rubber.
Simmondsia	Speculation holds that mature jojobas might produce the equivalent of 50 bbls/ha.

It might be added that these optimistic estimates of 50-125 bbls/ha are based on marginal weed species in areas of marginal inputs. But these are gross energy outputs. Whether it would take 100-250 bbls/ha input to obtain the 50-125 bbls/ha output is speculative. No one has analyzed the energy inputs required to obtain these optimistic outputs. Research should provide these numbers.

A more pessimistic note comes from Shell's "Ecolibrium" 9(4):1980, "According to the Gold Kist plant officials, a good peanut crop can reap 142 gallons an acre. And, unlike alcohol from grain, you don't have to distill peanuts to get oil, you just squeeze them. The peanut oil costs about $3.00 a gallon." The 142 gallons an acre is equivalent to less than 10 barrels per hectare.

This shows the wide disparity in figures used by optimists and pessimists. Scientific research should rectify this disparity.

It seems doubtful that the herbicide industry would encourage hand harvesting of weeds and their conversion into alcohol and/or protein. I advocate just that in TMF countries with unemployed hungry people. Almost all studies show that hand weeding, though utilizing human labor, results in better conventional yields than herbicide controls. In some cultivated communities, weeds constitute 8-27% of the shoot biomass. This 25% might represent 2.5-5 MT on a tropical hectare, which could be harvested and converted to fuel, at the same time increasing the yield of the crops the weeds were competing with.

Tropical Moist Forest Biomass

Do energy farms produce more biomass than the pristine moist forest produces? Those who speak of highly productive TMF mention great quantities of biomass.

The climax forest is in equilibrium, metabolizing as much as it synthesizes, so that although gross production may be extremely high, metabolism erases the profit, leaving no net biomass increase. Do agroecosystems produce more total biomass than native forest ecosystems? I cannot say categorically. The optimist figures on arid land weeds yielding 50-125 barrels of oil per hectare, the pessimist peanut prospectus lies at less than 10 barrels per hectare. And we see estimates of up to 150 MT dry weight from some tropical grasses under sewage irrigation. These figures suggest to me that agroforestry is more productive of biomass than the climax forest. Estimates of the net primary production of tropical forests (Table 1) presented by UNESO (1978) range from 9 to 32.

Table 1. Estimates of net primary production (MT/ha/yr) in tropical forests. (UNESCO, 1978)

Forest type	Location	Net Production
Equatorial	Yangambi, Zaire	32
Equatorial	Khao Chong, Thailand	29
Secondary forest 40 years old	Kade, Ghana	24
Lowland dipterocarp	Pasoh, Malaysia	22
Bamboo in monsoon forest	Burma	20*
Subequatorial (Banco plateau)	Ivory Coast	17
Bamboo in rain forest	Burma	16*
Dry deciduous	Varanasi, India	16
Lower montane	El Verde, Puerto Rico	16
Subequatorial (Yapo plateau)	Ivory Coast	15
Seasonal rain	Anguededou, coastal Ivory Coast	13
Mangrove	Puerto Rico	9

*Estimate does not include roots.

More specifically, I list in the computer printout estimates of standing phytomass and net primary productivity for some of the various vegetation types that micht be expected in a tropical country with elevational releif enough to range into subtropical formations. I believe, but cannot prove, that intensively managed agroecosystems used in places formerly occupied by these forest types could produce two to five times as much (except for thew alluvial swamp forests). I do not advocate replacement of forest with agroecosystem, but better management of existing farms.

For comparative purposes, I list in Tables 2-5 conventional yields of tropical crops which can be grown in the lands occupied by some or all of the forests mentioned in Table 1. These data, gathered from a wide diversity of sources do not consistently represent maxima, minima or means, nor are such data available to me. Hence, the fact that one species in the table has a higher yield number than another has no significance whatsoever. These numbers cannot be compared. The generation of reliable maxima, minima, and means would be another string I would tie to any AID money I controlled.

I defer to an appendix a printout from our embryonic biomass data bank. I am proud of it. It did not exist two weeks ago. Today it has close to a thousand entries in it. EBL is probably the best equipped lab in the USDA to compare biomass potential of different monocultural, polycultural and natural ecosystems. Consequently, I have brought my computer to this workshop so you can check it out on the spot. Incidentally, EBL is probably the best equipped lab in the USDA to give you the ecological amplitudes, nutritional analyses, and folk-medicinal attributes of the little known economic plants of TMF, some of which now extant, may soon be extinct.

Table 2. Tropical Fruits
(Yields in MT/ha)

Trees

Akee	Blighia sapida
Almond, Java	Canarium indicum
Annatto	Bixa orellana 4.5
Apple, custard	Annona reticulata
Avocado	Persea americana 13.5
Breadfruit	Artocarpus altilis 9
Cacao	Theobroma cacao 3.3 (sd)
Cashew	Anacardium occidentale 1 (sd)
Cherimoya	Annona cherimola 5
Citron	Citrus medica
Coconum	Cocos nucifera 5
Coffee	Coffee arabica 6
Durian	Durio zibethinus
Grapefruit	Citrus paradisi 45
Guava	Psidium guajava 16
Jackfruit	Artocarpus heterophylla 9
Lemon	Citrus limon 100
Longan	Dimocarpus longan 19
Mango	Mangifera indica 50
Mangosteen	Garcinia magostana 25
Orange	Citrus auranthium 50
Papaya	Carica papaya 100
Peachpalm	Bactris gasipaes 3.5
Soursop	Annona muricata 20
Tangerine	Citrus reticulata 50
Treetomato	Cyphomandra betacea 5.4

Vines

Barbadine	Passiflora quadrangularis 200
Granadilla, purple	Passiflora edulis 23
Granadilla, sweet	Passiflora ligularis 15
Passionfruit, banana	Passiflora mollissima 45

Table 3. Tropical Root Crops
(Yields in MT/ha)

Arrowroot	37
Canna	85
Cassava	56
Gallan	120
Ginger	30
Groundnut (bambarra)	4
Leren	12
Lotus	5
Peanut	5
Sweet Potato	36
Taro	128
Turmeric	35
Yambean	90
Yautia	32

Table 4. Tropical Vegetables

Banana	18 MT
Cantaloupe	14 MT
Eggplant	24 MT
Garlic	10 MT
Okra	23 MT
Onion	29 MT
Pepper	14 MT
Pigeonpea	13 MT
Plantain	45 MT
Pumpkin	23 MT
Squash	23 MT
Tomato	22 MT
Tomatillo	36 MT
Yardlong Bean	10 MT
Watermelon	20 MT

Table 5. Tropical Spices

Trees

Allspice:	Pimenta dioica
Bayrum tree:	Pimenta racemosa
Camphor:	Cinnamomum camphora
Cassia:	Cinnamomum aromaticum
Cinnamon:	Cinnamomum verum
Mace:	Myristica fragrans

Herbs and Vines

Lemongrass:	Cymbopogon citratus	95 MT WM
Patchouli:	Pogostemon cablin	36 MT WM
Pepper, black	Piper nigrum	6 MT (fr)
Vanilla:	Vanilla fragrans	1 MT (sd)
Vetiver:	Vetiveria zizanioides	2.5 MT (rt)

More specifically I list (from printout) In Table 6 estimates of standing phytomass and net primary productivity for some of the various vegetation types that might be expected in a tropical country with elevational relief enough to range into subtropical formations. I believe but cannot prove that intensively managed agroecosystems used in places formerly occupied by these forest types could produce two to five times as much (except for the alluvial swamp forests). I do not advocate replacement of forest with agroecosystem, but better management of existing agroecosystems.

Table 6
NET PRIMARY PRODUCTIVITY

	Republic of Panama Phytomass MT/ha	NPP MT/ha
TROPICAL	240	18
HUMID TROPICS	440	29
Bright Ferrallitic Evergreen	650	30
Dark Ferrallitic Evergreen	600	27
Swamp Forest	500	25
Bogs	300	150
Monsoon Forest (Savanna) Red	200	16
Monsoon (Dark Soil)	80	15
Alluvial Forests	250	70
Mangrove	130	10
Submontane Evergreen	700	25
Submontane Monsoon	450	29
SEMIARID TROPICS	107	14
Xerophytic Forest (Ferrallitic)	250	17
Grass Shrub Savanna (Redbrown)	40	12
Grass Shrub Savanna (Black)	30	11
Grass Shrub Savanna (Solonets)	20	7
Swamp Savanna	60	14
Alluvial Gallery	200	60
Sub montane Xerophytic Forest	200	15
Sub montane Savanna	40	12
ARID TROPICS	7	2
Savanna (red-brown soils)	15	4
Alluvial gallery	150	40
Tropical Desert	1.5	1
Psammophyte on sand	1.0	0.1
Desert (Coalessed soil)	1.0	0.2
Halophytes (solanchaks)	1.0	0.1
Submontane Desert	7.0	2.0

SUBTROPICAL	133	14
HUMID SUBTROPICS	366	25
Bright ferrallitic Evergreen	450	20
Rendaina Evergreen	380	16
Prairie	30	13
Swamp Forest	400	22
Meadow Bog	200	130
Gallery Forest	250	40
Submontane Forest	410	18
SEMIARID SUBTROPICS	99	14
Xerophytic Forests	170	16
Shrub-steppe (Gray-Brown soil)	35	10
Shrub-steppe (Solonetz)	20	6
Shrub-steppe (Chernozemoid)	25	8
Psammophyte on sand	20	5
Halophytes on Glanchak	1.5	0.5
Gallery Forest	250	70
Submontane Forest	120	13
Submontane Shrub-steppe	99	14
ARID SUBTROPICS	14	7
Steppe desert (Serozem)	12	10
Desert (sub-desert soil)	2	1
Psammophytes on sand	3	0.1
Desert on takyrs	1	0.5
Halophyte on solonchak	1	0.2
Gallery Forest	200	90
Submontane Desert (Serozem)	15	12
Submontane Desert (Desert soil)	3	1

Source Rodin & Bazil in Lieth, 1978

Recommendations

1. Research should analyze:

a. sustained yield potential of all tropical tree species (including palms) used for food, drugs, rubber, oil, chewing gum, etc., with emphasis on species that appear to be approaching the endangered status.

b. whole plant or residue energy potential of the tropical economic species, grown under various ecological scenarios. What conventional yields are attainable with minimal or input? What residue yields remain? Such numbers, unavailable at present, are critically needed for any meaningfull system analysis.

c. the synergistic and antagonistic interactions of tropical species in intercropping schemata. Can we control weeds and diseases and insects with residues from chemurgic crops?

d. relative gross and net yields of fuel per hectare, in barrels per hectare.

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PHYTOMASS FILE
ECONOMIC BOTANY LABORATORY

SPECIES	AGE (YEAR)	LOCATION	STANDING PHYTOMASS (MT/HA)	ANNUAL PRODUCTIVITY (MT/HA)	LEAF AREA INDEX	SOURCE
ABIES BALSAMEA	45	CAN	138	9	X	BASKERVILLE 1965
ABIES BALSAMEA	45	CAN	133	9	X	BASKERVILLE 1965
ABIES BALSAMEA	45	CAN	149	10	X	BASKERVILLE 1965
ABIES BALSAMEA	45	CAN	147	11	X	BASKERVILLE 1965
ABIES BALSAMEA	45	CAN	193	12	X	BASKERVILLE 1965
ABIES BALSAMEA	45	CAN	200	13	X	BASKERVILLE 1965
ABIES BALSAMEA	49	US	77	X	X	YOUNG & CARPENTER 1967
ABIES FRASERI	X	US	210	6	X	WHITTAKER 1966
ABIES FRASERI	X	US	200	7	X	WHITTAKER 1966
ABIES GRANDIS	41	UK	355	19	X	OVINGTON 1956
ABIES GRANDIS	34	UK	165	9	X	OVINGTON 1956
ABIES SACCHALINENSIS	25	JAPAN	X	13	X	SATOO 1966
ABIES SPECTABILIS	X	NEPAL	591	X	X	YODA 1968
ABIES SPECTABILIS	X	NEPAL	495	X	X	YODA 1968
ABIES SPECTABILIS	X	NEPAL	426	X	X	YODA 1968
ABIES SPECTABILIS	X	NEPAL	338	X	X	YODA 1968
ACACIA DARBOYNELLA	X	AUSTRAL	150	X	X	MOORE ET AL 1967
ACACIA MOLLISSIMA	4	JAPAN	31	35	9.7	TADAKI 1963
ACACIA MOLLISSIMA	3	JAPAN	44	25	X	TADAKI ET AL 1963
ACACIA MOLLISSIMA	3	JAPAN	57	21	X	TADAKI ET AL 1963
ACACIA MOLLISSIMA	5	JAPAN	74	32	X	TADAKI ET AL 1963
ACACIA MOLLISSIMA	5	JAPAN	121	30	X	TADAKI ET AL 1963
ACACIA MOLLISSIMA	5	JAPAN	72	24	X	TADAKI ET AL 1963
ACACIA MOLLISSIMA	7	JAPAN	77	24	X	TADAKI ET AL 1963
ACACIA MOLLISSIMA	7	JAPAN	100	31	X	TADAKI ET AL 1963
ACER RUBRUM	34	US	15	X	X	YOUNG & CARPENTER
ACER SPICATUM	1	CAN	1	1	X	POST 1970
ACER SPICATUM	3	CAN	2	1	X	POST 1970
ACER SPICATUM	8	CAN	13	2	X	POST 1970
ACER SPICATUM	11	CAN	16	1	X	POST 1970
ACER SPICATUM	13	CAN	23	2	X	POST 1970
ACER SPICATUM	16	CAN	26	2	X	POST 1970
ACER SPICATUM	19	CAN	22	1	X	POST 1970
ACER SPICATUM	21	CAN	34	1	X	POST 1970
ACER SPICATUM	27	CAN	31	1	X	POST 1970
ACER SPICATUM	45	CAN	45	2	X	POST 1970
ACROCYRAS ARGRUM	X	RHODESIA	X	7	X	BOGDAN 1977
ACROCYRAS ARGRUM	X	X	X	4	X	DUAF 1978
AEGICERAS AFRICANA	X	US(FLORIDA)	X	5	X	BOGDAN 1977
AEGICERAS AFRICANA	X	US(FLORIDA)	X	1	X	BOGDAN 1977
AGROPYRON DESERTORUM	X	X	X	2	X	DUAF 1978
AGROPYRON ELONGATUM	X	X	X	13	X	DUAF 1978
AGROPYRON INTERMEDIUM	X	X	X	2	X	DUAF 1978
AGROPYRON REPENS	X	X	X	5	X	DUAF 1978
AGROPYRON STRIGOSUM	X	X	X	2	X	DUAF 1978
AGROPYRON SMITHII	X	X	X	2	X	DUAF 1978
AGROPYRON TRACHYCAULON	X	X	X	2	X	DUAF 1978
ALNUS INCANA	22	UK	125	6	X	OVINGTON 1956
ALNUS INCANA	22	UK	74	5	X	OVINGTON 1956
ALNUS RUBRA	50	US	250	X	X	ZAVITOVSKI 1970
ALOPECURUS PRATENSIS	12	US	X	26	X	ZAVITOVSKI 1970
	X	X	X	6	X	DUAF 1978

APPENDIX I.

(SOURCE: U.S. BIOMASS DATA BANK)

PHYTOMASS FILE
ECONOMIC BOTANY LABORATORY

SPECIES	AGE (YEAR)	LOCATION	STANDING PHYTOMASS (MT/HA)	ANNUAL PRODUCTIVITY (MT/HA)	LEAF AREA INDEX	SOURCE
ALTERNANTHERA PHILOXEROIDES	X	ALABAMA	4	X	X	DUKE YIELDFILE 1979
ALYSICARPUS RUGOSUS	X	INDIA	X	28	X	BOGDAN 1977
ALYSICARPUS RUGOSUS	X	INDIA	X	2	X	BOGDAN 1977
ALYSICARPUS RUGOSUS	X	INDIA	X	3	X	BOGDAN 1977
ALYSICARPUS VAGINALIS	X	TAIWAN	X	7	X	DUKE YIELDFILE 1979
AMBROSIA TRIFIDA	X	OKLAHOMA	X	14	X	DUKE YIELDFILE 1979
ANDROPOGON GAYANUS	X	AUSTRALIA	X	4	X	BOGDAN 1977
ANDROPOGON GAYANUS	X	CAMEROON	X	8	X	BOGDAN 1977
ANDROPOGON GAYANUS	X	MALI	X	7	X	BOGDAN 1977
ANDROPOGON GAYANUS	X	NIGERIA	X	10	X	BOGDAN 1977
ANDROPOGON GAYANUS	X	NIGERIA	X	14	X	BOGDAN 1977
ANDROPOGON GAYANUS	X	X	X	25	X	DUKE 1978
ANDROPOGON PSEUDAPRICUS	X	MALI	X	24	X	BOGDAN 1977
ANETHUM GRAVEOLENS	X	X	X	1	X	DUKE YIELDFILE 1979
ARACHIS GLABRATA	X	NL	X	5	X	BOGDAN 1977
ARACHIS GLABRATA	X	NL	X	6	X	BOGDAN 1977
ARACHIS GLABRATA	X	NL	X	9	X	BOGDAN 1977
ARACHIS HYPOGAEA	X	INDIA	X	3	X	BOGDAN 1977
ARACHIS HYPOGAEA	X	US	X	4	X	DUKE YIELDFILE 1979
ARACHIS HYPOGAEA	X	VENEZUELA	X	2	X	BOGDAN 1977
ARACHIS HYPOGAEA	X	VENEZUELA	X	3	X	BOGDAN 1977
ARACHIS HYPOGAEA	X	VENEZUELA	X	4	X	BOGDAN 1977
ARACHIS HYPOGAEA	X	VENEZUELA	X	5	X	BOGDAN 1977
ARACHIS HYPOGAEA	X	VENEZUELA	X	6	X	BOGDAN 1977
ARACHIS HYPOGAEA	X	VENEZUELA	X	7	X	BOGDAN 1977
ARRACACIA XANTHORRHIZA	X	X	X	1	X	DUKE YIELDFILE 1979
ARUNDO DONAX	X	X	X	59	X	DUKE 1978
ASCOPHYLLUM NODOSUM	X	NOVASCOTIA	X	12	X	WESTLAKE 1963
ATROPA BELLADONNA	X	X	X	2	X	DUKE 1978
AVENA SATIVA	X	COLOMBIA	X	28	X	BOGDAN 1977
AVENA SATIVA	X	MALAGASY	X	58	X	BOGDAN 1977
AXONOPUS AFFINIS	X	X	X	44	X	DUKE 1978
AXONOPUS COMPRESSUS	X	SURINAM	X	28	X	BOGDAN 1977
AXONOPUS SCOPARIUS	X	BRAZIL	X	20	X	BOGDAN 1977
AXONOPUS SCOPARIUS	X	BRAZIL	X	1	X	BOGDAN 1977
AXONOPUS SCOPARIUS	X	BRAZIL	X	6	X	BOGDAN 1977
AXONOPUS SCOPARIUS	X	COLOMBIA	X	19	X	BOGDAN 1977
AXONOPUS SCOPARIUS	X	COLOMBIA	X	14	X	BOGDAN 1977
BECKERIOPSIS UNISETA	X	RHODESIA	X	11	X	BOGDAN 1977
BETA MARITIMA	X	NETHERLAND	17	18	X	WESTLAKE 1963
BETULA ALBA	22	UK	63	3	X	OVINGTON 1956
BETULA ALBA	22	UK	59	3	X	OVINGTON
BETULA GRAMANII	22	JAPAN	63	X	5.6	SAIOO 1970
BETULA MAKIMOWICZINIANA	44	JAPAN	X	6	X	SAIOO 1966
BETULA MAKIMOWICZINIANA	47	JAPAN	X	8	X	SAIOO 1966
BETULA MAKIMOWICZINIANA	47	JAPAN	X	6	X	SAIOO 1966
BETULA MAKIMOWICZINIANA	47	JAPAN	143	X	X	OVINGTON 1962
BETULA MAKIMOWICZINIANA	47	JAPAN	91	X	X	OVINGTON 1962
BETULA MAKIMOWICZINIANA	47	JAPAN	117	X	X	OVINGTON 1962
BETULA PAPYRIFERA	32	US	11d	X	X	YOUNG & CARPENTER
BETULA PLATYPHILLA	10	JAPAN	20	5	3.5	TADAKI ET AL 1961
BETULA SP	X	USSR	220	12	X	RODIN & BAZILEVICH 1967

PHYTOMASS FILE
ECONOMIC BOTANY LABORATORY

SPECIES	AGE (YEAR)	LOCATION	STANDING PHYTOMASS (MT/HA)	ANNUAL PRODUCTIVITY (MT/HA)	LEAF AREA INDEX	SOURCE
BETULA VERRUCOSA	25	SWEDEN	47	X	X	OVINGTON 1962
BETULA VERRUCOSA	0	UK	2	X	X	OVINGTON & MADGWICK 1959
BETULA VERRUCOSA	24	UK	69	X	X	OVINGTON & MADGWICK 1959
BETULA VERRUCOSA	27	UK	79	X	X	OVINGTON & MADGWICK 1959
BETULA VERRUCOSA	37	UK	84	X	X	OVINGTON & MADGWICK 1959
BETULA VERRUCOSA	38	UK	70	X	X	OVINGTON & MADGWICK 1959
BETULA VERRUCOSA	42	UK	74	X	X	OVINGTON & MADGWICK 1959
BETULA VERRUCOSA	46	UK	121	X	X	OVINGTON & MADGWICK 1959
BETULA VERRUCOSA	53	UK	173	X	X	OVINGTON & MADGWICK 1959
BETULA VERRUCOSA	55	UK	219	X	X	OVINGTON & MADGWICK 1959
BETULA VERRUCOSA	20	USSR	80	X	X	OVINGTON 1962
BETULA VERRUCOSA	40	USSR	248	X	X	OVINGTON 1962
BETULA VERRUCOSA	90	USSR	224	X	X	OVINGTON 1962
BOTHRIOCHLOA CAUCASICA	X	X	X	13	X	DUKE 1978
BOTHRIOCHLOA INTERMEDIA	X	X	X	4	X	DUKE 1978
BOTHRIOCHLOA ISCHAEMUM	X	X	X	11	X	DUKE 1978
BOTHRIOCHLOA PERTUSA	X	CORA	X	15	X	BOGDAN 1977
BRACHIARIA BRIZANTHA	X	X	X	18	X	DUKE 1978
BRACHIARIA DECUMBENS	X	COLOMBIA	X	15	X	BOGDAN 1977
BRACHIARIA DECUMBENS	X	COLOMBIA	X	20	X	BOGDAN 1977
BRACHIARIA DECUMBENS	X	SARAWAK	X	20	X	DUKE YIELDFILE 1979
BRACHIARIA DECUMBENS	X	SARAWAK	X	22	X	BOGDAN 1977
BRACHIARIA DECUMBENS	X	SARAWAK	X	14	X	BOGDAN 1977
BRACHIARIA DECUMBENS	X	SARAWAK	X	22	X	BOGDAN 1977
BRACHIARIA DECUMBENS	X	SURINAM	X	36	X	BOGDAN 1977
BRACHIARIA HUMIDICOLA	X	FIJI	X	11	X	BOGDAN 1977
BRACHIARIA HUMIDICOLA	X	FIJI	X	34	X	BOGDAN 1977
BRACHIARIA MUTICA	X	PANAMA	X	6	X	BOGDAN 1977
BRACHIARIA MUTICA	X	PUERTO RICO	X	39	X	BOGDAN 1977
BRACHIARIA MUTICA	X	SURINAM	X	16	X	BOGDAN 1977
BRACHIARIA MUTICA	X	X	X	22	X	DUKE 1978
BRACHIARIA PARAPALOIDES	X	X	X	9	X	DUKE YIELDFILE 1979
BRACHIARIA RUTICANA	X	PUERTO RICO	X	54	X	BOGDAN 1977
BRACHIARIA RUZIZIENSIS	X	AUSTRALIA	X	4	X	BOGDAN 1977
BRACHIARIA RUZIZIENSIS	X	SURINAM	X	241	X	BOGDAN 1977
BRASENIA SCHREBERI	X	US	X	1	X	DUKE YIELDFILE 1979
BRASSICA OLERACEA(KALE)	X	FRANCE	X	6	X	BA 59022(046)
BROMUS BRIZEBOTTANII	X	NEVADA	X	4	X	DUKE YIELDFILE 1979
BROMUS INERMIS	X	X	X	11	X	DUKE 1978
BROMUS UNIOLOIDES	X	FRANCE	X	9	X	BA 03910(046)
BROMUS UNIOLOIDES	X	QUEENSLAND	X	8	X	BOGDAN 1977
BROMUS UNIOLOIDES	X	GA	X	9	X	BOGDAN 1977
CAJANUS CAJAN	X	COLOMBIA	X	24	X	BOGDAN 1977
CAJANUS CAJAN	X	COLOMBIA	X	63	X	BOGDAN 1977
CAJANUS CAJAN	X	CORA	X	17	X	BOGDAN 1977
CAJANUS CAJAN	X	FLORIDA	X	7	X	FCA 08171(029)
CALLUNA SP	X	UK	X	4	X	DUKE YIELDFILE 1979
CALOPOGONIUM MUCUNOIDES	X	NL	X	14	X	BOGDAN 1977
CALOPOGONIUM MUCUNOIDES	X	X	X	5	X	DUKE 1978
CAMELLIA JAPONICA	70	JAPAN	185	15	6.2	KAN ET AL 1965
CAMELLIA JAPONICA	77	JAPAN	152	14	5.5	KAN ET AL 1965
CAMELLIA JAPONICA	72	JAPAN	177	16	6.8	KAN ET AL 1965

PHYTOMASS FILE
ECONOMIC BOTANY LABORATORY

SPECIES	AGE (YEAR)	LOCATION	STANDING PHYTOMASS (MT/HA)	ANNUAL PRODUCTIVITY (MT/HA)	LEAF AREA INDEX	SOURCE
CANELLIA SINENSIS	X	X	X	5	X	DUAF 1978
CANAVALIA ENSIFORMIS	X	INDIA	X	.	X	BOGDAN 1977
CANAVALIA ENSIFORMIS	X	INDIA	X	6	X	BOGDAN 1977
CANNABIS SATIVA	X	US	X	6	X	DUAF YIELDFILE
CASTANEA SATIVA	47	UK	117	4	X	DYKSTRA 1956
CASTANOPSIS CUSPIDATA	11	JAPAN	80	14	8.0	TAKAHI 1965
CASTANOPSIS CUSPIDATA	43	JAPAN	219	31	8.7	KIRA ET AL 1965
CASTANOPSIS CUSPIDATA	43	JAPAN	196	28	9.5	KIRA ET AL 1965
CASTANOPSIS CUSPIDATA	17	JAPAN	57	19	5.2	KIRA ET AL 1965
CASTANOPSIS CUSPIDATA	12	JAPAN	66	25	7.2	KIRA ET AL 1965
CASTANOPSIS CUSPIDATA	10	JAPAN	43	19	12.0	TAKAHI ET AL 1962
CENCHRUS CILIARIS	X	INDIA	X	13	X	BOGDAN 1977
CENCHRUS CILIARIS	X	INDIA	X	24	X	BOGDAN 1977
CENCHRUS CILIARIS	X	INDIA	X	62	X	BOGDAN 1977
CENCHRUS CILIARIS	X	MALAWI	X	5	X	BOGDAN 1977
CENCHRUS CILIARIS	X	MALAWI	X	.	X	BOGDAN 1977
CENCHRUS CILIARIS	X	NIGERIA	X	3	X	BOGDAN 1977
CENCHRUS CILIARIS	X	PAKISTAN	X	13	X	BOGDAN 1977
CENCHRUS CILIARIS	X	TANZANIA	X	2	X	BOGDAN 1977
CENCHRUS CILIARIS	X	TANZANIA	X	4	X	BOGDAN 1977
CENCHRUS CILIARIS	X	TANZANIA	X	6	X	BOGDAN 1977
CENCHRUS GLAUCUS	X	INDIA	X	13	X	BOGDAN 1977
CENCHRUS GLAUCUS	X	INDIA	X	57	X	
CENTROSEMA BRASILIANUM	X	QUEENSLAND	X	15	X	BOGDAN 1977
CENTROSEMA PUBESCENS	X	AUSTRALIA	X	12	X	BOGDAN 1977
CENTROSEMA PUBESCENS	X	BRAZIL	X	3	X	BOGDAN 1977
CENTROSEMA PUBESCENS	X	BRAZIL	X	5	X	BOGDAN 1977
CENTROSEMA PUBESCENS	X	BRAZIL	X	4	X	BOGDAN 1977
CENTROSEMA PUBESCENS	X	CHINA	X	8	X	BOGDAN 1977
CERATOPHYLLUM DEMERSUM	X	X	7	.	X	WESTLAKE 1963
CHAMAECYPARIS OBTUSA	21	UK	297	11	X	DYKSTRA 1956
CHARA INTERMEDIA	X	CASPIAN	90	37	X	WESTLAKE 1963
CHLORIS GAYANA	X	FIJI	X	42	X	BOGDAN 1977
CHLORIS GAYANA	X	FIJI	X	106	X	BOGDAN 1977
CHLORIS GAYANA	X	FIJI	X	124	X	BOGDAN 1977
CHLORIS GAYANA	X	QUEENSLAND	X	6	X	BOGDAN 1977
CHLORIS GAYANA	X	QUEENSLAND	X	12	X	BOGDAN 1977
CHLORIS GAYANA	X	SOUTH AFRICA	X	.	X	BOGDAN 1977
CHLORIS GAYANA	X	SOUTH AFRICA	X	8	X	BOGDAN 1977
CHLORIS GAYANA	X	THAILAND	X	10	X	BOGDAN 1977
CHLORIS GAYANA	X	THAILAND	X	15	X	BOGDAN 1977
CHLORIS GAYANA	X	X	X	17	X	DUAF 1976
CHLORIS GAYANA	X	ZAMBIA	X	3	X	BOGDAN 1977
CHLORIS GAYANA	X	ZAMBIA	X	6	X	BOGDAN 1977
CHRYSOPOGON FULVUS	X	INDIA	X	13	X	BOGDAN 1977
CINNAMOMUM CAMPHORA	45	JAPAN	198	16	X	SATOO 1966
CINNAMOMUM CAMPHORA	52	JAPAN	X	19	X	SATOO 1966
CLADIUM JAMAICENSE	X	X	32	X	X	DUAF YIELDFILE 1979
CLITORIA TERNATEA	X	CUBA	X	44	X	BOGDAN 1977
CLITORIA TERNATEA	X	CUBA	X	59	X	BOGDAN 1977
CLITORIA TERNATEA	X	CUBA	X	62	X	BOGDAN 1977
CLITORIA TERNATEA	X	X	X	16	X	DUAF 1976

PHYTOMASS FILE
ECONOMIC BOTANY LABORATORY

SPECIES	AGE (YEAR)	LOCATION	STANDING PHYTOMASS (MT/HA)	ANNUAL PRODUCTIVITY (MT/HA)	LEAF AREA INDEX	SOURCE
CLITORIA TERNATEA COST MA	X	[illegible]	X	TOTAL	X	BOGDAN 1977
COIX LACRYMA-JOBI	7	MALI	X	5%	X	BOGDAN 1977
CROTALARIA INCANA	X	RHODESIA	X	4	X	BOGDAN 1977
CROTALARIA JUNCEA	X	INDIA	X	4	X	FCA 29068(029)
CROTALARIA JUNCEA	X	INDIA	X	5	X	BOGDAN 1977
CROTALARIA SPECTABILIS	X	X	X	64	X	DUKE 1978
CRYPTOMERIA JAPONICA	5	JAPAN	37	20	17.2	TADAKI ET AL 1966
CRYPTOMERIA JAPONICA	34	JAPAN	176	10	9.4	TADAKI ET AL 1965
CRYPTOMERIA JAPONICA	34	JAPAN	182	14	12.1	TADAKI ET AL 1965
CRYPTOMERIA JAPONICA	34	JAPAN	194	16	13.0	TADAKI ET AL 1965
CRYPTOMERIA JAPONICA	24	JAPAN	170	15	14.7	TADAKI ET AL 1965
CRYPTOMERIA JAPONICA	34	JAPAN	154	12	11.5	TADAKI ET AL 1965
CRYPTOMERIA JAPONICA	44	JAPAN	174	9	10.0	TADAKI ET AL 1965
CRYPTOMERIA JAPONICA	11	JAPAN	64	15	10.7	TADAKI ET AL 1965
CRYPTOMERIA JAPONICA	31	JAPAN	160	17	13.5	TADAKI ET AL 1965
CRYPTOMERIA JAPONICA	42	JAPAN	136	14	11.8	TADAKI ET AL 1965
CYAMOPSIS TETRAGONOLOBA	X	INDIA	X	5	X	BOGDAN 1977
CYMBOPOGON FLEXUOSUS	X	X	X	4	X	DUKE 1978
CYMBOPOGON FLEXUOSUS	X	X	X	2	X	DUKE 1978
CYNODON ARTHROPICUS	X	RHODESIA	X	12	X	BOGDAN 1977
CYNODON DACTYLON	X	TAIWAN	X	7	X	BOGDAN 1977
CYNODON DACTYLON	X	PUERTO RICO	X	25	X	BOGDAN 1977
CYNODON DACTYLON	X	US	X	7	X	BA 03394(046)
CYNODON DACTYLON	X	US	X	4	X	BOGDAN 1977
CYNODON DACTYLON	X	US	X	11	X	BOGDAN 1977
CYNODON DACTYLON	X	X	X	15	X	DUKE 1978
CYNODON DLEMFUENSIS	X	KENYA	X	2	X	BOGDAN 1977
CYNODON DLEMFUENSIS	X	RHODESIA	X	12	X	BOGDAN 1977
CYNODON DLEMFUENSIS	X	RHODESIA	X	12	X	BOGDAN 1977
CYPERUS PAPYRUS	X	X	70	X	X	DUKE YIELDFILE
DACTYLIS GLOMERATA	X	FRANCE	X	5	X	BA 04164(046)
DACTYLIS GLOMERATA	X	X	X	30	X	DUKE 1978
DACTYLOCTENIUM GIGANTEUM	X	KALAHARI	X	1	X	BOGDAN 1977
DACTYLOCTENIUM GIGANTEUM	X	KALAHARI	X	3	X	BOGDAN 1977
DESCHAMPSIA CESPITOSA	X	X	X	10	X	DUKE YIELDFILE 1979
DESMODIUM CANUM	X	HAWAII	X	7	X	BOGDAN 1977
DESMODIUM CANUM	X	HAWAII	X	8	X	BOGDAN 1977
DESMODIUM DICHROCARPUM	X	HAWAII	X	9	X	BOGDAN 1977
DESMODIUM DICHROCARPUM	X	HAWAII	X	7	X	BOGDAN 1977
DESMODIUM DISCOLOR	X	SRI LANKA	X	7	X	BOGDAN 1977
DESMODIUM GRIFFITHIANUM	X	US(FLORIDA)	X	6	X	BOGDAN 1977
DESMODIUM INTORTUM	X	HAWAII	X	6	X	BOGDAN 1977
DESMODIUM INTORTUM	X	HAWAII	X	7	X	BOGDAN 1977
DESMODIUM INTORTUM	X	MALAGASY	X	68	X	BOGDAN 1977
DESMODIUM INTORTUM	X	MALAGASY	X	8	X	BOGDAN 1977
DESMODIUM INTORTUM	X	SOUTH AFRICA	X	9	X	BOGDAN 1977
DESMODIUM INTORTUM	X	SOUTH AFRICA	X	17	X	BOGDAN 1977
DESMODIUM INTORTUM	X	UGANDA	X	12	X	BOGDAN 1977
DESMODIUM INTORTUM	X	UGANDA	X	2	X	BOGDAN 1977
DESMODIUM INTORTUM	X	X	X	6	X	DUKE 1978
DESMODIUM UNCINATUM	X	GHANA	X	5	X	BOGDAN 1977
DESMODIUM UNCINATUM	5	SOUTH AFRICA	X	7	X	BOGDAN 1977

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PHYTOMASS FILE
ECONOMIC BOTANY LABORATORY

SPECIES	AGE (YEAR)	LOCATION	STANDING PHYTOMASS (MT/HA)	ANNUAL PRODUCTIVITY (MT/HA)	LEAF AREA INDEX	SOURCE
DESMODIUM UNCINATUM	X	TANZANIA	X	2	X	BOGDAN 1977
DESMODIUM UNCINATUM	X	TANZANIA	X	21	X	BOGDAN 1977
DICHANTHIUM ANNULATUM	X	CUBA	X	17	X	BOGDAN 1977
DICHANTHIUM ANNULATUM	X	INDIA	X	13	X	BOGDAN 1977
DICHANTHIUM ANNULATUM	X	INDIA	X	16	X	BOGDAN 1977
DICHANTHIUM ANNULATUM	X	INDIA	X	13	X	BOGDAN 1977
DICHANTHIUM ANNULATUM	X	INDIA	X	24	X	BOGDAN 1977
DICHANTHIUM ANNULATUM	X	X	X	7	X	DUKE 1978
DICHANTHIUM CARICOSUM	X	CUBA	X	15	X	BOGDAN 1977
DICHANTHIUM CARICOSUM	X	INDIA	X	13	X	BOGDAN 1977
DIGITARIA DECUMBENS	X	AUSTRALIA	X	28	X	BOGDAN 1977
DIGITARIA DECUMBENS	X	COLUMBIA	X	3	X	BOGDAN 1977
DIGITARIA DECUMBENS	X	CUBA	X	6	X	BOGDAN 1977
DIGITARIA DECUMBENS	X	CUBA	X	17	X	BOGDAN 1977
DIGITARIA DECUMBENS	X	CUBA	X	19	X	BOGDAN 1977
DIGITARIA DECUMBENS	X	EGYPT	X	17	X	BOGDAN 1977
DIGITARIA DECUMBENS	X	GUYANA	X	7	X	BOGDAN 1977
DIGITARIA DECUMBENS	X	GUYANA	X	12	X	BOGDAN 1977
DIGITARIA DECUMBENS	X	HAWAII	X	13	X	BOGDAN 1977
DIGITARIA DECUMBENS	X	PUERTO RICO	X	22	X	BOGDAN 1977
DIGITARIA DECUMBENS	X	PUERTO RICO	X	33	X	BOGDAN 1977
DIGITARIA DECUMBENS	X	PUERTO RICO	X	36	X	BOGDAN 1977
DIGITARIA DECUMBENS	X	PUERTORICO	X	18	X	DUKE TIFLOFILE 1979
DIGITARIA DECUMBENS	X	SARAWAK	X	6	X	BOGDAN 1977
DIGITARIA DECUMBENS	X	TAIWAN	X	23	X	DUKE TIFLOFILE 1979
DIGITARIA DECUMBENS	X	WI	X	5	X	BOGDAN 1977
DIGITARIA DECUMBENS	X	WI	X	20	X	BOGDAN 1977
DIGITARIA DECUMBENS	X	WI	X	3	X	BOGDAN 1977
DIGITARIA DECUMBENS	X	WI	X	7	X	BOGDAN 1977
DIGITARIA DECUMBENS	X	WI	X	8	X	BOGDAN 1977
DIGITARIA DECUMBENS	X	X	X	31	X	DUKE 1978
DIGITARIA DIANTHA	X	PUERTO RICO	X	45	X	BOGDAN 1977
DIGITARIA MILANOIANA	X	FIJI	X	5	X	BOGDAN 1977
DIGITARIA MILANOIANA	X	PUERTO RICO	X	34	X	BOGDAN 1977
DIGITARIA PENTZII	X	BRAZIL	X	27	X	BOGDAN 1977
DIGITARIA PENTZII	X	CAMEROON	X	3	X	BOGDAN 1977
DIGITARIA PENTZII	X	CAMEROON	X	6	X	BOGDAN 1977
DIGITARIA PENTZII	X	PUERTO RICO	X	27	X	BOGDAN 1977
DIGITARIA PENTZII	X	PUERTO RICO	X	31	X	BOGDAN 1977
DIGITARIA SETIVALVA	X	GUYANA	X	2	X	BOGDAN 1977
DIGITARIA SETIVALVA	X	GUYANA	X	4	X	BOGDAN 1977
DIGITARIA SETIVALVA	X	GUYANA	X	6	X	BOGDAN 1977
DIGITARIA SETIVALVA	X	GUYANA	X	7	X	BOGDAN 1977
DIGITARIA SETIVALVA	X	GUYANA	X	9	X	BOGDAN 1977
DIGITARIA SMUTSII	X	PUERTO RICO	X	27	X	BOGDAN 1977
DIGITARIA SMUTSII	X	PUERTO RICO	X	33	X	BOGDAN 1977
DIGITARIA VALIDA	X	CAMEROON	X	5	X	BOGDAN 1977
DIGITARIA VALIDA	X	CAMEROON	X	11	X	BOGDAN 1977
DIGITARIA VALIDA	X	PUERTO RICO	X	19	X	BOGDAN 1977
DISTYLIUM RACEMOSUM	X	JAPAN	22J	19	8.8	AIMURA 1960
ECHINOCHLOA CRUSGALLI	X	X	X	10	X	DUKE 1978
ECHINOCHLOA POLYSTACHYA	X	SURINAM	X	38	X	BOGDAN 1977

PHYTOMASS FILE
ECONOMIC BOTANY LABORATORY

SPECIES	AGE (YEAR)	LOCATION	STANDING PHYTOMASS (MT/HA)	ANNUAL PRODUCTIVITY (MT/HA)	LEAF AREA INDEX	SOURCE
ECHINOCHLOA POLYSTACHYA	X	VENEZUELA	X	6	X	BOGDAN 1977
ECHINOCHLOA POLYSTACHYA	X	VENEZUELA	X	12	X	BOGDAN 1977
ECHINOCHLOA POLYSTACHYA	X	VENEZUELA	X	20	X	BOGDAN 1977
ECHINOCHLOA POLYSTACHYA	X	VENEZUELA	X	30	X	BOGDAN 1977
ECHINOCHLOA STAGNINA	X	PHILIPPINES	X	17	X	BOGDAN 1977
EICHHORNIA CRASSIPES	X	US	15	3*	X	DUKE YIELDFILE 1979
ELAEIS GUINEENSIS	X	ZAIRE	85	37	X	*STEARE 1963
ELEOCHARIS EQUISETOIDES	X	US	4	4	X	DUKE YIELDFILE 1979
ELEOCHARIS QUADRANGULATA	X	US	9	X	X	DUKE YIELDFILE 1979
ELEUSINE CORACANA	X	INDIA	X	2	X	BOGDAN 1977
ELEUSINE CORACANA	X	INDIA	X	9	X	BOGDAN 1977
ELEUSINE INDICA	X	MALI	X	38	X	BOGDAN 1977
ENTEROPOGON MACROSTACHYUS	X	KENYA	X	1	X	BOGDAN 1977
ENTEROPOGON MACROSTACHYUS	X	KENYA	X	3	X	BOGDAN 1977
			X			
ERAGROSTIS CHLOROMELAS	X	INDIA	X	18	X	BOGDAN 1977
ERAGROSTIS CHLOROMELAS	X	X	X	2	X	DUKE 1978
ERAGROSTIS CURVULA	X	INDIA	X	1	X	BOGDAN 1977
ERAGROSTIS CURVULA	X	INDIA	X	38	X	BOGDAN 1977
ERAGROSTIS CURVULA	X	SOUTH AFRICA	X	2	X	BOGDAN 1977
ERAGROSTIS CURVULA	X	SOUTH AFRICA	X	10	X	BOGDAN 1977
ERAGROSTIS CURVULA	X	X	X	8	X	DUKE 1978
ERAGROSTIS SUPERBA	X	SENEGAL	X	3	X	BOGDAN 1977
ERAGROSTIS SUPERBA	X	SENEGAL	X	4	X	BOGDAN 1977
ERAGROSTIS SUPERBA	X	SENEGAL	X	5	X	BOGDAN 1977
ERAGROSTIS TEF	X	KENYA	X	2	X	BOGDAN 1977
EUCALYPTUS GRANDIS	X	CAL	X	22	X	SACHS ET AL 1980
EUCHLAENA MEXICANA	X	INDIA	X	38	X	BOGDAN 1977
EUCHLAENA MEXICANA	X	INDIA	X	78	X	BOGDAN 1977
EUCHLAENA MEXICANA	X	INDIA	X	6	X	BOGDAN 1977
EUCHLAENA MEXICANA	X	INDIA	X	14	X	BOGDAN 1977
EUCHLAENA MEXICANA	X	US	X	58	X	BOGDAN 1977
EUCHLAENA MEXICANA	X	X	35	X	X	DUKE YIELDFILE 1979
FAGUS GRANDIFOLIA	X	US	130	7	2.9	WHITTAKER 1966
FAGUS GRANDIFOLIA	X	US	170	9	X	WHITTAKER 1966
FAGUS SP	X	EUROPE	370	13	X	KODIN & BAZILEVICH 1967
FAGUS SP	45	HOLLAND	X	14	X	LIETH 1962
FAGUS SYLVATICA	80	SWISS	X	18	X	BURGEP 1940
FAGUS SYLVATICA	39	UK	133	5	X	OVINGTON 1956
FESTUCA ARUNDINACEA	X	FRANCE	X	14	X	BA 03862(046)
FESTUCA ARUNDINACEA	X	X	X	18	X	DUKE 1978
FESTUCA PRATENSIS	X	X	X	9	X	DUKE 1978
GLYCERIA MAXIMA	X	US	12	X	X	DUKE YIELDFILE 1979
GLYCINE MAX	X	BRAZIL	X	28	X	BOGDAN 1977
GLYCINE MAX	X	COLUMBIA	X	38	X	BOGDAN 1977
GLYCINE MAX	X	INDIA	X	38	X	BOGDAN 1977
GLYCINE MAX	X	INDIA	X	98	X	BOGDAN 1977
GLYCINE MAX	X	US	X	2	X	BOGDAN 1977
GLYCINE MAX	X	US	X	11	X	BOGDAN 1977
GLYCINE MAX	X	X	X	25	X	DUKE 1978
GLYCINE WIGHTII	X	BRAZIL	X	1	X	BOGDAN 1977
GLYCINE WIGHTII	X	BRAZIL	X	6	X	BOGDAN 1977

PHYTOMASS FILE
ECONOMIC BOTANY LABORATORY

SPECIES	AGE (YEAR)	LOCATION	STANDING PHYTOMASS (MT/HA)	ANNUAL PRODUCTIVITY (MT/HA)	LEAF AREA INDEX	SOURCE
GLYCINE WIGHTII	X	NL	X	3	X	BOGDAN 1977
GLYCINE WIGHTII	X	NL	X	4	X	BOGDAN 1977
GLYCINE WIGHTII	X	X	X	6	X	DUKE 1978
GOMYCHIDA CONDAMINA	X	X	3	X	X	DUKE YIELDFILE 1979
HELIANTHUS ANNUUS	X	FRANCE	X	9	X	EA CUSCZ(1976)
HEMARTHRIA ALTISSIMA	A	X	X	12	X	DUKE 1978
HETEROPOGON CONTORTUS	X	INDIA	X	23	X	BOGDAN 1977
HORDEUM VULGARE	A	X	X	45	X	WESTLAKE 1963
HYDROCOTYLE CAROLINENSIS	X	US	2	X	X	DUKE YIELDFILE 1979
HYDROCOTYLE UMBELLATA	A	X	4	X	X	DUKE YIELDFILE 1979
HYDROTRIUM CAROLINIANA	X	US	3	X	X	DUKE YIELDFILE 1979
HYMENACHNE AMPLEXICAULIS	X	SURINAM	X	26	X	BOGDAN 1977
HYMENACHNE AMPLEXICAULIS	X	SURINAM	X	23	X	BOGDAN 1977
HYPARRHENIA RUFA	X	COSTARICA	13	X	X	DUKE YIELDFILE 1979
HYPARRHENIA RUFA	X	COLOMBIA	X	35	X	BOGDAN 1977
HYPARRHENIA RUFA	A	EGYPT	X	6	X	BOGDAN 1977
HYPARRHENIA RUFA	X	UGANDA	X	12	X	BOGDAN 1977
HYPARRHENIA RUFA	A	UGANDA	X	19	X	BOGDAN 1977
HYPARRHENIA RUFA	X	X	X	17	X	DUKE 1978
ILEX AQUIFOLIUM	62	UK	211	15	6.6	PETERKEN & NEWBOULD 1966
ILEX AQUIFOLIUM	190	UK	131	17	5.6	PETERKEN & NEWBOULD 1966
ILEX AQUIFOLIUM	42	UK	39	2	5.7	PETERKEN & NEWBOULD 1966
ILEX AQUIFOLIUM	94	UK	72	4	4.9	PETERKEN & NEWBOULD 1966
ILEX AQUIFOLIUM	89	UK	60	4	5.3	PETERKEN & NEWBOULD 1966
ILEX OPACA	150	US	176	11	5.9	ABEE & BARRY 1978
IMPERATA CYLINDRICA	X	X	4	X	X	DUKE YIELDFILE
ISCHAEMUM ARISTATUM	X	X	X	3	X	DUKE YIELDFILE 1979
ISCHAEMUM ARISTATUM	X	X	X	9	X	DUKE YIELDFILE 1979
ISCHAEMUM CYCLELIT	X	SARAWAK	X	3	X	BOGDAN 1977
ISCHAEMUM CYCLELIT	A	SARAWAK	4	6	X	BOGDAN 1977
ISCHAEMUM CYCLELIT	X	SARAWAK	X	9	X	BOGDAN 1977
ISCHAEMUM CYCLELIT	A	SARAWAK	A	14	X	BOGDAN 1977
ISCHAEMUM TIMORENSE	X	SURINAM	X	32	X	BOGDAN 1977
IXOPHORUS UNISETUS	A	BRAZIL	A	28	X	BOGDAN 1977
IXOPHORUS UNISETUS	X	BRAZIL	X	32	X	BOGDAN 1977
JUNCUS EFFUSUS	X	US	3	A	X	DUKE YIELDFILE 1979
JUNCUS EFFUSUS	X	US	11	X	X	DUKE YIELDFILE 1979
JUSSIAEA DECURRENS	A	X	2	A	X	DUKE YIELDFILE 1979
JUSSIAEA PERUVIANA	X	X	5	X	X	DUKE YIELDFILE 1979
JUSTICIA AMERICANA	A	US	20	A	X	DUKE YIELDFILE 1979
JUSTICIA AMERICANA	X	US	4	X	X	DUKE YIELDFILE 1979
KOCHIA SCOPARIA	A	CAN	7	7	X	DUKE YIELDFILE 1979
KOCHIA SCOPARIA	X	X	X	11	X	DUKE 1978
LABLAB PURPUREUS	A	AUSTRALIA	A	2	X	BOGDAN 1977
LABLAB PURPUREUS	X	SUDAN	X	12	X	BOGDAN 1977
LAMINARIA LONGICURIS	X	NOVASCOTIA	X	18	X	WESTLAKE 1963
LARIX DECIDUA	50	SWISS	X	5	X	BURGER 1945
LARIX DECIDUA	135	SWISS	A	4	X	BURGER 1945
LARIX DECIDUA	220	SWISS	X	1	X	BURGER 1945
LARIX DECIDUA	46	UK	189	6	X	OVINGTON 1956
LARIX EUROLEPIS	23	UK	148	10	X	OVINGTON 1956
LARIX LEPTOLEPIS	21	JAPAN	A	19	X	SATOO 1966

PHYTOMASS FILE
ECONOMIC BOTANY LABORATORY

SPECIES	AGE (YEAR)	LOCATION	STANDING PHYTOMASS (MT/HA)	ANNUAL PRODUCTIVITY (MT/HA)	LEAF AREA INDEX	SOURCE
LANTA LEPTOLEPIS	22	UA	86	5	X	OVINGTON 1956
LANTA LEPTOLEPIS	22	UA	78	4	X	OVINGTON 1956
LASIURUS HIRSUTUS	X	INDIA	X	2	X	BOGDAN 1977
LASIURUS HIRSUTUS	X	INDIA	X	5	X	BOGDAN 1977
LEENSIA HEXANDRA	X	SURINAM	X	1%	X	BOGDAN 1977
LESPEDEZA STIPULACEA	X	X	X	5	X	DUKE 1978
LESPEDEZA STRIATA	X	X	X	6	X	DUKE 1978
LEUCAENA LEUCOCEPHALA	X	AUSTRALIA	X	2	X	BOGDAN 1977
LEUCAENA LEUCOCEPHALA	X	AUSTRALIA	X	13	X	BOGDAN 1977
LEUCAENA LEUCOCEPHALA	X	HAWAII	X	4%	X	BOGDAN 1977
LEUCAENA LEUCOCEPHALA	X	HAWAII	X	5%	X	BOGDAN 1977
LEUCAENA LEUCOCEPHALA	X	MAURITIUS	X	35	X	BOGDAN 1977
LEUCAENA LEUCOCEPHALA	X	NEW GUINEA	X	13	X	BOGDAN 1977
LEUCAENA LEUCOCEPHALA	X	TAIWAN	X	25	X	DUKE LIST
LEUCAENA LEUCOCEPHALA	X	TAIWAN	X	19	X	DUKE YIELDFILE 1979
LEUCAENA LEUCOCEPHALA	X	VIRGIN I	X	3	X	BOGDAN 1977
LEUCAENA LEUCOCEPHALA	X	VIRGIN I	X	13	X	BOGDAN 1977
LEUCAENA LEUCOCEPHALA	X	VIRGIN I	X	19	X	BOGDAN 1977
LEUCAENA LEUCOCEPHALA	X	VIRGIN I	X	21	X	BOGDAN 1977
LIRIODENDRON TULIPIFERA	X	US	220	24	X	WHITTAKER 1966
LOBELIA INFLATA	X	US	X	2	X	DUKE YIELDFILE 1979
LOLIUM MULTIFLORUM	X	FRANCE	X	5	X	HA 03810(046)
LOLIUM MULTIFLORUM	X	X	X	24	X	DUKE YIELDFILE 1979
LOTONONIS BAINESII	X	AUSTRALIA	X	2	X	BOGDAN 1977
LOTONONIS BAINESII	X	AUSTRALIA	X	8	X	BOGDAN 1977
LUPINUS ALBUS	X	X	X	7	X	DUKE 1978
LUPINUS ANGUSTIFOLIUS	X	X	X	7	X	DUKE 1978
LUPINUS LUTEUS	X	X	X	7	X	DUKE 1978
MACROPTILIUM ATROPURPUREUM	X	X	X	9	X	DUKE 1978
MACROPTILIUM LATHYROIDES	X	NL	X	3	X	BOGDAN 1977
MACROPTILIUM LATHYROIDES	X	TROPICS	X	60	X	BOGDAN 1977
MACROTYLOMA UNIFLORUM	X	AUSTRALIA	X	6	X	BOGDAN 1977
MACROTYLOMA UNIFLORUM	X	MALI	X	2%	X	BOGDAN 1977
MACROTYLOMA UNIFLORUM	X	MALI	X	3%	X	BOGDAN 1977
MARRUBIUM VULGARE	X	US	X	2	X	DUKE YIELDFILE 1979
MEDICAGO ARABICA	X	X	X	7	X	DUKE 1978
MEDICAGO POLYMORPHA	X	X	X	7	X	DUKE 1978
MEDICAGO SATICA	X	X	X	7	X	DUKE 1978
MEDICAGO SATIVA	X	FRANCE	X	7	X	HA 04164(046)
MEDICAGO SATIVA	X	NZ	X	24	X	HA 03801(046)
MELALEUCA LEUCADENDRON	X	CAMBODIA	172	X	7.1	BOZDWI ET AL 1969
MELILOTUS INDICA	X	INDIA	X	1%	X	BOGDAN 1977
MELILOTUS INDICA	X	INDIA	X	2%	X	BOGDAN 1977
MELILOTUS OFFICINALIS	X	X	X	6	X	DUKE 1978
MELILOTUS SUAVEOLENS	X	X	X	2	X	DUKE YIELDFILE 1979
MELINIS MINUTIFLORA	X	COLOMBIA	X	6	X	BOGDAN 1977
MELINIS MINUTIFLORA	X	COLOMBIA	X	8	X	BOGDAN 1977
MELINIS MINUTIFLORA	X	COLOMBIA	X	12	X	BOGDAN 1977
MELINIS MINUTIFLORA	X	COLOMBIA	X	15	X	BOGDAN 1977
MELINIS MINUTIFLORA	X	COSTA RICA	X	8%	X	BOGDAN 1977
MELINIS MINUTIFLORA	X	COSTA RICA	X	4%	X	BOGDAN 1977
MELINIS MINUTIFLORA	X	X	X	38	X	DUKE 1978

PHYTOMASS FILE
ECOLOGY BOTANY LABORATORY

SPECIES	AGE (YEARS)	LOCATION	STANDING PHYTOMASS (MT/HA)	ANNUAL PRODUCTIVITY (MT/HA)	LEAF AREA INDEX	SOURCE
MELISSA OFFICINALIS	X	X	X	3	X	DUKE YIELDFILE 1979
MENTHA SPICATA	X	X	X	X	X	DUAE 1976
MENTHA SPICATA	X	X	X	3	X	DUKE YIELDFILE 1979
MUCUNA DEERINGIANA	X	X	X	16	X	DUAE 1976
MUCUNA DEERINGIANA	X	X	X	5	X	DUKE YIELDFILE 1979
MUCUNA PRURIENS	X	COLOMBIA	X	23	X	BOGDAN 1977
MUCUNA PRURIENS	X	COLOMBIA	X	33	X	BOGDAN 1977
NELUMBO LUTEA	X	X	1	X	X	DUKE YIELDFILE 1979
NOTHOFAGUS OBLIQUA	22	UK	81	5	X	OVINGTON 1956
NOTHOFAGUS TAUCATA	110	NZ	39	X	X	OVINGTON 1962
NUPHAR LUTEA	X	X	1	X	X	DUKE YIELDFILE 1979
NYMPHAEA ODORATA	X	X	-	X	X	DUAE YIELDFILE 1979
NYMPHOIDES AQUATICUM	X	X	-	X	X	DUAE YIELDFILE 1979
OCIMUM BASILICUM	X	X	7	X	X	DUAE YIELDFILE 1979
OCIMUM KILIMANDSCHARICUM	X	INDIA	X	6	X	DUAE YIELDFILE 1979
OCIMUM KILIMANDSCHARICUM	X	X	4	X	X	DUAE YIELDFILE 1979
ORNITHOPUS COMPRESSUS	X	NZ	X	5	X	PRA 09952(D46)
ORNITHOPUS SATIVUS	X	NZ	X	10	X	PRA 09958(D46)
ORNITHOPUS SATIVUS	X	X	X	5	X	DUAE 1978
ORONTION AQUATICUM	X	US	2	X	X	DUAE YIELDFILE 1979
ORYZA SATIVA	X	AUSTRAL	40	40	X	WESTLAKE 1963
OSCILLATORIA BORNETII	X	DENMARK	X	12	X	WESTLAAE 1963
	X		X		X	
PANICUM ANTIDOTALE	X	EXPECT	X	3	X	BOGDAN 1977
PANICUM ANTIDOTALE	X	INDIA	X	3	X	BOGDAN 1977
PANICUM ANTIDOTALE	X	INDIA	X	4	X	BOGDAN 1977
PANICUM ANTIDOTALE	X	INDIA	X	9	X	BOGDAN 1977
PANICUM ANTIDOTALE	X	INDIA	X	15	X	BOGDAN 1977
PANICUM COLORATUM	X	AUSTRALIA	X	23	X	BOGDAN 1977
PANICUM COLORATUM	X	AUSTRALIA	X	12	X	BOGDAN 1977
PANICUM COLORATUM	X	KENYA	X	2	X	BOGDAN 1977
PANICUM COLORATUM	X	KENYA	X	6	X	BOGDAN 1977
PANICUM COLORATUM	X	KENYA	X	9	X	BOGDAN 1977
PANICUM COLORATUM	X	RHODESIA	X	19	X	BOGDAN 1977
PANICUM COLORATUM	X	RHODESIA	X	29	X	BOGDAN 1977
PANICUM COLORATUM	X	RHODESIA	X	11	X	BOGDAN 1977
PANICUM COLORATUM	X	RHODESIA	X	7	X	BOGDAN 1977
PANICUM COLORATUM	X	RHODESIA	X	7	X	BOGDAN 1977
PANICUM COLORATUM	X	RHODESIA	X	19	X	BOGDAN 1977
PANICUM COLORATUM	X	X	X	43	X	DUKE 1978
PANICUM DENTIDOMUM	X	X	X	11	X	DUKE 1978
PANICUM MAXIMUM	X	BRAZIL	X	8	X	BOGDAN 1977
PANICUM MAXIMUM	X	BRAZIL	X	11	X	BOGDAN 1977
PANICUM MAXIMUM	X	COLOMBIA	X	50	X	BOGDAN 1977
PANICUM MAXIMUM	X	EXPECT	X	5	X	BOGDAN 1977
PANICUM MAXIMUM	X	FR. GUIANA	X	14	X	BOGDAN 1977
PANICUM MAXIMUM	X	INDIA	X	29	X	DUKE YIELDFILE 1979
PANICUM MAXIMUM	X	INDIA	X	40	X	DUAE YIELDFILE 1979
PANICUM MAXIMUM	X	INDIA	X	10	X	BOGDAN 1977
PANICUM MAXIMUM	X	INDIA	X	23	X	BOGDAN 1977
PANICUM MAXIMUM	X	NIGERIA	X	36	X	DUKE YIELDFILE 1979
PANICUM MAXIMUM	X	PUERTO RICO	X	37	X	BOGDAN 1977

PHYTOMASS FILE
ECONOMIC BOTANY LABORATORY

SPECIES	AGE (YEAR)	LOCATION	STANDING PHYTOMASS (MT/HA)	ANNUAL PRODUCTIVITY (MT/HA)	LEAF AREA INDEX	SOURCE
PANICUM MAXIMUM	X	TAIWAN	X	14	X	DUKE YIELDFILE 1979
PANICUM MAXIMUM	X	TAIWAN	X	24	X	DUKE YIELDFILE 1979
PANICUM MAXIMUM	X	THAILAND	X	29	X	BOGDAN 1977
PANICUM MAXIMUM	X	UGANDA	X	8	X	BOGDAN 1977
PANICUM MAXIMUM	X	UGANDA	X	12	X	BOGDAN 1977
PANICUM MAXIMUM	X	UGANDA	X	11	X	BOGDAN 1977
PANICUM REPENS	X	RHODESIA	X	6	X	BOGDAN 1977
PANICUM REPENS	X	RHODESIA	X	8	X	BOGDAN 1977
PANICUM REPENS	X	RHODESIA	X	21	X	BOGDAN 1977
PANICUM VIRGATUM	X	X	X	9	X	DUKE 1976
PASPALUM COMMERSONII	X	QUEENSLAND	X	1	X	BOGDAN 1977
PASPALUM COMMERSONII	X	QUEENSLAND	X	4	X	BOGDAN 1977
PASPALUM CONJUGATUM	X	SARAWAK	X	3	X	BOGDAN 1977
PASPALUM CONJUGATUM	X	SARAWAK	X	6	X	BOGDAN 1977
PASPALUM CONJUGATUM	X	SARAWAK	X	14	X	BOGDAN 1977
PASPALUM CONJUGATUM	X	SURINAM	X	53	X	BOGDAN 1977
PASPALUM CONJUGATUM	X	X	X	29	X	DUKE YIELDFILE 1979
PASPALUM CONJUGATUM	X	X	X	140	X	DUKE YIELDFILE 1979
PASPALUM DILATATUM	X	FIJI	X	48	X	BOGDAN 1977
PASPALUM DILATATUM	X	FIJI	X	63	X	BOGDAN 1977
PASPALUM DILATATUM	X	QUEENSLAND	X	1	X	BOGDAN 1977
PASPALUM DILATATUM	X	QUEENSLAND	X	5	X	BOGDAN 1977
PASPALUM DILATATUM	X	RHODESIA	X	25	X	BOGDAN 1977
PASPALUM DILATATUM	X	X	X	24	X	DUKE 1976
PASPALUM GUENOARUM	X	RHODESIA	X	6	X	BOGDAN 1977
PASPALUM NICORAE	X	GEORGIA(ATHENS)	X	4	X	BOGDAN 1977
PASPALUM NICORAE	X	GEORGIA(ATHENS)	X	7	X	BOGDAN 1977
PASPALUM NICORAE	X	GEORGIA(ATHENS)	X	9	X	BOGDAN 1977
PASPALUM NICORAE	X	GEORGIA(ATHENS)	X	11	X	BOGDAN 1977
PASPALUM NOTATUM	X	AUSTRALIA	X	17	X	BOGDAN 1977
PASPALUM NOTATUM	X	CUBA	X	14	X	BOGDAN 1977
PASPALUM NOTATUM	X	FARCT	X	5	X	BOGDAN 1977
PASPALUM NOTATUM	X	INDIA	X	9	X	BOGDAN 1977
PASPALUM NOTATUM	X	RHODESIA	X	21	X	BOGDAN 1977
PASPALUM NOTATUM	X	RHODESIA	X	37	X	BOGDAN 1977
PASPALUM NOTATUM	X	TAIWAN	X	18	X	DUKE YIELDFILE 1979
PASPALUM NOTATUM	X	TAIWAN	X	24	X	DUKE YIELDFILE 1979
PASPALUM NOTATUM	X	UGANDA	X	5	X	BOGDAN 1977
PASPALUM NOTATUM	X	US	X	2	X	BOGDAN 1977
PASPALUM NOTATUM	X	US	X	4	X	BOGDAN 1977
PASPALUM NOTATUM	X	X	X	24	X	DUKE1978
PELARGONIUM CHAVEOLENS	X	ALGERIA	X	30	X	DUKE YIELDFILE 1979
PENNISETUM AMERICANUM	X	AUSTRALIA	X	20	X	BOGDAN 1977
PENNISETUM AMERICANUM	X	AUSTRALIA	X	13	X	BOGDAN 1977
PENNISETUM AMERICANUM	X	AUSTRALIA	X	22	X	BOGDAN 1977
PENNISETUM AMERICANUM	X	AUSTRALIA	X	10	X	BOGDAN 1977
PENNISETUM AMERICANUM	X	INDIA	X	21	X	BA 53364(CAB)
PENNISETUM AMERICANUM	X	INDIA	X	58	X	BOGDAN 1977
PENNISETUM AMERICANUM	X	RHODESIA	X	54	X	BOGDAN 1977
PENNISETUM AMERICANUM	X	RHODESIA	X	45	X	BOGDAN 1977
PENNISETUM CLANDESTINUM	X	AUSTRALIA	X	25	X	BOGDAN 1977
PENNISETUM CLANDESTINUM	X	AUSTRALIA	X	10	X	BOGDAN 1977

PHYTOMASS FILE
ECOLOGIC PRIMARY LABORATORY

SPECIES	AGE (YEAR)	LOCATION	STANDING PHYTOMASS (MT/HA)	ANNUAL PRODUCTIVITY (MT/HA)	LEAF AREA INDEX	SOURCE
PENNISETUM CLANDESTINUM	X	AUSTRALIA	X	12	X	BOGDAN 1977
PENNISETUM CLANDESTINUM	X	HAWAII	X	17	X	BOGDAN 1977
PENNISETUM HYBRID	X	INDIA	X	35	X	RA 03345(84F)
PENNISETUM PEDICELLATUM	X	CAMEROON	X	4	X	BOGDAN 1977
PENNISETUM PEDICELLATUM	X	CAMEROON	X	7	X	BOGDAN 1977
PENNISETUM PEDICELLATUM	X	CAMEROON	X	8	X	BOGDAN 1977
PENNISETUM PEDICELLATUM	X	INDIA	X	32	X	BOGDAN 1977
PENNISETUM PEDICELLATUM	X	INDIA	X	42	X	BOGDAN 1977
PENNISETUM PEDICELLATUM	X	INDIA	X	52	X	BOGDAN 1977
PENNISETUM PEDICELLATUM	X	INDIA	X	52	X	BOGDAN 1977
PENNISETUM POLYSTACHYA	X	INDIA	X	32	X	BOGDAN 1977
PENNISETUM POLYSTACHYA	X	INDIA	X	7	X	BOGDAN 1977
PENNISETUM POLYSTACHYA	X	INDIA	X	10	X	BOGDAN 1977
PENNISETUM POLYSTACHYA	X	INDIA	X	42	X	BOGDAN 1977
PENNISETUM POLYSTACHYA	X	INDIA	X	52	X	BOGDAN 1977
PENNISETUM PURPUREUM	X	AUSTRALIA	X	7	X	BOGDAN 1977
PENNISETUM PURPUREUM	X	AUSTRALIA	X	15	X	BOGDAN 1977
PENNISETUM PURPUREUM	X	AUSTRALIA	X	19	X	BOGDAN 1977
PENNISETUM PURPUREUM	X	BRAZIL	X	8	X	BOGDAN 1977
PENNISETUM PURPUREUM	X	BRAZIL	X	4	X	BOGDAN 1977
PENNISETUM PURPUREUM	X	BRAZIL	X	12	X	BOGDAN 1977
PENNISETUM PURPUREUM	X	BRAZIL	X	13	X	BOGDAN 1977
PENNISETUM PURPUREUM	X	COSTA RICA	X	4	X	BOGDAN 1977
PENNISETUM PURPUREUM	X	COSTA RICA	X	14	X	BOGDAN 1977
PENNISETUM PURPUREUM	X	COSTA RICA	X	58	X	BOGDAN 1977
PENNISETUM PURPUREUM	X	EL SALVADOR	X	65	X	BOGDAN 1977
PENNISETUM PURPUREUM	X	EGYPT	X	22	X	BOGDAN 1977
PENNISETUM PURPUREUM	X	KENYA	X	22	X	BOGDAN 1977
PENNISETUM PURPUREUM	X	KENYA	X	47	X	BOGDAN 1977
PENNISETUM PURPUREUM	X	PUERTO RICO	X	84	X	BOGDAN 1977
PENNISETUM PURPUREUM	X	PUERTO RICO	X	31	X	BOGDAN 1977
PENNISETUM PURPUREUM	X	PUERTO RICO	X	46	X	BOGDAN 1977
PENNISETUM PURPUREUM	X	PUERTO RICO	X	58		
PENNISETUM PURPUREUM	X	UGANDA	X	13	X	BOGDAN 1977
PENNISETUM PURPUREUM	X	UGANDA	X	30	X	BOGDAN 1977
PENNISETUM SQUAMULATUM	X	INDIA	X	78	X	BOGDAN 1977
PENNISETUM SQUAMULATUM	X	MALI	X	14	X	BOGDAN 1977
PENNISETUM X PURPUREUM	X	INDIA	X	39A	X	BOGDAN 1977
PENNISETUM X PURPUREUM	X	INDIA	X	27A	X	BOGDAN 1977
PENNISETUM X PURPUREUM	X	INDIA	X	29A	X	BOGDAN 1977
PENNISETUM X PURPUREUM	X	THAILAND	X	32	X	BOGDAN 1977
PHALARIS AQUATICA	X	X	X	12	X	DUKE 1978
PHALARIS ARUNDINACEA	X	X	X	19	X	DUKE 1978
PHLEUM PRATENSE	X	FRANCE	X	13	X	RA 03902(84A)
PHRAGMITES AUSTRALIS	X	X	X	59	X	DUKE 1978
PICEA ABIES	39	JAPAN	169	X	X	OVINGTON 1962
PICEA ABIES	39	JAPAN	89	X	X	OVINGTON 1962
PICEA ABIES	45	JAPAN	169	X	X	OVINGTON 1962
PICEA ABIES	37	JAPAN	X	13	X	SATOO 1966
PICEA ABIES	45	JAPAN	X	9	X	SATOO 1966
PICEA ABIES	39	JAPAN	X	13	X	SATOO 1966
PICEA ABIES	45	JAPAN	X	13	X	SATOO 1966

PHYTOMASS FILE
COLORADO STATE UNIVERSITY

SPECIES	AGE (YEARS)	LOCATION	STANDING PHYTOMASS (MT/HA)	ANNUAL PRODUCTIVITY (MT/HA)	LEAF AREA INDEX	SOURCE
PICEA ABIES	47	JAPAN	[illegible]	14	X	SATOO 1966
PICEA ABIES	53	JAPAN	[illegible]	A	X	OVINGTON 1962
PICEA ABIES	53	JAPAN	[illegible]	A	X	OVINGTON 1962
PICEA ABIES	55	JAPAN	X	[illegible]	X	BURGER 1953
PICEA ABIES	25	UK	215	11	X	OVINGTON 1956
PICEA ABIES	47	UK	140	7	X	OVINGTON 1956
PICEA ABIES	47	UK	200	7	X	OVINGTON 1956
PICEA ABIES	24	USSR	101	A	X	OVINGTON 1962
PICEA ABIES	38	USSR	141	A	X	OVINGTON 1962
PICEA ABIES	50	USSR	171	A	X	OVINGTON 1962
PICEA ABIES	43	USSR	305	A	X	OVINGTON 1962
PICEA GLAUCA	65	CAN	93	[illegible]	X	WEETMAN ET AL 1964
PICEA GLAUCA	21	UK	247	14	X	OVINGTON 1956
PICEA GLAUCA	97	US	79	A	X	YOUNG & CARPENTER 1967
PICEA SP	A	USSR	102	5	X	RODIN ET AL 1967
PICEA SP	A	USSR	[illegible]	7	X	RODIN ET AL 1967
PICEA SP	A	USSR	370	8	X	RODIN ET AL 1967
PINUS DENSIFLORA	13	JAPAN	A	12	X	SATOO 1966
PINUS DENSIFLORA	13	JAPAN	X	11	X	SATOO 1966
PINUS DENSIFLORA	13	JAPAN	A	13	X	SATOO 1966
PINUS DENSIFLORA	13	JAPAN	X	15	X	SATOO 1966
PINUS DENSIFLORA	16	JAPAN	59	A	X	OVINGTON 1962
PINUS DENSIFLORA	16	JAPAN	170	A	X	OVINGTON 1962
PINUS DENSIFLORA	15	JAPAN	88	10	X	SATOO 1967
PINUS DENSIFLORA	15	JAPAN	A	15	X	SATOO 1966
PINUS CONTORTA	X	US	141	9	2.8	WHITTAKER 1966
PINUS CONTORTA	X	US	141	15	X	WHITTAKER 1966
PINUS NIGRA	13	UK	174	10	X	OVINGTON 1956
PINUS NIGRA	22	UK	122	6	X	OVINGTON 1956
PINUS NIGRA	22	UK	142	7	X	OVINGTON 1956
PINUS NIGRA	46	UK	242	5	X	OVINGTON 1956
PINUS NIGRA CALABRICA	14	UK	46	A	X	WRIGHT ET AL 1956
PINUS NIGRA CALABRICA	28	UK	68	A	X	WRIGHT ET AL 1956
PINUS NIGRA CALABRICA	43	UK	114	A	X	WRIGHT & WILL 1958
PINUS PINASTER	14	AUSTRAL	233	9	17.0	KRAY & BURTON 1970
PINUS PINASTER	14	AUSTRAL	191	7	14.0	KRAY & BURTON 1970
PINUS RADIATA	3	AUSTRAL	6	9	X	FORREST ET AL 1970
PINUS RADIATA	5	AUSTRAL	13	7	X	FORREST ET AL 1970
PINUS RADIATA	7	AUSTRAL	53	26	X	FORREST ET AL 1970
PINUS RADIATA	9	AUSTRAL	75	13	X	FORREST ET AL 1970
PINUS RADIATA	12	AUSTRAL	119	14	X	FORREST ET AL 1970
PINUS RADIATA	17	NZ	175	12	X	WILL 1966
PINUS SP	X	USSR	81	X	X	RODIN ET AL 1967
PINUS SP	A	USSR	142	6	X	RODIN ET AL 1967
PINUS STROBUS	41	JAPAN	104	A	X	OVINGTON 1962
PINUS STROBUS	41	JAPAN	104	A	X	OVINGTON 1962
PINUS STROBUS	34	US	47	A	X	YOUNG & CARPENTER 1967
PINUS SYLVESTRIS	47	UK	157	5	X	OVINGTON 1956
PINUS SYLVESTRIS	3	UK	X	12	X	OVINGTON 1957
PINUS SYLVESTRIS	7	UK	7	12	2.2	OVINGTON 1957
PINUS SYLVESTRIS	11	UK	26	22	6.0	OVINGTON 1957
PINUS SYLVESTRIS	17	UK	49	22	9.3	OVINGTON 1957

PHYTOMASS FILE
ECONOMIC BOTANY LABORATORY

SPECIES	AGE (YEAR)	LOCATION	STANDING PHYTOMASS (MT/HA)	ANNUAL PRODUCTIVITY (MT/HA)	LEAF AREA INDEX	SOURCE
PINUS SYLVESTRIS	20	UK	55	22	10.8	OVINGTON 1957
PINUS SYLVESTRIS	14	UK	33	22	6.9	OVINGTON 1957
PINUS SYLVESTRIS	23	UK	97	22	5.3	OVINGTON 1957
PINUS SYLVESTRIS	31	UK	127	22	9.5	OVINGTON 1957
PINUS SYLVESTRIS	35	UK	153	22	10.1	OVINGTON 1957
PINUS SYLVESTRIS	55	UK	154	22	7.5	OVINGTON 1957
PINUS SYLVESTRIS	33	UK	186	X	X	OVINGTON ET AL 1959
PINUS SYLVESTRIS	18	UK	55	X	X	WRIGHT & WILL 1958
PINUS SYLVESTRIS	28	UK	94	X	X	WRIGHT & WILL 1958
PINUS SYLVESTRIS	64	UK	119	X	X	WRIGHT & WILL 1958
PINUS SYLVESTRIS	11	UK	52	X	X	OVINGTON 1957
PINUS SYLVESTRIS	14	UK	43	X	X	OVINGTON 1957
PINUS TAEDA	X	NC	X	22	X	LILLY 1979
PINUS THUNBERGII	17	JAPAN	57	X	X	ANDO 1965
PINUS THUNBERGII	17	JAPAN	39	X	X	ANDO 1965
PINUS THUNBERGII	23	JAPAN	68	X	X	ANDO 1965
PINUS THUNBERGII	19	JAPAN	27	X	X	ANDO 1965
PINUS THUNBERGII	17	JAPAN	44	X	X	ANDO 1965
PINUS THUNBERGII	17	JAPAN	23	X	X	ANDO 1965
POA PRATENSIS	X	X	X	6	X	DUAF 1976
POPULUS DAVIDIANA	40	JAPAN	119	X	X	OVINGTON 1962
POPULUS DAVIDIANA	40	JAPAN	X	12	X	SATOO 1966
POPULUS SP	13	US	3	X	X	YOUNG & CARPENTER 1967
POPULUS SP	28	US	54	X	X	YOUNG & CARPENTER
POPULUS SP	39	US	67	X	X	BRAY & DUDAIEWICZ 1963
POPULUS TREMULOIDES	41	US	204	X	X	BRAY & DUDAIEWICZ 1963
PRUNUS PENSYLVANICA	14	US	58	13	5.4	ART & MARKS 1979
PRUNUS PENSYLVANICA	X	US	X	X	1.1	ART & MARKS 1979
PRUNUS PENSYLVANICA	4	US	24	13	X	ART & MARKS 1979
PSATHYRUSTACHYS JUNCEA	X	X	X	3	X	DUAF 1976
PSEUDOTSUGA MENZIESII	21	UK	115	7	X	OVINGTON 1956
PSEUDOTSUGA MENZIESII	22	UK	186	9	X	OVINGTON 1956
PSEUDOTSUGA MENZIESII	22	UK	191	9	X	OVINGTON 1956
PSEUDOTSUGA MENZIESII	47	UK	452	13	X	OVINGTON 1956
PSEUDOTSUGA MENZIESII	35	US	206	10	X	COLE ET AL 1967
PSEUDOTSUGA MENZIESII	37	US	75	X	X	KIZEKER 1967
PSEUDOTSUGA MENZIESII	32	US	80	X	X	KIZEKER 1967
PSEUDOTSUGA MENZIESII	33	US	105	X	X	KIZEKER 1967
PSEUDOTSUGA MENZIESII	19	US	178	X	X	KIZEKER 1967
PSEUDOTSUGA MENZIESII	52	US	223	X	X	KIZEKER 1967
PSEUDOTSUGA MENZIESII	12	US	37	X	X	KIZEKER 1967
PSEUDOTSUGA MENZIESII	19	US	158	X	X	KIZEKER
PSEUDOTSUGA MENZIESII	37	US	274	X	X	KIZEKER 1967
PSEUDOTSUGA MENZIESII	39	US	235	X	X	KIZEKER 1967
PSEUDOTSUGA MENZIESII	75	US	244	X	X	KIZEKER 1967
PSEUDOTSUGA MENZIESII	X	X	134	X	X	OVINGTON 1965
PTERIDIUM AQUILINUM	X	SCOTLAND	83	24	X	WSTLAKE 1963
PUERARIA PHASEOLOIDES	X	AUSTRALIA	X	X	X	BOGDAN 1977
PUERARIA PHASEOLOIDES	X	CUBA	X	20	X	BOGDAN 1977
PUERARIA PHASEOLOIDES	X	SAPLOCI	X	8	X	BOGDAN 1977
PUERARIA PHASEOLOIDES	X	NL	X	5	X	BOGDAN 1977
PUERARIA PHASEOLOIDES	X	NL	X	17	X	BOGDAN 1977

PHYTOMASS FILE
ECOLOGIC BOTANY LABORATORY

SPECIES	AGE (YEAR)	LOCATION	STANDING PHYTOMASS (MT/HA)	ANNUAL PRODUCTIVITY (MT/HA)	LEAF AREA INDEX	SOURCE
QUERCUS PHELLOIDES	X	TAIWAN	X	7	X	DUKE YIELDFILE 1979
QUERCUS MORFALIS	X	US	137	8	X	WHITTAKER 1966
QUERCUS PETRAEA	21	UK	42	2	X	OVINGTON 1956
QUERCUS PRINUS	X	US	422	15	6.3	WHITTAKER 1966
QUERCUS ROBUR	150	SWEDEN	240	15	X	ANDERSSON 1970
QUERCUS ROBUR	47	UK	125	4	X	OVINGTON 1956
QUERCUS RUBRA	21	UK	43	2	X	OVINGTON 1956
QUERCUS SP	44	UK	92	3	X	OVINGTON 1956
QUERCUS SP	X	USSR	302	9	X	RODIN & BAZILEVICH 1967
QUERCUS SP	22	USSR	99	4	X	OVINGTON 1962
QUERCUS SP	47	USSR	170	4	X	OVINGTON 1962
QUERCUS SP	95	USSR	232	4	X	OVINGTON 1962
QUERCUS SP	200	USSR	350	4	X	OVINGTON 1962
RHYNCHOSIA MINIMA REPENS	X	INDIA	X	48	X	BOGDAN 1977
RHYNCHOSIA MINIMA REPENS	X	INDIA	X	68	X	BOGDAN 1977
ROTTBOELLIA EXALTATA	X	SUDAN	X	48	X	BOGDAN 1977
RUTA GRAVEOLENS	X	X	X	X	X	DUKE 1978
SACCHARUM OFFICINARUM	X	BRAZIL	X	254	X	BOGDAN 1977
SACCHARUM OFFICINARUM	X	BRAZIL	X	50	X	BOGDAN 1977
SACCHARUM OFFICINARUM	X	BRAZIL	X	86	X	BOGDAN 1977
SACCHARUM OFFICINARUM	X	BRAZIL	X	72	X	BOGDAN 1977
SACCHARUM OFFICINARUM	X	HAWAII	73	33	X	WESTLAKE 1963
SACCHARUM OFFICINARUM	X	JAVA	65	94	X	WESTLAKE 1963
SACCHARUM SINENSE	X	FIJI	X	48	X	BOGDAN 1977
SAGITTARIA LATIFOLIA	X	US	7	X	X	DUKE YIELDFILE 1979
SAGITTARIA LONGA	X	US	8	X	X	DUKE YIELDFILE 1979
SALSOLA KALI	X	US	26	X	X	DUKE YIELDFILE 1979
SALVIA OFFICINALIS	X	X	X	1	X	DUKE 1978
SATUREJA HORTENSIS	X	X	X	0	X	DUKE 1978
SAUROPUS CERNUUS	X	US	4	X	X	DUKE YIELDFILE 1979
SAUROPUS CERNUUS	X	US	22	X	X	DUKE YIELDFILE 1979
SCIRPUS ATROVIRENS	X	US	4	X	X	DUKE YIELDFILE 1979
SCIRPUS CYPERINUS	X	X	26	X	X	DUKE YIELDFILE 1979
SCIRPUS FLUVIATILIS	X	X	X	46	X	WESTLAKE 1963
SCIRPUS VALIDUS	X	US	14	X	X	DUKE YIELDFILE 1979
SCIRPUS MYCROSTACHYA	X	INDIA	X	4	X	BOGDAN 1977
SCIRPUS MYCROSTACHYA	X	INDIA	X	0	X	BOGDAN 1977
SETARIA ANCEPS	X	BRAZIL	X	156	X	BOGDAN 1977
SETARIA ANCEPS	X	FIJI	X	19	X	BOGDAN 1977
SETARIA ANCEPS	X	FIJI	X	27	X	BOGDAN 1977
SETARIA ANCEPS	X	INDIA	X	48	X	BOGDAN 1977
SETARIA ANCEPS	X	QUEENSLAND	X	28	X	BOGDAN 1977
SETARIA ANCEPS	X	QUEENSLAND	X	23	X	BOGDAN 1977
SETARIA ANCEPS	X	QUEENSLAND	X	11	X	BOGDAN 1977
SETARIA ANCEPS	X	QUEENSLAND	X	8	X	BOGDAN 1977
SETARIA ANCEPS	X	QUEENSLAND	X	14	X	BOGDAN 1977
SETARIA SPACELATA	X	AUSTRAL	X	4	X	DUKE YIELDFILE 1979
SETARIA SPACELATA	X	X	X	10	X	DUKE 1978
SETARIA SPELENDIDA	X	AUSTRAL	X	4	X	DUKE YIELDFILE 1979
SETARIA SPELENDIDA	X	KENYA	X	4	X	BOGDAN 1977
SETARIA SPELENDIDA	X	KENYA	X	9	X	BOGDAN 1977
SORGHUM ALBUM	X	AUSTRALIA	X	14	X	BOGDAN 1977

PHYTOMASS FILE
ECONOMIC BOTANY LABORATORY

SPECIES	AGE (YEAR)	LOCATION	STANDING PHYTOMASS (MT/HA)	ANNUAL PRODUCTIVITY (MT/HA)	LEAF AREA INDEX	SOURCE
SORGHUM ALNUM	X	CANADA	X	15	X	BOGDAN 1977
SORGHUM ALNUM	X	EAPECI	X	7	X	BOGDAN 1977
SORGHUM ALNUM	X	QUEENSLAND	X	11	X	BOGDAN 1977
SORGHUM ALNUM	X	SOUTH AFRICA	X	6	X	BOGDAN 1977
SORGHUM ALNUM	X	SOUTH AFRICA	X	5	X	BOGDAN 1977
SORGHUM ALNUM	X	SOUTH AFRICA	X	5	X	BOGDAN 1977
SORGHUM ALNUM	X	SOUTH AFRICA	X	5	X	BOGDAN 1977
SORGHUM ALNUM	X	SOUTH AFRICA	X	5	X	BOGDAN 1977
SORGHUM ALNUM	X	US	X	14	X	BOGDAN 1977
SORGHUM ALNUM	X	US(TEXAS)	X	13	X	BOGDAN 1977
SORGHUM ALNUM	X	X	X	12	X	DUKE 1978
SORGHUM BICOLOR	X	BRAZIL	X	13	X	BOGDAN 1977
SORGHUM BICOLOR	X	BRAZIL	X	15	X	BOGDAN 1977
SORGHUM BICOLOR	X	EAPECI	X	6	X	BOGDAN 1977
SORGHUM BICOLOR	X	INDIA	X	12	X	BOGDAN 1977
SORGHUM BICOLOR	X	INDIA	X	13	X	BOGDAN 1977
SORGHUM BICOLOR	X	SUDAN	X	7	X	HADLEY(1968)
SORGHUM BICOLOR	X	US(TEXAS)	X	14	X	BOGDAN 1977
SORGHUM BICOLOR	X	US(TEXAS)	X	17	X	BOGDAN 1977
SORGHUM BICOLOR	X	X	X	62	X	DUAE 1976
SORGHUM HALEPENSE	X	INDIA	X	7	X	BOGDAN 1977
SORGHUM HALEPENSE	X	INDIA	X	9	X	BOGDAN 1977
SORGHUM HALEPENSE	X	INDIA	X	13	X	BOGDAN 1977
SORGHUM HALEPENSE	X	INDIA	X	15	X	BOGDAN 1977
SORGHUM HALEPENSE	X	X	X	17	X	DUKE 1978
SORGHUM SUDANENSE	X	INDIA	X	13	X	BOGDAN 1977
SORGHUM SUDANENSE	X	INDIA	X	98	X	BOGDAN 1977
SORGHUM SUDANENSE	X	INDIA	X	1	X	BOGDAN 1977
SORGHUM SUDANENSE	X	INDIA	X	2	X	BOGDAN 1977
SORGHUM SUDANENSE	X	INDIA	X	5	X	BOGDAN 1977
SORGHUM SUDANENSE	X	X	X	47	X	DUKE 1978
SORGHUM X SUDAN	X	FRANCE	X	17	X	MA 04164(044)
SPARGANIUM EURYCARPUM	X	MINNESOTA	9	X	X	LOKE VIELEFILE 1979
SPARTINA ALTERNIFLORA	X	X	42	37	X	WESTLAKE 1963
STENOTAPHRUM SECUNDATUM	X	X	X	17	X	DUKE 1978
STENOTAPHRUM SECUNDATUM	X	US(FLORIDA)	X	63	X	BOGDAN 1977
STIPA TENACISSIMA	X	X	X	7	X	DUAE 1976
STYLOSANTHES GUIANENSIS	X	EAPECI	X	6	X	BOGDAN 1977
STYLOSANTHES GUIANENSIS	X	GAMBIA	X	15	X	BOGDAN 1977
STYLOSANTHES GUIANENSIS	X	X	X	6	X	DUAE 1976
STYLOSANTHES HUMILIS	X	EAPECI	X	2	X	BOGDAN 1977
SYMPHYTUM SP	X	X	X	21	X	DUAE 1976
TAMARIXIX GALLICA	X	X	X	11	X	DUAE 1978
TERMINALIA CATALPA	X	X	X	15	X	DUAE 1976
TERMINALIA MOLLIS	X	X	X	17	X	DUAE 1978
TERAMNUS UNCINATUS	X	BRAZIL	X	2	X	BOGDAN 1977
TERAMNUS UNCINATUS	X	BRAZIL	X	4	X	BOGDAN 1977
THALASSIA TESTUDINUM	X	X	X	40	X	WESTLAKE 1963
THUJA OCCIDENTALIS	77	US	135	X	X	YOUNG & CARPENTER 1967
THUJA PLICATA	22	US	68	3	X	OVINGTON 1956
TRIFOLIUM ALEXANDRINUM	X	EAPECI	X	53	X	BOGDAN 1977
TRIFOLIUM ALEXANDRINUM	X	EAPECI	X	64	X	BOGDAN 1977

PHYTOMASS FILE
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SPECIES	AGE (YEAR)	LOCATION	STANDING PHYTOMASS (MT/HA)	ANNUAL PRODUCTIVITY (MT/HA)	LEAF AREA INDEX	SOURCE
TRIFOLIUM ALEXANDRINUM	X	US(FLORIDA)	X	4	X	BOGDAN 1977
TRIFOLIUM ALEXANDRINUM	X	US(FLORIDA)	X	6	X	BOGDAN 1977
TRIFOLIUM ALEXANDRINUM	X	US(FLORIDA)	X	3	X	BOGDAN 1977
TRIFOLIUM FORMOSUM	X	AUSTRAL	X	4	X	DUAE YIELDFILE 1979
TRIFOLIUM HYBRIDUM	X	X	X	7	X	DUAE 1978
TRIFOLIUM INCARNATUM	X	X	X	12	X	DUAE 1978
TRIFOLIUM PRATENSE	X	X	X	7	X	DUAE 1978
TRIFOLIUM REPENS	X	X	X	7	X	DUAE 1978
TRIFOLIUM SUBTERRANEUM	X	NZ	X	6	X	PHA 09098(046)
TRIPSACUM LAXUM	X	BRAZIL	X	12	X	BOGDAN 1977
TRIPSACUM LAXUM	X	BRAZIL	X	35	X	BOGDAN 1977
TRIPSACUM LAXUM	X	KENYA	X	11	X	BOGDAN 1977
TRIPSACUM LAXUM	X	KENYA	X	25	X	BOGDAN 1977
TRITICUM AESTIVUM	X	X	X	19	X	WESTLAKE 1963
TSUGA CANADENSIS	X	US	610	12	X	WHITTAKER 1966
TSUGA CANADENSIS	27	US	31	X	X	YOUNG & CARPENTER
TSUGA DUMOSA	X	NEPAL	640	X	X	YODA 1968
TSUGA HETEROPHYLLA	23	UK	250	13	X	OVINGTON 1956
TYPHA DOMINGENSIS	X	US	15	X	X	DUAE YIELDFILE 1979
TYPHA GLAUCA	X	MINNESOTA	17	X	X	DUAE YIELDFILE 1979
TYPHA LATIFOLIA	X	US	20	X	X	DUAE YIELDFILE 1979
TYPHA LATIFOLIA	X	X	6	X	X	DUAE YIELDFILE 1979
TYPHA SP	X	X	X	29	X	WESTLAKE 1963
ULEX EUROPAEUS	X	X	X	9	X	DUAE YIELDFILE 1979
UROCHLOA MOSAMBICENSIS	X	AUSTRALIA	X	1	X	BOGDAN 1977
UROCHLOA MOSAMBICENSIS	X	AUSTRALIA	X	7	X	BOGDAN 1977
UROCHLOA MOSAMBICENSIS	X	FIJI	X	28	X	BOGDAN 1977
UROCHLOA MOSAMBICENSIS	X	INDIA	X	4	X	BOGDAN 1977
VICIA DASYCARPA	X	TAIWAN	X	3	X	DUAE YIELDFILE 1979
VICIA DASYCARPA	X	TAIWAN	X	5	X	DUAE YIELDFILE 1979
VICIA FABA	X	CZECH	X	15	X	FCA 04016(029)
VICIA SATIVA	X	X	X	6	X	DUAE 1978
VIGNA ACONITIFOLIA	X	US	X	6	X	BOGDAN 1977
VIGNA ACONITIFOLIA	X	US	X	7	X	BOGDAN 1977
VIGNA ACONITIFOLIA	X	X	X	8	X	DUAE YIELDFILE 1979
VIGNA ANGULARIS	X	BRAZIL	X	28	X	BOGDAN 1977
VIGNA MARINA	X	USSR	X	78	X	BOGDAN 1977
VIGNA MARINA	X	USSR	X	98	X	BOGDAN 1977
VIGNA RADIATA	X	X	X	6	X	DUAE YIELDFILE 1979
VIGNA UMBELLATA	X	BRAZIL	X	98	X	BOGDAN 1977
VIGNA UNGUICULATA	X	INDIA	X	38	X	BOGDAN 1977
VIGNA UNGUICULATA	X	INDIA	X	43	X	BOGDAN 1977
VIGNA UNGUICULATA	X	INDIA	X	58	X	BOGDAN 1977
VIGNA UNGUICULATA	X	TAIWAN	X	5	X	DUAE YIELDFILE 1979
VT(ABIES-PRUNUS-QUERCUS)	X	NEPAL	198	X	X	YODA 1968
VT(ABIES-TSUGA)	X	NEPAL	520	X	X	YODA 1968
VT(BLANKET BOG)	X	UK	5	X	X	DUAE YIELDFILE 1979
VT(CALLUNA-ERIOPHORUM)	X	UK	2	X	X	DUAE YIELDFILE 1979
VT(COVE FOREST)	X	US	501	11	6.2	WHITTAKER & WOODWELL 1969
VT(DECIDUOUS FOREST)	X	FRANCE	X	5	X	LIETH 1978
VT(DIPTEROCARP FOREST)	X	MALAYSIA	X	22	X	UNESCO 1978
VT(DWARF SHRUB HEATH)	X	AUSTRIA	X	8	X	LIETH 1978

PHYTOMASS FILE
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SPECIES	AGE (YEAR)	LOCATION	STANDING PHYTOMASS (MT/HA)	ANNUAL PRODUCTIVITY (MT/HA)	LEAF AREA INDEX	SOURCE
VT([illegible])	X	ZAIRE	X	35	X	UNESCO 1[illegible]
VT(ERIODOPTION)	X	UK	1	X	X	JOHF VIEL[illegible] 79
VT(EUCALYPTUS GALLERY)	X	THAILAND	394	X	X	UVINGTON [illegible]
VT(EUCALYPTUS SP.)	X	BELGIUM	X	6	X	LIETH 1978
VT(EUCALYPTUS GLOBULUS)	X	CAMBODIA	335	X	7.3	BRUZUNI ET AL 1969
VT(EUCALYPTUS GRANDIS)	X	CAMBODIA	348	X	7.3	BRUZUNI ET AL 1969
VT(EUCALYPTUS MORISSI [illegible])	X	PUERTO RICO	X	15	X	UNESCO 1978
VT(MANGROVE)	X	PANAMA	250	X	X	COLLEY ET AL 1975
VT(MANGROVE)	X	PUERTO RICO	X	9	X	UNESCO 1978
VT(MESICARP-PLUTUTA)	X	NA	X	31	X	HA C3801(C46)
VT(MICRO DIPTEROCARP)	X	THAILAND	87	X	X	UVINGTON 1962
VT(MICRO PASTURE)	X	NIGERIA	X	30	X	AA 25743(C46)
VT(MONSOON FOREST)	X	BURMA	X	20	X	UNESCO 1978
VT(MONSOON FOREST)	X	THAILAND	267	X	X	COLLEY ET AL 1975
VT(OAK ISM)	133	BELGIUM	390	14	X	DUVIGNEAUD & DENAEYER-DESMET 1970
VT(OAK BEECH)	72	BELGIUM	196	14	6.8	DUVIGNEAUD & DENAEYER-DESMET 1970
VT(OAK FOREST)	X	US	X	7	X	BRAY 1962
VT(OAK HICKORY)	X	US	157	5	4.0	BURK ET AL 1970
VT(OAK HICKORY)	X	US	375	12	X	BURK ET AL 1970
VT(OAK SAVANNA)	X	US	X	3	X	BRAY 1962
VT(OPEN OAK FOREST)	X	US	X	4	X	BRAY 1962
VT(PHRAGMA)	X	GREECE	X	4X	X	LIETH 1978
VT(PICEA ABIES)	X	US	302	18	X	WHITTAKER
VT(PICEA-ABIES)	X	US	341	10	14.6	WHITTAKER 1966
VT(PICEA-LUCIA)	X	US	310	7	X	WHITTAKER 1966
VT(PICEA-RHODODENDRON)	X	US	321	6	X	WHITTAKER 1966
VT(PINE HEATH)	X	US	72	5	5.4	WHITTAKER & WOODWELL 1969
VT(PINUS-ILEA)	X	SPAIN	X	18	X	LIETH 1978
VT(PINUS-CUPRESSUS)	X	US	192	17	3.8	WHITTAKER & WOODWELL 1969
VT(PINUS-CUPRESSUS)	X	US	142	5	7.8	WHITTAKER & WOODWELL 1969
VT(PINUS-CUPRESSUS)	X	US	114	4	X	WHITTAKER & WOODWELL 1969
VT(PRAIRIE-FOREST)	X	WISCONSIN	X	8	X	LIETH 1978
VT(PRECOMPANY ART FOREST)	X	PANAMA	272	X	X	COLLEY ET AL 1975
VT(PRUNUS-PSEUDUS)	5	US	34	17	6.1	ART & MARKS 1978
VT(PSEUDOTSUGA-TSUGA)	X	WASHINGTON	X	18	X	LIETH 1978
VT(PSEUDOTSUGA-TSUGA)	X	WASHINGTON	X	2	X	LIETH 1978
VT(PINEY CONIFER [illegible])	X	US	19	2	X	WHITTAKER & WOODWELL 1969
VT(QUERCUS SPP)	X	US	98	6	X	WHITTAKER 1966
VT(QUERCUS-CAMELLIA)	72	JAPAN	228	20	7.5	KIRA ET AL 1965
VT(QUERCUS-CAMELLIA)	72	JAPAN	212	19	7.0	KIRA ET AL 1965
VT(QUERCUS-CAMELLIA)	72	JAPAN	139	19	6.7	KIRA ET AL 1965
VT(QUERCUS-CINNAMOMUM)	X	NEPAL	570	X	6.9	YODA 1968
VT(QUERCUS-MACHILUS)	X	N.PAC	549	X	5.6	YODA 1968
VT(QUERCUS-PANAX)	30	JAPAN	410	43	6.9	YODA 1965
VT(QUERCUS-PANAX)	30	JAPAN	280	28	9.4	YODA 1965
VT(QUERCUS-PANAX)	30	JAPAN	404	45	7.7	KIRA ET AL 1965
VT(RAINFOREST BRMMCO)	X	BURMA	X	18	X	UNESCO 1978
VT(SEASONAL RAINFOREST)	X	IVORYCOAST	X	13	X	UNESCO 1978
VT(SEDGE-GRASS TUNDRA)	X	ALASKA	X	1	X	LIETH 1978
VT(SHORE-OLIGOTROPHOUS)	X	MALAYSIA	X	41	X	LIETH 1978
VT(SHORT-GRASS PRAIRIE)	X	JAPAN	X	8	X	LIETH 1978
VT(SHORT-GRASS PRAIRIE)	X	US	X	X	X	LIETH 1978

PHYTOMASS FILE
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SPECIES	AGE (YEAR)	LOCATION	STANDING PHYTOMASS (MT/HA)	ANNUAL PRODUCTIVITY (MT/HA)	LEAF AREA INDEX	SOURCE
VT(SUBEQUATORIAL FOREST)	X	IVORYCOAST	X	17	X	UNESCO 1978
VT(SUBEQUATORIAL FOREST)	X	IVORYCOAST	X	15	X	UNESCO 1978
VT(TALL-GRASS PRAIRIE)	X	JAPAN	X	6	X	LIETH 1978
VT(TEMPERATE BEECH)	X	EUROPE	X	15	X	LIETH 1978
VT(TEMPERATE EVERGREEN)	X	THAILAND	235	X	X	OVINGTON 1962
VT(TILIA-CARPINUS)	X	POLAND	X	10	X	LIETH 1978
VT(TRF)	X	PANAMA	263	X	X	GOLLEY ET AL 1975
VT(TRF)	X	PANAMA	368	X	X	GOLLEY ET AL 1975
VT(TRF)	X	THAILAND	365	29	12.3	KIRA ET AL 1964
VT(TRF)	X	THAILAND	404	X	10.7	OGAWA ET AL 1965
VT(TRF)	X	THAILAND	324	29	11.4	KIRA ET AL 1967
VT(TROPIC DECIDUOUS FOREST)	X	INDIA	X	16	X	UNESCO 1978
VT(TROPIC EVERGREEN)	X	IVORYCOAST	X	16	X	LIETH 1978
VT(TROPIC EVERGREEN)	X	THAILAND	238	X	X	GOLLEY ET AL 1975
VT(TROPIC FOREST)	18	CONGO	192	X	X	GREENLAND & ADWAL 1960
VT(TROPIC FOREST)	50	GHANA	390	X	X	GREENLAND & ADWAL 1960
VT(TROPIC MONTANE EVERGREEN)	X	BRAZIL	140	X	X	GOLLEY ET AL 1975
VT(TROPIC RAIN FOREST)	X	THAILAND	370	X	X	GOLLEY ET AL 1975
VT(TROPIC SECONDARY FOREST)	X	CONGO	122	X	X	GOLLEY ET AL 1975
VT(TROPIC SECONDARY FOREST)	40	GHANA	X	24	X	UNESCO 1978
VT(TROPICAL GALLERY)	X	PANAMA	1176	X	X	GOLLEY ET AL 1975
VT(TSUGA-FAGUS)	X	US	193	13	X	WHITTAKER 1966
VT(TSUGA-QUERCUS)	X	NEPAL	692	X	X	TOLA 1968
VT(TSUGA-RHODODENDRON)	X	US	511	10	13.1	WHITTAKER 1966
VTA(ARID TROPIC FORMATIONS)	X	WORLD	7.0	2.0	X	RODIN & BAZILEVICH 1967
VTA(ARID TROPIC GALLERY)	X	WORLD	150	40	X	RODIN & BAZILEVICH 1967
VTA(BEECH FOREST)	X	X	194	X	X	OVINGTON 1965
VTA(BOREAL BOG)	X	WORLD	35	3.5	X	RODIN & BAZILEVICH 1967
VTA(BOREAL BROADLEAF FOREST)	X	WORLD	370	8.0	X	RODIN & BAZILEVICH 1967
VTA(BOREAL FOREST)	X	WORLD	X	6	X	LIETH 1978
VTA(BOREAL FOREST)	X	X	200	8	X	WHITTAKER 1975
VTA(BOREAL FORMATIONS)	X	WORLD	190	6.5	X	RODIN & BAZILEVICH 1967
VTA(BOREAL GALLERY)	X	WORLD	87	6.0	X	RODIN & BAZILEVICH 1967
VTA(BOREAL MARITIME FOREST)	X	WORLD	120	17.0	X	RODIN & BAZILEVICH 1967
VTA(BOREAL MICROPHILL FOREST,SOLONIC)	X	WORLD	200	9.0	X	RODIN & BAZILEVICH 1967
VTA(BOREAL MONTANE MEADOW,FOREST SOIL)	X	WORLD	300	7.5	X	RODIN & BAZILEVICH 1967
VTA(BOREAL MONTANE MEADOW,MEADOW SOIL)	X	WORLD	35	12	X	RODIN & BAZILEVICH 1967
VTA(BOREAL TUNDRA-WOODLAND)	X	WORLD	25	5.0	X	RODIN & BAZILEVICH 1967
VTA(BOREAL)	X	WORLD	X	5	X	LIETH 1978
VTA(CHAPARRAL)	X	WORLD	X	8	X	LIETH 1978
VTA(DESERT SAVANNA,RED-BROWN)	X	WORLD	15	3	X	RODIN & BAZILEVICH 1967
VTA(DESERT SCRUB)	X	WORLD	X	1	X	LIETH 1978
VTA(FRESHWATER SWAMP)	X	WORLD	X	20	X	LIETH 1978
VTA(HUMID SUBBOREAL FORMATIONS)	X	WORLD	342	12.6	X	RODIN & BAZILEVICH 1967
VTA(HUMID TROPIC BOG)	X	WORLD	300	150	X	RODIN & BAZILEVICH 1967
VTA(HUMID TROPIC FORMATIONS)	X	WORLD	440	29	X	RODIN & BAZILEVICH 1967
VTA(HUMID TROPIC GALLERY)	X	WORLD	250	73	X	RODIN & BAZILEVICH 1967
VTA(HUMID TROPIC MANGROVE)	X	WORLD	130	19	X	RODIN & BAZILEVICH 1967
VTA(HUMID TROPIC MONTANE,FERRALITIC)	X	WORLD	760	35	X	RODIN & BAZILEVICH 1967
VTA(HUMID TROPIC SWAMPFOREST,FERRALITIC)	X	WORLD	500	25	X	RODIN & BAZILEVICH 1967
VTA(MIDDLE TAIGA,PERMAFROST)	X	WORLD	200	6.0	X	RODIN & BAZILEVICH 1967
VTA(MIDDLE TAIGA,PODZOL)	X	WORLD	260	7.0	X	RODIN & BAZILEVICH 1967

PHYTOMASS FILE
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SPECIES	AGE (YEAR)	LOCATION	STANDING PHYTOMASS (MT/HA)	ANNUAL PRODUCTIVITY (MT/HA)	LEAF AREA INDEX	SOURCE
VTA(MIXED FORESTS, MOD)	X	WORLD	60	4.0	X	ROLIN & BAZILEVICH 1967
VTA(MIXED FORESTS, TURF GRASS)	X	WORLD	350	15.0	X	ROLIN & BAZILEVICH 1967
VTA(MIXED FORESTS, TURF PODZOL)	X	WORLD	300	7.5	X	ROLIN & BAZILEVICH 1967
VTA(MIXED FORESTS, YELLOW PODZOL)	X	WORLD	350	10.0	X	ROLIN & BAZILEVICH 1967
VTA(MONTANE TAIGA, FORMATIONS)	X	WORLD	180	5.0	X	ROLIN & BAZILEVICH 1967
VTA(MONTANE TAIGA, PODZOL)	X	WORLD	170	6.0	X	ROLIN & BAZILEVICH 1967
VTA(POLAR DESERT, MOD)	X	WORLD	4	0.2	X	ROLIN & BAZILEVICH 1967
VTA(POLAR DESERT)	X	WORLD	5	1.0	X	ROLIN & BAZILEVICH 1967
VTA(POLAR FORMATIONS)	X	WORLD	17.1	1.6	X	ROLIN & BAZILEVICH 1967
VTA(POLAR GALLERY)	X	WORLD	10	1.7	X	ROLIN & BAZILEVICH 1967
VTA(POLAR MONTANE DESERT)	X	WORLD	3	1.5	X	ROLIN & BAZILEVICH 1967
VTA(POLAR MONTANE TUNDRA)	X	WORLD	7	0.7	X	ROLIN & BAZILEVICH 1967
VTA(POLAR TUNDRA)	X	WORLD	24	2.5	X	ROLIN & BAZILEVICH 1967
VTA(RAINFOREST, PIAGET)	X	WORLD	4	15	X	STETH 1979
VTA(RAINFOREST, ECOTONE)	X	WORLD	X	15	X	LIETH 1979
VTA(SEMI-ARID TROPIC FORMATIONS)	X	WORLD	107	14	X	ROLIN & BAZILEVICH 1967
VTA(SEMI-ARID TROPIC GALLERY)	X	WORLD	170	60	X	ROLIN & BAZILEVICH 1967
VTA(SOUTHERN TAIGA, MOD)	X	WORLD	90	4.0	X	ROLIN & BAZILEVICH 1967
VTA(SOUTHERN TAIGA, TURF GLEY)	X	WORLD	350	14.0	X	ROLIN & BAZILEVICH 1967
VTA(SOUTHERN TAIGA, TURF PODZOL)	X	WORLD	300	7.5	X	ROLIN & BAZILEVICH 1967
VTA(SOUTHERN TAIGA, YELLOW PODZOL)	X	WORLD	350	10.0	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL ARID DESERT, GRAY-BROWN)	X	WORLD	4.5	1.5	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL ARID DESERT, TAKYR)	X	WORLD	3	1.0	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL ARID FORMATIONS)	X	WORLD	11.7	2.3	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL ARID GALLERY)	X	WORLD	80	13	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL ARID HALOPHYTE, SOLONCHAK)	X	WORLD	1.5	0.5	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL ARID MONTANE DESERT)	X	WORLD	7	1.5	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL ARID MONTANE SEMI-DESERT)	X	WORLD	7	3	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL ARID PSAMMOPHYTE)	X	WORLD	30	5.0	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL ARID STEPPE-DESERT	X	WORLD	12	4	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL ARID STEPPE-DESERT, COMPLEX)	X	WORLD	10	3.5	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL ARID STEPPE-DESERT, SOLONETS)	X	WORLD	5	3.4	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL MOD)	X	WORLD	57	25	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL BROADLEAF SWAMP)	X	WORLD	30	13	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL BROADLEAF, FOREST SOIL)	X	WORLD	900	19	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL BROADLEAF, PODZOLIC)	X	WORLD	370	12	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL DRY STEPPE, CHERNOZEM)	X	WORLD	13	5	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL DRY STEPPE, SOLONETS)	X	WORLD	14	5	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL DRY STEPPE, TUSSAKHT)	X	WORLD	20	9	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL GALLERY)	X	WORLD	90	12	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL HALOPHYTE, SOLONCHAK)	X	WORLD	12	4	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL PSAMMOPHYTE, CHERNOZEM)	X	WORLD	35	15	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL PSAMMOPHYTE, SAND)	X	WORLD	10	5	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL SEMI-ARID MOD)	X	WORLD	15	7	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL SEMI-ARID FORMATIONS)	X	WORLD	20.9	6.2	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL SEMI-ARID GALLERY)	X	WORLD	80	12	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL SEMI-ARID HALOPHYTE)	X	WORLD	20	2.7	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL SEMI-ARID MONTANE MEADOW)	X	WORLD	25	11	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL SEMI-ARID MONTANE STEPPE)	X	WORLD	25	17	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL SEMI-ARID PSAMMOPHYTE)	X	WORLD	15	6	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL STEPPE, LEACHED CHERNOZEM)	X	WORLD	25	13	X	ROLIN & BAZILEVICH 1967
VTA(SUBBOREAL STEPPE, SOLONETS CHERNOZEM)	X	WORLD	20	8	X	ROLIN & BAZILEVICH 1967

PHYTOMASS FILE
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VTA(SUBBOREAL STEPPE,SOLONETS)	X	WORLD	16	5	X	RODIN & BAZILEVICH 1967
VTA(SUBBOREAL STEPPE,SOUTHERN CHERNOZEM)	X	WORLD	20	6	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC ARID DESERT)	X	WORLD	2	1	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC ARID DESERT,SEROZEM)	X	WORLD	12	10	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC ARID DESERT,TAKYR)	X	WORLD	1	0.5	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC ARID GALLERY)	X	WORLD	200	9	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC ARID HALOPHYTE)	X	WORLD	1	0.2	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC ARID PSAMMOPHYTE)	X	WORLD	3	0.1	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC DECIDUOUS)	X	X	410	24	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC HUMID BOG)	X	WORLD	200			
VTA(SUBTROPIC HUMID BROADLEAF,RED & YELLOW)	X	WORLD	450	23	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC HUMID BROADLEAF,BROWN)	X	WORLD	380	16	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC HUMID FORMATIONS)	X	WORLD	360	25.5	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC HUMID GALLERY)	X	WORLD	250	9	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC HUMID MOUNTAIN)	X	WORLD	410	18	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC HUMID PRAIRIE)	X	WORLD	30	13	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC HUMID SWAMP)	X	WORLD	400	22	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC SEMIARID FORMATIONS)	X	WORLD	58.7	13.8	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC SEMIARID GALLERY)	X	WORLD	250	40	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC SEMIARID HALOPHYTE)	X	WORLD	1.5	0.5	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC SEMIARID MOUNTAIN SHRUB-STEPPE)	X	WORLD	30	6	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC SEMIARID MOUNTAIN)	X	WORLD	120	13	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC SEMIARID PSAMMOPHYTE)	X	WORLD	20	5	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC SHRUB-STEPPE,CHERNOZEM)	X	WORLD	25	3	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC SHRUB-STEPPE,GRAY BROWN)	X	WORLD	35	14	X	RODIN & BAZILEVICH 1967
VTA(SUBTROPIC SHRUB-STEPPE,SOLONETS)	X	WORLD	20	6	X	RODIN & BAZILEVICH 1967
VTA(SUMMERGREEN FOREST)	X	WORLD	X	10	X	LIETH 1978
VTA(TAIGA,GLEY-PERMAFROST)	X	WORLD	100	4.0	X	RODIN & BAZILEVICH 1967
VTA(TAIGA,GLEY-PODZOL)	X	WORLD	125	5.0	X	RODIN & BAZILEVICH 1967
VTA(TEMPERATE BIRCH)	X	X	140	X	X	OVINGTON 1965
VTA(TEMPERATE CONIFER)	X	X	X	28	X	WESTLAKE 1963
VTA(TEMPERATE DECIDUOUS)	X	X	X	12	X	WESTLAKE 1963
VTA(TEMPERATE FOREST)	X	X	300	13	X	WHITTAKER 1975
VTA(TEMPERATE GRASSLAND)	X	WORLD	X	5	X	LIETH 1978
VTA(TEMPERATE GRASSLAND)	X	WORLD	X	8	X	LIETH 1978
VTA(TEMPERATE OAK)	X	X	175	X	X	OVINGTON 1965
VTA(TEMPERATE PINE)	X	X	162	X	X	OVINGTON 1965
VTA(TEMPERATE SPRUCE)	X	X	165	X	X	OVINGTON 1965
VTA(TMF)	X	WORLD	X	25	X	LIETH 1978
VTA(TPF)	X	WORLD	X	28	X	LIETH 1978
VTA(TMF)	X	X	750	37	X	RODIN & BAZILEVICH 1967
VTA(TPF)	X	X	471	X	X	OVINGTON 1965
VTA(TPF)	X	X	X	5	X	WESTLAKE 1963
VTA(TROPIC DESERT)	X	WORLD	1.5	1	X	RODIN & BAZILEVICH 1967
VTA(TROPIC DESERT,SALESCHO SOIL)	X	WORLD	1.5	0.2	X	RODIN & BAZILEVICH 1967
VTA(TROPIC FOREST)	X	X	450	20	X	WHITTAKER 1975
VTA(TROPIC GRASSLAND)	X	WORLD	X	7	X	LIETH 1978
VTA(TROPIC GRASSLAND)	X	WORLD	X	6	X	LIETH 1978
VTA(TROPIC HALOPHYTE,SOLONCHAK)	X	WORLD	1.0	0.1	X	RODIN & BAZILEVICH 1967
VTA(TROPIC HUMID EVERGREEN,DARK RED)	X	WORLD	600	27	X	RODIN & BAZILEVICH 1967
VTA(TROPIC HUMID EVERGREEN,FERRALITIC)	X	WORLD	650	30	X	RODIN
VTA(TROPIC MOUNTAIN DESERT)	X	WORLD	1.0	0.1	X	RODIN & BAZILEVICH 1967

PHYTOMASS FILE
ECONOMIC BOTANY LABORATORY

SPECIES	AGE (YEAR)	LOCATION	STANDING PHYTOMASS (MT/HA)	ANNUAL PRODUCTIVITY (MT/HA)	LEAF AREA INDEX	SOURCE
VTA(TROPIC MONTANE SAVANNA)	X	WORLD	40	12	X	RODIN & BAZILEVICH 1967
VTA(TROPIC PSAMMOPHYTE,SAND)	X	WORLD	1.0	0.1	X	RODIN & BAZILEVICH 1967
VTA(TROPIC SAVANNA,BLACK SOIL)	X	WORLD	30	11	X	RODIN & BAZILEVICH 1967
VTA(TROPIC SAVANNA,FERRALITIC)	X	WORLD	40	12	X	RODIN & BAZILEVICH 1967
VTA(TROPIC SAVANNA,SOLONETS)	X	WORLD	22	7	X	RODIN & BAZILEVICH 1967
VTA(TROPIC SEASONAL EVERGREEN,BLACK SOIL)	X	WORLD	80	15	X	RODIN & BAZILEVICH 1967
VTA(TROPIC SEASONAL EVERGREEN,FERRALITIC)	X	WORLD	200	18	X	RODIN & BAZILEVICH 1967
VTA(TROPIC SEASONAL MONTANE,FERRALITIC)	X	WORLD	450	22	X	RODIN & BAZILEVICH 1967
VTA(TROPIC SHARP SAVANNA)	X	WORLD	80	14	X	RODIN & BAZILEVICH 1967
VTA(TROPIC XEROPHYTIC FOREST,FERRALITIC)	X	WORLD	250	17	X	RODIN & BAZILEVICH 1967
VTA(TROPIC XEROPHYTIC MONTANE)	X	WORLD	200	15	X	RODIN & BAZILEVICH 1967
VTA(TUNDRA)	X	WORLD	X	1	X	LIETH 1978
VTA(WARM TEMPERATE)	X	WORLD	X	10	X	LIETH 1978
VTA(WOODLAND)	X	WORLD	X	6	X	LIETH 1978
VTL(ARMEROO)	X	SENEGA	X	X	X	DUKE YIELDFILE 1979
ZEA MAYS	X	INDIA	X	5	X	BOGDAN 1977
ZEA MAYS	X	INDIA	X	15	X	BOGDAN 1977
ZEA MAYS	X	ISRAEL	36	36	X	WESTLAKE 1963
ZEA MAYS	X	KENYA	X	4	X	BOGDAN 1977
ZEA MAYS	X	MINNESOTA	X	25	X	DUKE YIELDFILE 1979
ZEA MAYS	X	SURINAM	X	2	X	BOGDAN 1977
ZEA MAYS	X	SURINAM	X	6	X	BOGDAN 1977
ZEA MAYS	X	TRINIDAD	X	60	X	BOGDAN 1977
ZEA MAYS	X	TROPICS	X	-	X	BOGDAN 1977
ZEA MAYS	X	TROPICS	X	20	X	BOGDAN 1977
ZOYSIA MATRELLA	X	X	X	23	X	DUKE 1978

VT = Vegetation Type, VTA = Vegetation Type Average

% = Assumes Dry Matter

(DM) = 100% Wet Weight. All data reported as DM

X = No data available

Under Source, HA = Herbage Abstract

PAPER NO. 2. MAGIC MOUNTAIN, 2000 AD

(By J. A. Duke[1])

Twas the year 2000 on Magic Mountain, Tropical Moist Forest Life Zone. None of the natives lived by the river anymore. After the last flood they abandoned the last alluvial homesite and moved up on top of Old Magic. This freed 100 of their most productive hectares for agriculture. Untended slopes yield 30 MT/ha/ann. biomass and the ridges where they now have their residences yield only 15. The bottomland they abandoned, fertilized by the floods that used to destroy their homes periodically, yields 150 MT/ha without fertilizer. With the help of leaf-protein extraction equipment, they are getting 3 MT protein per bottomland hectare, but the bulk of their bottomland biomass goes into barrels, as ethanol. Lo and behold, they are getting 2 barrels of alcohol for every MT of biomass, using firewood and residues to fuel the distillation, applying the ashes back to the farm. That's big money these days with ethanol at $100 a barrel, oil at $200. Instead of sending them arms, powdered milk, peanut butter, and fertilizer, the U.S. sent them LP (leaf protein) extractors, seeds (computer-selected for this ecosystem), innoculum, stills, and energy-producing portajohns.

Back in the 90's some of the donors from the overdeveloped countries realized that they could nitrogenate more acres in the tropical backwoods with a kilo of innoculated legume seed than a kilo of nitrogen. Adventist Missionaries made their point back in 1990 when they showed the natives that they could get 10-20 times as much protein from leaves if they did the conversion themselves rather than let the cattle do it. So now for each hectare they have three tons of protein instead of 300 kg. As a by-product they have 100 barrels of ethanol, worth 10,000 dollars. With their tropical climate, conducive to higher productivity, they are now exporting ethanol to the U.S. at $100 a barrel, while the Arabs are having trouble finding buyers for their oil at $200 a barrel. Instead of bananas at 5¢ a finger or coffee at one clam per kilo, the barge that chugs up the river hauls ethanol out for those profligate spenders up in the U.S. who are still sitting on their coal, to give them the energetic upper hand in case the Russians don't get out of Poland, Afghanistan, Syria and Iran (all of whose oil had been burned up by saboteurs). Neophytes to the tropics thought that Magic Mountain was Virgin Rain Forest, but those of us in the know knew that nearly all of Magic Mountain was a multitiered, multiuse agroecosystem. The Virgin Rain Forest was the next ridge over, by Rocky Rapid River, i.e. Meyers Mountain. Rocky Rapid River still provides cold clear water and the electricity consumed on Magic Mountain. Meyers Mountain, now a State Park, has several endemic species, which are being studied by the Natural Products people looking for better contraceptives and cancer cures. Neophytes thought this was Virgin Forest because it had more than 100 tree species per hectare in at least two tiers. Palms and legumes stuck out on top, with coffee and cacao in the lower tiers of some, leguminous vines in others, lemongrass in others, yams in others, and zingiberacous spices in the shade of others.

1/ Fictional Presentation by Jim Duke to Office of Technology Assessment, November 24
Personal opinions of the author, (not cleared by USDA).

Finding forest on magic mountain suprised a lot of armchair botanists, who, back in the 80's predicted that the isthmian forest would be reduced to savannoid "red desert" following the interamerican hiway through the Darien Gap. But there were at least three strikes against the "red desert" hypothesis (1) Secretary of State Kissinger had convinced President Reagan that trees alleviated rather than aggravated the pollution problem, so Americans weren't running a "Down With Trees" campaign (2) Natives had experienced fewer bug and disease problems in their multitiered agroecosystems than in their brief monocultural experiments, and (3) Americans had encouraged a forest "barrier" between the hoof-and-mouth disease of Colombia and the McDonald Farms in Central America, still devoid of aftosa. The Neophytes thought that the Americans had taught the Indians this multi-tiered approach, but, in fact, the Indians had taught the Americans. Even in temperate America, the Indians were intercropping when Columbus got here, with beans fixing a little nitrogen to supplement that left by the decaying fish they placed with their C-4 corn seed. The C-3 pumpkins we used for our Thanksgiving pie were used by the Indians as well. But they knew that the cucurbits smothered weeds long before young Dr. Duke discovered that cucurbits not only smothered the weeds, but allelochemically discouraged them.

The standard of living was almost as high on Magic Mountain as it was in New York City. A few hippies and naturalists thought it was even better. It seems that in spite of marvelous inventions in solar energy and energy conservation (halving the consumption of individual appliances), the Americans were still energy guzzlers. hey now had electric nail clippers, electric combs, and electric toothpicks, and they had to recharge their electric cars in off-peak hours with their palm oil and ethanol-fueled generators. These were located on offshore barges for the receipt of the barrels of ethanol and palm oil flowing in from the neotropics. The gringo still heats his home six months of the year to 72°F and cools it six months of the year to 62°F, wearing short sleeves in the wintertime around the house and coat and tie during his air-conditioned summer. Jim Duke said you could fuel America with sewage-irrigated biomass (if Americans went vegetarian) and Melvin Calvin said Arizona planted to the petroleum plant (Euphorbia lathyris) could satisfy the energy needs of the U.S., and Szego and Kemp said you could do it with BTU bushes. But America went on and paved its bottomlands, its most productive farmland, now selling at $200,000 per hectare. No one really knew who was right. Should they have believed Vergara and Pimentel who said that all the biomass in the U.S. would support only 2-1/2% of their energy needs (while OTA, 1980 concluded that biomass already supply 2% of U.S. energy consumption and could supply up to 20% by this year), or estimates of 10% (like Dugas came up with in California), or Falkehag (1979) who said U.S. consumption about equals the net annual storage of solar energy in U.S. biomass, or Vietmeyer (1980, OTA) who accepts Calvin's suggestion that Arizona planted with petroleum plants could fuel all the U.S.?

There aren't too many animals on Magic Mountain and these are there more for biocontrol than for meat. Sam Swindell has a bunch of pigs which are rotated from one alluvial farm to another when the nutgrass gets out of control. Seems that the nutgrass was evolving just as fast as the herbicides. The last generation of nutgrass herbicides reduced yields of the crop by 50%. One group of hippies down in Guyana had started making a beverage (Chufa Cola) out of the nutgrass tubers, using the aerial biomass to generate the energy

to run their operation. But nutgrass got so rare around Georgetown that Chufa Cola is barely competitive with Coca Cola anymore. Tommy Tucker intercrops turkeys with the legumes in his orchards, largely to control weeds as suggested by Surguladze (1979). Joe Groats has a few goats he stakes out whenever the tropical Rubus the gringos introduced for nitrogen fixation gets out of hand. The Rice-Azolla farmers let the geese help the Azolla keep down the other weeds, while the grass carp keeps down the Azolla and finishes off the zeolite-treated human refuse. They're returning the residues from the essential oil still provided by AID, to the soil. But not just any residue anywhere. Seems that back in 1985, Duke quit talking and computerized all that data showing which plants (and their residues) had positive effects like alfalfa on crop yields and which had negative effects on crops and weeds. Getting 3 MT of leaf protein from alfalfa left a lot of spent residue around, even after ethanol generation. Some of the triacontinol persisted even in these second generation residues, enough to boost the yields of tomatoes by 10%, beans by 15%. With the computerized systems analysis of the allelochemic nsecticides and fungicidal, as well as insect-regulatory aspects of spent residues, there was real planning as to distribution of the allelopathic residues. The natives went all out on Vietmeyer's winged bean when they found germplasm for seeds resistant to bruchids. In the past, bruchids had consumed half of their stored grain. This minor discovery had the effect of doubling their yields of dry beans. Besides, they got more nitrogen fixed than from the haricot bean, and edible roots instead of poisonous roots, as reported for Phaseolus.

Following up on McKell's suggestion back in 1980, the Magic Mountaineers are utilizing native species in their multitiered agroecosystems. Ipecac, here, like ginseng to the north, only grows in the shade. The natives are using by-products from their overstory tonka bean (coumarin producer Dipteryx odorata) to stimulate rooting of new cuttings of ipecac (Cephaelis ipecacuanha) as they harvest roots of the older ipecac. Coumarin has been shown to stimulate cuttings. Both these species, like shade-loving Piper dariense (used for toothache, fish poison), are adapted to the cooler, higher slopes of the Subtropical Montane Forests. Gradually tonka beans and oil-producing palms and diesel trees are being introduced into the forest canopy as other species are felled or die. Magic Mountaineers still don't believe Calvin's estimates that they can get 125 barrels of "diesel" per hectare from their "diesel trees," Copaifera sp., but the resin is now selling for $10.00 a kilo and they can harvest renewably a few hundred dollars worth a year as they are harvesting ipecac, chicle, rubber, ivorypalm, quinine, and tonka beans from TMF species over on Meyer's Mountain. The nature lovers still prefer to gather their items renewably from Meyer's Mountain National Forest, while the homebodies are transplanting their species as money making trees for the upper story of their agroforestry enterprises.

One of the Magic Mountaineers was raising crocodiles for the export market in his water chestnut patch. If harvested young, they did not thrash around too much and mess up his water chestnuts. However, the crocodiles did eat his fish and prawn yield down by 50%. He had trouble getting his hides shipped directly to the U.S. Endangered species authorities thought that cultivating crocodiles might endanger them in the wild. Another Magic Mountaineer had been exporting butterflies to the U.S. until the endangered species people shut off the port. When the farmer abandoned his operation, two species went extinct,

as far as Magic Mountain was concerned. Perhaps they still exist over on Meyer's Mountain. Another was exporting amaranth seed to the U.S. health food market until APHIS stopped this traffic, trying to avoid the importation of another weed. Boyscouts back in the U.S. quietly filled this market need by harvesting the amaranth seeds from weedy cornfields. The amaranth news shared the headlines with other weed species the Magic Mountaineers were finally consuming. Organic Gardening, at least the Spanish Edition, came in on the barge each month.

On the gravelly limestone ridge, where the 4 m annual rainfall quickly percolated through, some of Felker's Prosopis was doing well, but the natives still preferred the tamarinds (Dialium, Tamarindus). Of all things they tend to vary their diets with other legumes, some mentioned by Felker; Cassia, Enterolobium, Hymenaea, Inga, Parkia, Prosopis. The Prosopis yield of 12 MT/ha didn't carry so much weight here in the humid tropics as it did back on the Chilean desert. One Chilean tree was reported to yield at the rate of 12,700 kg fruit/ha, clearly a good yield, if accurate, for the desert. But none of the Arid Tropical species compete well in the Humid Tropics and vice versa. As Felker points out, the Chilean yield is 500-fold higher than some yields (14 kg/ha).

A cord of mesquite will yield 30 million BTU compared to 25 million BTU from a ton of coal (Anon, 1980). Arizona pinon-juniper yields 18 million BTU. And Magic Mountaineers, still cooking with wood, were impressed by Vietmeyer's (1980) statement that a hectare of Leucaena would yield 10 times as much wood as a well managed pine plantation. The new fuel-efficient stoves the Swedes sent in had cut down on firewood consumption, leaving them with less ash to fertilize their vegetable plots.

Since they weren't fond of hairless beef, the natives of Magic Mountain weren't fond of Leucaena, some of them even lamenting that they had sown it for cover on the old landslide. It's seeds were coming up everywhere, but it didn't seem to be a real weed anywhere except on the scarp. Nitrogen is, after water, the most frequent limiting factor in the tropics, so Leucaena is viewed by some as a good N source. Our Magic Mountaineers were impressed with Halliday's statement that BNF is "economically more sound and environmentally more acceptable than nitrogen fertilizer use in agriculture" and his statistics; most legumes fix 100 kg/ha, with Leucaena at 350 Kg/ha, and a potential of 800 kg/ha. Bill Liebhardt estimated Rhizobial Nitrogen fixation of pure strands of Leucaena at 50-900 kg/ha. Still certain government agencies sent millions of dollars worth of N to the third world, when appropriately innoculated legumes, cheaper to distribute, would have done the job renewably. Efficiency was the excuse, it takes less paperwork to spend 100 million at one fell swoop than to make 100 separate million dollar investments.

The Chinese on the steep slopes of the wet side of the mountain are intercropping azolla, rice, fish and duck, in their intricately terraced rice paddies. They were getting 15 MT rice per hectare as Clark had reported in 1980. They were not getting 150 MT dry weight of Azolla as suggested by Clark, but they had devised a system for raking off the bulk of the Azolla every 10 days, after it doubled its biomass, and adding the biomass as a mulch to truck gardens on the ferralsols. As back in the days of the Canal Zone, the Chinese grow the

best vegetables in Panama. And they sell a lot of azolla-fed fish and ducks off their rice terraces. There's a persistent rumor they are adding night soil to their rice-azolla farms. But their terraced slopes are as productive as the alluvial bottomland.

Duke had always pushed the sunchoke (sunflower x artichoke) as a biomass candidate for the temperate zone. The Chinese have squeezed it, like so many other temperate species, into the humid tropics. Sunchoke accomplishes some of the things enthusiasts for perennial corn were pushing back in the 80's. The roots are perennial and produce at least 20 MT/ha edible root, leaving behind more than enough to reseed itself and feed the last of the wild peccaries. The annual sunflower parent would have to be replanted but not the artichoke, it kept coming back like a song, more like a weed. One farmer who wishes to go into a different agrotechnology had to borrow the biocontrol pigs to clear his land of sunchokes. Chinese learned to add the raw artichoke at the last minute to Chinese dishes to substitute for water chestnut. Turns out that the aerial biomass, cut three or four times a year, was good for leaf protein and ethanol synthesis. Still this sunchoke did not yield as highly as some of the other scenarios. Some of the Magic Mountaineers accused Johnny Sunchokeseed of introducing a weed to the tropics. Take it home, yankee.

Down in the swamps, the natives were producing closer to the lower than the upper predictions of DOE back in 1980, 60-270 barrels of ethanol per hectare from cattails. They were getting higher yields from some of the native swamp species Acrostichum, Dieffenbachia, Gynerium, Erythrina, Montrichardia, Panicum and Pennisetum, species that DOE hadn't even considered back in the 80's.

Before Panama took over the canal, U.S. germplasm specialists provded many useful palm for trial on Magic Mountain. Finally the Orbignya from Brazil was bearing seed, but the smuggled seed had triggered an incident. Brazil broke relations with Panama and the U.S., for collecting germplasm without a permit. Back in the 80's at a congressional OTA workshop, Duke had taken some of Schultes' optimistic numbers for Orbignya martiana, some trees of which were reported to yield more than a MT of fruit per year, 10% of which was kernel, 50% of which was oil for a yield of 40 kg oil per tree or a barrel of oil for every 4 trees, accompanied by 40 kg protein per tree and perhaps 350 kg carbohydrate per tree. Duke feared these projections were optimistic, like Melvin Calvin's estimates of gopherweed oil. Still he recommended that OTA urge investigation of all palms,
because of some of their adaptations to marginal tropical habitats. Some of the Magic Mountaineers did get nearly these high yields with trees at 100 to 200 trees per hectare. Above this per-tree yields dropped off. Still some of our Magic Mountaineers are getting 100 barrels of palm oil per hectare on marginal soils. There was almost as much protein, and more carbohydrate for ethanol production.

Magic Mountaineers had really been impressed with Mumpton's zeolites, increasing their fish biomass by 10% with 5% clinoptilolite, chickenfeed efficiencies by 20% with 10% zeolite, beef profitability by 20%, calf growth by 20% with 5% zeolite, and swine growth by 25-30% with 5% clinoptilolite. They are using the clinoptilolite in the treatment of feces in their portajohns, lessening the odor. The nitrogen is held longer after the zeolite is applied to the soil.

Zeolitic catalysts are being used in the production of the ethanol exported to the U.S. Nearer Panama City, the zeolites were being imported from the interior to slow-down plant uptake of heavy metals in the sewage sludge energy farms and in the purification of low-BTU methane produced by anaerobic fermentation of beef excrement in McDonald's Hamburger Farm.

One oilpalm farmer with several dozen hectares persisted in grazing beef and milk cows in the partial shade of his oil palms and coconuts. He heard that he could increase his oil yields by 2 MT (= 6 barrels) per hectare simply by interplanting with tropical kudzu and butterfly pea. He found that by limited grazing, he could maintain his oil production. When asked what he was doing with his oil and cattle he said, "Those carnivorous Americans are still after our cheap hamburgers. Why at McDonald's you can get a centigrammer (centigram hamburger) for $2.00. Some people hint that it's laced with pr.-protein, one of our byproducts here. And the Americans are running their soybean farms with diesel tractors fueled with palmoil which is considerably cheaper than soyoil." "And what about your milk?" "Oh, we dehydrate that and send it to the Americans too. I understand it doesn't upset their Caucasian stomachs!"

PAPER NO. 3. DEVELOPMENT OF LOW WATER AND NITROGEN REQUIRING PLANT ECOSYSTEMS TO INCREASE AND STABILIZE AGRICULTURAL PRODUCTION OF ARID LAND DEVELOPING COUNTRIES

(By Dr. Peter Felker, Department of Soil and Environmental Sciences, University of California—Riverside*)

ABSTRACT

A low industrial input, commodity oriented approach to stimulating economies of arid land countries of arid land countries is described using arid adapted plant species. Tree legume biomass farms using Acacia, Leucaena, and Prosopis genera are suggested to provide increased fuelwood. Increased soil fertility and ensuing water use efficiency could be achieved by use of deeply rooted drought adapted nitrogen fixers such as Acacia albida and Prosopis cineraria. Stable production of cash crops would be provided from arid adapted shrubs such as jojoba (Simmondsia chinensis), and guayule (Parthenium argentatum). Prosopis and Acacia pods, atriplex forage, Leucaena forage, and cactus pods could increase livestock food supplies. Increased production of traditional food staples such as millet, sorghum and peanuts can be achieved by intercropping them with arid adapted legumes. A reduction in the spread of desertification could be achieved with aggressive management of above mentioned plant genera. Little government support has been made available to support these activities despite their widespread use by indigenous farmers at subsistence levels. A research and development program is outlined to establish living germplasm collections, and to select and propagate superior clones. No more than several months after stand establishment, these plant systems can be grown without supplemental irrigation by using groundwater within 10 m of the surface or by using a minimum of 250 mm annual rainfall. Phosphate fertilizer, micronutrients, and rhizobial inoculation are required but the nitrogen needs of the system will be provided by nitrogen fixing plants. Machinery to till these systems will be

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less than for annual plant systems. Widescale implementation of these systems would greatly enhance agricultural productivity at the local level where it is most needed, and indirectly stimulate non-agricultural sectors of the economy. Increased economic well being of lower farming classes could lead to decreased political unrest and greater stability of governments in arid lands. Foreign policy efforts to strengthen the peace by buildup of military hardware systems has proven futile in Ethiopia, Iran and Iraq. Development of arid land plant production systems is a viable alternative to enhancing peace in politically-volatile arid land countries.

INTRODUCTION

This document was prepared at the request of the Office of Technology Assessment (OTA) of the U.S. Congress to provide guidance in development of low energy, nitrogen, and machinery requiring agricultural systems for semi-arid developing countries. The format of this document closely follows OTA requests to address specific issues and questions. For the convenience of the reader these requests are reproduced on page 4.

Identification of plant physiological, morphological, and ecological characters that lend themselves to a minimal machinery, capital, and fossil fuel derived energy input agriculture is the subject of a paper by Felker and Bandurski (1979) in which orchards of leguminous trees were suggested to most closely approximate an ideal system for minimizing industrial inputs. Other closely related shrub ecosystems have been suggested by McKell (1975) to achieve similar objectives. Identification of arid land plant species that would lead to more stable and productive ecosystems has been most intensively investigated by Felger (1979). Recent review volumes (Anon., 1979; Ritchie, 1979) and symposia (LeHouerou, 1980; Burgess, 1980) have dealt at length with arid land plant resources. This document attempts to synthesize the identification and development of arid land plant species, with development of minimal energy input agriculture into a pragmatic commodity oriented framework designed to provide major needs such as fuel, forage, and food staples required for arid land based economies.

September 25, 1980

Work Statement

Development of low energy input technologies to increase and stabilize productivity of agricultural ecosystems in dry regions of less developed countries.

Contractor shall:

1. Describe how the technology operates and what beneficial or adverse impacts it has or might have on enhancing the sustained production of food and forage from tropical and subtropical soils.

2. Describe where this technology is being used. Describe whether the technology is being used on a commercial level, a subsistence level, as a pilot program, or is being applied only in the research state. Describe who is conducting the major research on the technology. Describe what organizations (AID, FAO, and others using U.S. funds) are funding development of the technology and what organizatins are implementing it on a project scale.

3. Explain in some technical detail how this technology increases or decreases the need for fertilizers, pesticides, irrigation, and machinery when applied to tropical/subtropical soils.

4. Discuss the potential role of this technology being used to restore, improve, or sustain in perpetuity the food and forage productivity of tropical and subtropical soils, and the likelihood that this technology will be used widely.

We appreciate that the author may not be a specialist in economics or sociology; however, his experience and insights on the following questions still are still of interest to OTA, especially as they relates to lesser-developed countries. Therefore the contractor shall:

5. Describe a plausible research, development, and implementation scenario in which this technology realizes its potential in enhancing productivity of tropical soils. What organizations would be involved? What levels of capital and trained personnel would be necessary? What degree of attitudinal changes would be necessary for consumers, farmers, government agricultural experts, bureaucrats, politicians, foreign advisors, policymakers in foreign aid or lending institutions, etc.? What biophysical (soils, climate, topography), cultural, and socioeconomic conditions would be most conducive to successful implementation of the technology? Where do these conditions exist or where are they likely to develop? To indicate the priority of the various steps that need to be taken on this technology, contractor

shall discuss how he (if he were the head of a wealthy foundation) would spend $10 million on research, development, or implementation of the technology.

6. Describe the major scientific, environmental, cultural, economic, and political constraints on development and implementation of this technology.

7. Describe how implementation of this technology would affect the need, in the region where it was implemented, for inputs of capital (agricultural chemicals, machinery, credit, seed, and other materials from the implementing farm), labor, and land.

8. Describe what the impact of wide-scale implementation of this technology would be on the socioeconomic structure of agiculture in the implementing regions. For example, does the technological implementation give rise to economies of scale, or diseconomies of scale, that would make large or small farm units more competitive? How would the technology either displace or create demand for farm laborers?

DELIVERABLES:

The contractor shall deliver to OTA the original copy (not a reproduction) of the typewritten 25-to-35-page report, acceptable to OTA, with abstract and literature citations, by November 24, 1980.

I. Beneficial aspects of semi-arid plant production technologies on semi-arid developing countries.

Development of leguminous trees (Felker and Bandurski, 1979) and associated semi-arid ecosystem plant components such as saltbush (Atriplex spp.) (Goodin, 1979), leucaena (Leucaena leucocephala) (Brewbaker and Hutton, 1979), cactus (Opuntia and Cereus spp.) (Monjauze and LeHouerou, 1965 and Xolocotzi, 1970), jojoba (Simmondsia chinensis) (Hogan, 1979), and guayule (Parthenium argentatum) (Vietmeyer, 1979) can make a significant contribution to meeting the major commodity needs of people in semi-arid developing countries. Some of the main biological needs and appropriate approaches to supplying them are as follows:

1. Need: increased availability of inexpensive fuelwood.

   Approach: use of leguminous tree biomass farms with Prosopis, Leucaena, and Acacia species.

2. Need: increased soil fertility to triple or quadruple water use efficiencies of food staples so that productivity is water-limited and not fertility-limited.

   Approach: use locally well-respected drought-adapted nitrogen-fixing tree legumes, such as Acacia albida and Prosopis cineraria, use of shrubby legumes such as Dalea species and use of perennial arid adapted herbaceous legumes, such as Zornia and Tephrosia.

3. Need: production of cash crops for farmers and for foreign exchange.

   Approach: use of perennial arid adapted plants, such as jojoba, guayule and high value drought adapted annuals and ephemerals, such as sesame when grown in conjunction or rotation with arid adapted nitrogen fixers.

4. Need: production of livestock food and forage.

   Approach: use of arid adapted salt tolerant shrubs, such as saltbush (*Atriplex* species) in conjunction with high water to dry matter conversion plant specialists, such as spineless cactus (*Opuntia ficus-indica*) and high protein and/or sugar content pods of leguminous tree species of *Acacia tortilis*, *Acacia albida*, and *Prosopis* spp.

5. Need: sustained production of traditional food staples, such as millet, sorghum, groundnuts, and cowpeas.

   Approach: intercrop the annual staples with nitrogen fixing trees previously demonstrated to stimulate annual legume yields such as the association with *Acacia albida* and peanuts.

6. Need: slow spread of desertification.

   Approach: when intensive management of forage, fuelwood and staple products are carried out as outlined above desertification will be greatly reduced.

II. Geographical areas of technology use and stage of development (subsistence, commercial or research).

1. DEVELOPMENT OF TREE LEGUMES FOR FUELWOOD

A. Area where technology is being used

Prosopis alba and *P. nigra* were reported to have fired industrial boilers and steam locomotives during World War I I in Argentina (D'Antoni and Solbrig, 1977). In Chile the leguminous trees chanar (*Geoffrea decorticans*) and espino (*Acacia caven*) have been widely harvested by Indians and present day subsistence farmers for fuel (Aschmann, 1979). Mesquite wood and charcoal (*Prosopis* species) is highly esteemed and widely used in southwestern United States in steakhouses for barbecues and home heating. From 1956 to 1965 78,000 metric tons of mesquite charcoal and 200,000 m^3 of mesquite firewood were recorded as items of commerce in Mexico (Lorence, 1970). In the Jodphur state of India, *Prosopis* was declared the "royal plant" because it provided the bulk of the fuel to the local population (Gupta and Balera, 1972). *Acacia* forests are harvested along the Nile 400 km upstream from Khartoum, Sudan, and brought to Khartoum for brick making and other industrial uses (A. Houri, 1979). In the Sahelian zones of Africa many of the *Acacia* species such as *A. tortilis*, *A. seyal*, and *A. senegal* are consumed for woody biofuel.

B. Research facilities supporting legume fuelwood production

The Central Arid Zone Research Institute in Jodphur has been conducting research on leguminous trees as sources of biofuels since the early 1940s (Ahmed, 1961). Their work is meagerly documented in the scientific literature and, from the lack of recent papers in literature, their current research on tree legumes does not appear to be very active.

The Forestry Research Institute in Khartoum, Sudan, has received about $200,000 from the International Development Research Center (Ottawa) to evaluate Prosopis species under approximately 200, 300, and 400 mm annual rainfall regimes. Much of the seed material for this experiment was supplied by the U.C. Riverside mesquite project. The United Nations Development Program (UNDP) provided support for Felker to supply seeds, mesquite rhizobia, plants, containers, and consultation to conduct varietal trials with 30 selections of leguminous trees (mostly Prosopis) in the Sudan at the Forestry Research Institute. Over 400 acres of Prosopis have been planted along irrigation canals in the Sudan courtesy of the Sudan Council of Churches to prevent sand from blowing into and filling the canals (Khalifa, 1979).

Dr. J. Brewbaker at the University of Hawaii has been conducting extensive research in Hawaii, Colombia, and the Philippines, on the development of Leucaena as a biofuel crop. In the United States, the U.S. Dept. of Energy has funded research on Prosopis under Felker at the University of California, Riverside, to develop an arid adapted germplasm collection; to evaluate the collections in field conditions under drought, heat, and frost stress; to study nitrogen fixation and salt tolerance; and to clonally propagate outstanding single trees.

2. USE OF NITROGEN FIXING TREES TO INCREASE SOIL FERTILITY

A. Areas where technology is being used

Prosopis cineraria has been used on a subsistence level by farmers in the India-Pakistan region to increase the yields of their pearl millet crops. Soil chemistry studies (Shankar et al., 1976) corroborated increased nutrient

contents and forage yields under P. cineraria trees versus other trees and open control areas. Acacia albida is widely used on a subsistence level in the West African countries of Senegal, Upper Volta, Mali, Niger and Chad to increase the yields of sorghum, millet, and peanuts grown beneath the tree canopies (Felker, 1978). Parkia biglobosa was observed by this author growing in sorghum fields in a 400 mm annual rainfall regime where farmers stated the Parkia also increased the yields of their crops.

Yields of grasses and forbs grown in a growth chamber on soil from beneath mesquite canopies were four times greater than herbage yields grown on soils from outside mesquite canopy cover (Liedemann and Klemmedson, 1973). The stimulation of forage yields after mesquite removal in southwestern United States is probably due to increases in soil fertility supported by nitrogen fixation and reduction in competition for water. Mesquite nitrogen fixation and soil fertility increases on the 72 million acres (Parker and Martin, 1952) presently occupied by mesquite in southwestern United States is an unrecognized resource. Leucaena (Leucaena leucocephala) has been widely used in the Philippines in rotation with other crops, as a companion crop, and as a green manure with other crops to increase soil fertility (Anon., 1977).

B. Research organizations working on nitrogen fixing aspects of arid adapted legumes

Dr. Y. Dommergue, working for ORSTOM in Dakar, Senegal, West Africa, has conducted rhizobial inoculation trials with many African Acacias including Acacia albida and at this writing is actively involved in nitrogen fixation aspects of semi-arid soils. Dr. Habish at the University of Khartoum, Sudan,

has published excellent papers on characterization of Acacia-rhizobia symbioses (Habish and Khairi, 1970) but is now a dean at the University and no longer actively involved in research. A University of Arizona group, funded by NSF, with Dr. Penper as principal investigator, is collecting and characterizing rhizobia strains from many arid adapted legumes. A three-year $650,000 NSF grant has been awarded to quantitate nitrogen cycling in a mesquite dominated desert ecosystem in southern California. This project involves: (1) an ecology group headed by Dr. Philip Rundel at the University of California, Irvine, that is conducting dry matter productivity analyses, (2) a U.C. Riverside soils group headed by Dr. Wesley Jarrell, the principal investigator of the entire project, that is converting dry matter productivity measurements of the Irvine group into nitrogen productivity, and conducting soil moisture profile measurements with 20 ft deep neutron probes, quantitating soil chemical characteristics on and around the site, quantitating denitrification, and developing in situ acetylene assays, and (3) a Washington University (St. Louis) group headed by Dr. D. H. Kohl that is correlating the above-mentioned findings with natural abundance $^{15}N/^{14}N$ measurements to develop qualitative and perhaps semi-quantitative assays of nitrogen fixation from dried plant samples.

A Department of Energy funded study with Felker as principal investigator has studied cross-inoculation of 13 Prosopis species (Felker and Clark, 1980), has conducted greenhouse studies of effect of heat and drought stress on Prosopis nitrogen fixation, and has developed models comparing efficiencies of water and nitrogen inputs to increasing productivity of semi-arid rangelands (Felker et al., 1980). USDA scientists Drs. A. L. Black and J. R. Wight

from Sidney, Montana, have demonstrated that fertility can dramatically increase water use efficiency of rangeland species in a 10-year study on Montana rangelands (Wight and Black, 1979). The US AID supported Niftal group at the University of Hawaii maintains large stocks of Rhizobia. Basak and Goyal (1980) at the Central Arid Zone Research Institute at Jodphur have published cross-inoculation data and temperature and salinity tolerance characteristics for rhizobia for semi-arid adapted leguminous trees in India.

3. DEVELOPMENT OF CASH CROPS ON SEMI-ARID LANDS

A. Areas currently under development

Jojoba (*Simmondsia chinensis*) a non-legume, is one of the most promising cash crops for arid lands. The jojoba seeds contain a rancidity-resistant non-allergenic, liquid wax with lubricating properties equivalent to an oil obtained from the endangered sperm whale (Anon., 1971). Jojoba is under development in southern California, Arizona, Mexico and many of the less developed countries of semi-arid regions (D. M. Yermanos, 1980). Mature jojoba plantations should yield over 1,000 kg/ha^{-1} at over one dollar per kg which yield gross return of over $1,000 per hectare (Anon., 1977). Guayule (*Parthenium argentatum*) a plant native to the Chihuahuan deserts, contains natural rubber and is under extensive development by both the United States and Mexican governments (Vietmeyer, 1979). There is no reason guayule could not be cultivated in other semi-arid regions of the world as a cash crop. Hydrocarbon bearing plants such as *Euphorbia lathyris* have been suggested by Calvin (1979) as raw materials for oil and gasoline production. The drought adapted tree legume *Acacia senegal* exudes a gum from wounds of the

trunk and stems known as gum arabic which has many industrial and food uses (Glicksman and Sand, 1973). Eighty-five percent of the world's annual supply of gum arabic amounting to about 50,000 to 60,000 metric tons is harvested and exported from the Sudan at prices of about $1 per kg (Glicksman and Sand, 1973). Other Acacia and tree legumes such as Prosopis exude gums which could be developed for cash crops. Seeds of the fast-growing drought-tolerant annual sesame sell for $1-2 per Kg and show potential for an arid zone cash crop (D. Yermanos, 1980). The fruits of the cactus Opuntia ficus-indica can produce dessert or table quality fruits. This author was served an excellent cactus fruit with a meal on a Chilean airline. Commercial (5 ha and larger) Opuntia ficus-indica orchards are currently operating in southern California to supply these fruits to supermarket chains (Felker, unpublished observation). There are several little-known species of cactus which possess fruits equal or superior in quality to Opuntia ficus-indica which could also be developed (Felger, 1979). Due to the high water use efficiency of cactus they should support fruit and cash crop production in semi-arid areas.

The pods of carob (Ceratonia siliqua) are broken into pieces, kibbled, and separated into seed and pod fractions. The pod fractions are sold for livestock food in Europe and are imported into the United States where they are manufactured into chocolate substitutes (Anon., 1979). Industrial quality gums are extracted from the seeds. In 1970 the world production of carob seed gum was 15,000 tons at prices ranging from $0.62 to $1.10 per kg (Rol, 1973). The pods of Parkia biglobosa and P. clappertoniana, and a fermented product of the seeds known as dawa-dawa are sold for human

food on the subsistence levels in markets in Senegal and other parts of West Africa.

B. Research facilities supporting arid land cash crops

The most extensive germplasm collections, plantings, and cytogenetic studies of jojoba are being made at the University of California, Riverside, under Dr. D. M. Yermanos. Work under Yermanos has been funded by UNDP, NSF and the California State Legislature. Another large-scale jojoba research operation is being carried out at the University of Arizona under Dr. L. Hogan. There are numerous commercial jojoba developers, some of whom are quite unscrupulous. Donor agencies should contact Yermanos or Hogan before dealing with private jojoba developers. Dr. Yermanos has also developed non-shattering sesame types and mechanical harvesting sesame devices with UNDP support. The USDA has a multi-million-dollar budget to develop guayule in the southwestern United States.

The Diamond Shamrock Company is currently supporting a multi-million-dollar project at the University of Arizona Office of Arid Land Studies to develop potential of hydrocarbon producing plants such as *Euphorbia lathyris*.

The Canadian IDRC is supporting a research program to develop gum arabic for West Africa through the "Eaux et Foret" in Dakar, Senegal. The University of Chapingo, Mexico, has a program to develop spineless cactus (Xolocotzi, 1970). Dr. Richard Felger at the Arizona/Sonora Desert Museum has identified numerous arid land crops with potential including several outstanding cactus varieties. Dr. Felger has had very limited financial support from several extramural agencies.

4. PRODUCTION OF LIVESTOCK FOOD AND FORAGE

A. Areas where production is taking place

In Mexico, *Prosopis glandulosa* var. *glandulosa*, and *Prosopis laevigata* are presently harvested from wild trees and sold to wholesale dealers for incorporation into livestock rations. In 1965 40,000 tons of mesquite pods were sold in commercial operations in Mexico (Lorence, 1970). Undoubtedly, many more pods were used or bartered locally that never entered into the agricultural statistics reporting services. One thousand ha of *P. juliflora* has been established in the Peruvian coastal desert under partial irrigation. By providing 250 mm of irrigation the first year and 160 mm thereafter, pod production of 6-7 t ha^{-1} have been obtained from the Peruvian plantings (report of R. Peck to IDRC). In nearby Chile, 30-year-old *P. tamarugo* trees growing in the *Atacama* salt desert have produced 6,000 kg ha^{-1} of leaves and pods which is used to support a sheep-raising industry (Salinas and Sanchez, 1971). Twenty-two thousand hectares of *P. tamarugo* have been planted by the Chilean corporation CORFO (Zelada, 1980). Felker has visited these areas to assist CORFO with vegetative propagation, selection techniques, and nitrogen fixing inoculants.

In southwestern United States mesquite pods were the staple for Indians in southern California and Arizona deserts (Felker, 1979), but today are only marginally important in supporting wildlife habitat. In West and East Africa the pods of *A. albida* and *A. tortilis* are highly regarded as a supplemental livestock feed (Felker, 1978; Anon., 1979). Some *A. albida* pods are collected and stored for later rationing to cattle on a subsistence level, but no organized or commercial use of pods has been attempted (Felker, 1978).

The forage of Acacia xanthophlea and A. hockii supplies much of the diet of giraffes in the Serengetti National Park in East Africa. Pellew (1980) has suggested that the Acacia-giraffe ecosystem be managed for meat production.

Forage systems based around the spineless cactus (Opuntia ficus-indica) have been widely used in Mexico and North Africa where the spineless pads are fed to cattle. Selections of saltbush (Atriplex species) are high in protein and carotenoids and constitute a useful livestock forage. The Chilean corporation CORFO has planted thousands of hectares of saltbush in contour ridges along the Chilean coast for use as cattle food (Felker, personal observation). In Tunisia commercial scale government supported plantings of saltbush have taken place to provide forage for grazing animals (Hadri, 1980).

In Mexico cattle rations have been formulated from high energy, sweet, highly-palatable mesquite pods; high protein, high carotenoid and low palatability saltbush foliage; and high-energy containing cactus pads (Lorence, 1979). These three plants possess the complimentary physiological characters of high salt tolerance in saltbush, high water to dry matter conversion efficiencies of cactus, and nitrogen fixing properties of mesquite.

B. Research and development support of livestock food and forage arid land plants.

Surprisingly, little is being done in support of the previously mentioned forage producing plants. The Tunisian and Chilean governments are supporting the largest developments of forage producing plants. The Chilean company CORFO has planted thousands of hectares of Atriplex. CORFO has investigated plant spacing, canopy closure, and pod productivity as a function of age for 36-year-old Prosopis tamarugo plantations (Salinas and Sanchez, 1971). They

are just beginning to become involved with selection work, nitrogen fixation, and vegetative propagation. The Tunisian government has employed large earth-moving equipment and water transport vehicles to establish saltbush and cactus plantings (Hadri, 1980). The Algerian government has also initiated some Opuntia plantings (Monjauze and LeHouerou, 1965). Dr. Henri LeHouerou, formerly of the International Livestock Center (ILCA) in Addis Abba, has been a key figure in North African developments of Atriplex and Opuntia. The Chapingo Agricultural Experiment Station outside of Mexico City has made selection of Opuntia with promising economic characters (Xolocotzi, 1970). Lopez et al. (1977) at the Antonio Narro Agricultural University in Saltillo, Mexico, has conducted a thorough analysis of the productivity and ecosystem characters of economically important aspects of Opuntia production in Mexico. The International Development Research Center (IDRC) Ottawa is supporting the Prosopis juliflora forage production project in Peru.

In the United States, Dr. C. M. McKell now of Plant Resources, Inc., Salt Lake City, and Dr. J. Goodin of Texas Tech University, have conducted extensive research on development of saltbush as an economically important forage crop. Felker at U.C. Riverside has made Prosopis selections for pod producing characteristics in cooperation with Becker and Saunders at the USDA Western Regional Research Center who have conducted proximate analyses and feeding trials on the pods.

5. INTERCROPPING TRADITIONAL FOOD STAPLES WITH ARID ADAPTED LEGUMES TO SUSTAIN HIGH FOOD STAPLE YIELDS

A. Areas where development is taking place

Prosopis cineraria has been widely used in the Indian-Pakistan region on

a subsistence level to increase yields of pearl millet and other forage crops grown beneath its canopy (Mann and Shankarnarayan, 1980). Acacia albida has been used in West Africa to increase yields of millet, sorghum, and peanuts (Dancette and Poulain, 1969; Charreau and Vidal, 1965; and Felker, 1978). Farmers in the 400 mm annual rainfall region of Senegal remarked to this author that Parkia biglobosa had the same fertilizing effect as Acacia albida on millet and sorghum.

B. Research and development supporting intercropping of food staples and arid adapted legumes.

The French overseas development organization ORSTOM commissioned the soil fertility studies carried out by Dancette and Poulain (1969) and Charreau and Vidal (1965). AID commissioned a state-of-the-art report on Acacia albida in 1978 (Felker, 1978). FAO supported a nursery scheduled for termination in 1978 in Kebemer, Senegal, dedicated to raising enough Acacia albida seedlings to plant 1,000 ha per year at 45 trees per hectare. A CARE project in Chad was involved in some manner in reforestation with Acacia albida. No serious field study has ever been conducted to develop genetic stock and management practices for arid adapted leguminous trees to improve yields of traditional food staples.

6. SLOW THE SPREAD OF DESERTIFICATION IN ARID REGIONS

Little work is being carried out in this activity. K. O. Khalifa working for the Sudan Council of Churches has planted 400 acres of Prosopis along irrigation canals to prevent the wind from filling them shut. The Indian government has been planting shelterbelts with Prosopis and other arid adapted trees since the 1920s and 1930s (Kaul, 1970). No serious efforts

employing arid adapted shock, e.g., Prosopis, Acacia or Leucaena, and modern forestry practices have been applied to control of desertification in less developed countries.

III. FERTILIZER, PESTICIDE, IRRIGATION, AND MACHINERY REQUIREMENTS

1. Irrigation requirements

Probably well over 90% of semi-arid land masses in semi-arid regions must rely on rainfall without supplemental irrigation (excluding areas where water harvesting technologies are possible). All of the desert adapted trees, shrubs, and ephemerals described here have the capability to grow dryland (without irrigation) in semi-arid zones. If water is not available these plants can close stomates, shut down photosynthesis and transpiration, allow their finely divided leaflets to reach air temperature and adjust their water potentials to minus 40 to 50 bars and wait for the next rain (Fischer and Turner, 1978). Annuals would wilt and die under the same conditions. Reasonable production from reproductive structures, such as mesquite pods, jojoba nuts or cactus fruits cannot be expected below 250 mm annual rainfall unless they are located in water drainage areas, or areas where water accumulates. Growth of vegetative parts for wood or forage production probably will continue from 250 to 150 mm annual rainfall. The deep rooted tree and shrub production systems tend to integrate rainfall events and avoid transient effects of moisture stress common to shallow rooted annuals. Optimal water use of the agro-system will use an optimal mix of nitrogen fixers and water to dry matter conversion specialists. When it is possible to use cactus with a 5-fold greater efficiency of con-

verting water to dry matter than legumes (Fisher and Turner, 1978) legumes should not be used to produce the energy portion of livestock feed. However, legume leaf litter will be required to create good fertility in order for the cactus to achieve its maximum water use efficiency. For the same reason cactus should not be used to produce the protein and nitrogen needs of livestock when it is possible to use legumes. Livestock need both energy and protein rations and both energy and protein producing plant specialists are required.

2. Fertilizer requirements

A central component of this technology is widespread incorporation of arid adapted nitrogen fixing legumes that are capable of fixing nitrogen under conditions too harsh for temperate legumes such as clover, alfalfa, etc. These legumes will require no nitrogen themselves and when properly incorporated into a diversified ecosystem they will reduce nitrogen needs for non-legumes as well. Many of these plants, both leguminous, e.g., mesquite, and non-leguminous, e.g., jojoba, have very deep root systems (Felker, 1979) capable of mining nutrients found in clays, bedrock, and parent materials such as calcium, magnesium and potassium. Additionally, these deeper rooted shrubs would be expected to have a higher capture ratio of applied fertilizers by not allowing nutrients to leach beyond its deep root zone. As many of these plants are perennial, they would be expected to reduce wind erosion and perhaps water induced erosion. Under rainfall situations as low as 300 mm it may be desirable to practice clean cultivation or use herbicides between rows of mesquite, cactus, saltbush, jojoba and guayule to increase water infiltration and to reduce water competition from

grasses and forbs. Once established, the risk of wind and water erosion present with clean cultivated shrubs and tree crops should be less than the similar risk with annual crops. Drought-hardy shrubs and trees not under severe physiologic water stress should make more effective use of applied nutrients than water stressed herbaceous annual crops.

If drought adapted legumes are widely incorporated into managed arid ecosystems, phosphate and sulfate will ultimately become limiting and will have to be supplied. Both nutrients stimulate legume production and can be supplied in single superphosphate.

3. Pesticide requirements

It is difficult to imagine how the plant ecosystems described here would be more or less susceptible to insect or bird attack than any other ecosystem. Once established perennial tree and shrub crops would survive competition from grasses and forbs without weed control measures. However, their productivity probably will be greatly enhanced if herbicides or cultivation were used to eliminate water competition from grasses and forbs. For the first one or two years of shrub and tree stand establishment, competition from grasses and forbs must be eliminated either by herbicides or cultivation.

4. Machinery requirements

A variety of options employing varying degrees of mechanization are available to establish tree and shrub plantations. This author envisions that most plantations will employ containerized seedlings planted with a liter or two of water. This can be accomplished manually with dibbles or post-hole diggers or mechanically with an 80 hp tractor pulling a transplanter

capable of planting 1,000 trees per hour. It may prove useful to establish a seedbed for seedling transplant with the same level of preparation given to annual crops. However, after the first year an annual deep cultivation as required for annual crops will not be necessary. Where fruits are to be harvested, e.g., jojoba, mesquite beans, etc., light surface harrowing or disking will prove useful for weed control, to increase water infiltration, and to provide a clean surface to pick up the fallen fruits. Pruning of tree and shrub crops will be necessary to allow access for harvesting of fruits. In biomass farming operations, where complete canopy closure is desired, annual cultivation would be unnecessary and impossible to carry out after canopy closure. As required for annual crops an annual ground preparation and planting, carefully timed with arrival of rains to allow germination and full utilization of the rainy season, will not be necessary for the tree and shrub crops. Peak labor shortages may occur at planting time with annual crops which do not allow farmers to plant as much as they would like. Established annual and perennial crops will not face this labor shortage. The light cultivation that may be useful with tree and shrub crops can be performed on a much less rigid schedule when labor, draft animals, and/or machinery are available. If herbicides were available and acceptable they could be used in lieu of light cultivation. Tree and shrub crops would require much lighter equipment than annual crops and the yearly intensive site preparation necessary for annuals could be avoided with tree or shrub crops.

IV. RESTORING AND SUSTAINING PRODUCTIVITY OF SUBTROPICAL SOILS

Use of drought adapted nitrogen fixers to increase yields of staple crops as described earlier in this report is a key component in this strategy. No environmental degradation is perceived that would not allow these systems to sustain themselves in perpetuity. These techniques are already widely used by subsistence farmers. Research and development is required to optimize the tree legume-annual staple cropping systems developed by subsistence farmers.

V. RESEARCH, DEVELOPMENT AND IMPLEMENTATION OF ARID ADAPTED PLANT ECOSYSTEM PRODUCTION TECHNOLOGIES

An outline of research required to develop these plants and cost estimates to do so are given in Table 1. Research centers are proposed in six locations to collect and store germplasm, to plant germplasm nurseries, to re-evalu promising nursery selections in larger sized plots, to compare input/output resource ratios of different plant systems, to evaluate monoculture and polyculture arid adapted systems, and to provide material and administrative support for the research.

The research program outlined in Table 1 is appropriate for the first phase of the research. Extensive germplasm collections and plantings would be required once at a cost of approximately $1,500 K. A funding effort 15% of the initial level would be appropriate after initial collections and plantings were made. Funds used for collections and plantings in the first phase should be allocated to weed and insect control, cultural operations such as harvesting, pruning, and planting methods for nursery stock, and extension short courses during the second phase of the research.

OUTLINE OF RESEARCH PROCEDURE

Level of support per year ($)	
	1. Develop germplasm collections where none exist
	A. Collect single tree selections of leguminous trees over broad range for: 1) pod production 2) large size 3) thorn characters 4) leaf litter
	B. Collect following genera:
100 K	1) *Acacia tortilis* and *A. seyal* in East Africa
100 K	2) *Acacia albida* in East and West Africa
100 K	3) *Parkia biglobosa* in West Africa
100 K	4) *Prosopis cineraria* in Indian-Pakistan region
200 K	5) *Prosopis alba*, *P. articulata*, *P. chilensis*, *P. nigra* and *P. tamarugo* in Mexico, Hawaii, southwestern United States, Argentina, Chile, and Peru
100 K	6) Make cactus collections in southwestern United States and Mexico
100 K	7) Short, shrubby legumes, *Dalea* in southwestern United States, *Tephrosia* in deep South, and *Zornia* in Sahelian Africa
	2. Obtain good selection of following arid crops already subjected to germplasm collection and screening:
25 K	A. Jojoba - Drs. Yermanos & Hogan B. Guayule - USDA C. Euphorbia - Dr. Calvin D. Atriplex - Drs. McKell & Goodin E. Leucaena - Dr. Brewbaker
	3. Plant out four replicates of five trees (plants) of all accessions for germplasm nursery at a 300 mm and 500-600 mm annual rainfall regime in:
100 K	A. East Africa, e.g., Sudan
100 K	B. West Africa--Senegal
100 K	C. India-Pakistan region
100 K	D. South America
100 K	E. Southwestern United States
100 K	F. Site along coast to irrigate with seawater for salinity trials
60 K	4. Evaluate Niftal collection of rhizobia suitable for tree legumes. Develop techniques to insure effective nodulation.

Level of support per year ($)	
100 K	5. Conduct protein, sugar, fiber and toxicity analyses on pods that are produced.
120 K	6. Develop clonal propagation techniques at central facility: A. Rooting of cuttings B. Via tissue culture
450 K (6 sites x 75 K)	7. Evaluate germplasm nursery for: A. Height measurements first year B. Stem diameter measurements yearly C. Pod production and/or pod chemical characters D. Make clones of outstanding single trees
1,200 K (200 K x 6 sites)	8. Evaluate clonal outstanding material in replicated 0.1 ha minimum-sized plots.
180 K (30 K x 6 sites)	9. Multiply and distribute best selections to interested individuals and organizations.
1,200 K (200 K x 6 sites)	10. Evaluate comparative advantages of selections developed above in mono- and poly-culture with *Opuntia*, jojoba, guayule, atriplex, etc.
400 K (200 K x 2 sites)	11. Evaluate large N fixing trees with staple cereal crops in field plantings.
600 K (200 K x 3 sites)	12. Evaluate short N fixers with jojoba, guayule, saltbush, etc.
5,735 K	TOTAL DIRECT RESEARCH
4,265 K	Support facilities, travel, secretarial, library, statistical analyses, computer services, etc.
10,000 K	GRAND TOTAL

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Large genetically diverse germplasm collections and promising plant selections are available for some of the plants described here such as jojoba, guayule and atriplex species. For other plants, germplasm collections and selections of promising lines will have to be made. The plants which require germplasm collection and selection of promising lines and the methodology for accomplishing that is as follows.

Seeds should be taken and maintained as single plant selections from Acacia tortilis and A. seyal in East Africa, from A. albida in East and West Africa, from Parkia biglobosa in West Africa, from Prosopis cineraria in the Mideast and India-Pakistan region, and from P. alba, P. chilensis, P. tamarugo, P. pallida, P. articulata, P. tamarugo, etc. in Argentina, Chile, Peru, Mexico, and Hawaii. Short, shrubby legumes of the genus Dalea should be collected in southwestern United States, Tephrosia in Texan-Mexican area, and Zornia in Sahelian Africa. Cactus genera such as Opuntia and Cereus should be collected in southwestern United States. During these collections, attempts should be made to collect for as much diversity as possible as well as to collect for economically desirable characteristics, e.g., heavy pod production, size and sweetness of fruit, large trees, presence of large amounts of leaf litter, and presence or absence of thorns. The plant should be collected over its entire geographical and ecological range.

All of the collections should be evaluated in uniform treated plantations with a minimum of 4 replicates of 5 trees per replicate. For the trees, height measurements should be performed the first year, stem diameter measurements for biomass estimation should be performed every year, and pod productivity

measurements should continue indefinitely. One germplasm planting should be evaluated in a 300 and 500-600 mm annual rainfall regime in the India-Pakistan region, in East Africa, in West Africa, in the United States, and in South America. The purpose of the American planting would be to provide American researchers with biological research material and exposure to these different cropping systems. An additional site should be located near a seacoast to use seawater irrigation to screen for salt tolerant germplasm.

The Hawaiian Niftal rhizobia collection should be evaluated for rhizobia for the legumes and techniques developed to insure effective nodulation of field plantings. Soil samples from native stands might contain rhizobia with unique properties and should be used to inoculate native plants for comparative purposes.

Most Acacias (Seif-el-din, 1980) and probably all Prosopis (Simpson, 1977) are obligately outcrossed. As a result trees will not breed true from seed and clonal propagation techniques will be required. Both tissue culture propagation and traditional rooting of cuttings should be examined. Rooting of stem cuttings is possible for Prosopis with difficulty. To achieve success in rooting of cuttings required for large-scale plantings, a thorough evaluation of rooting of cutting methods including evaluation of mist, atomized fogging, and tent humidification devices, screening trials of hormone mixtures, evaluation of out-of-doors and greenhouse grown stock, and use of growth chambers to determine optimal light, temperature and humidity level for cuttings will be required.

Most annual legumes are highly self-fertile and breed true to type.

These selections will not require vegetative propagation but germplasm multiplication areas will be required.

Laboratory analysis of crude protein, sugar and fiber should be conducted on pods, fruit or other economically important plant structure.

Single tree selections should be made from the germplasm nursery on the basis of 1) height and biomass determinations, 2) pod production and pod chemical characters, 3) presence or absence of thorns, and 4) other characteristics deemed important. These selections should be clonally multiplied and re-evaluated with 4 replicates of 0.1 ha minimum sized plots per selection. Sufficient quantities of the clonally multiplied material should be made to allow distribution to requesting individuals and organizations.

Once reasonably productive single tree selections of the leguminous trees and cactus mentioned previously have been developed they should be compared with advanced strains of jojoba available from Yermanos and Hogan, from guayule available from USDA, and from saltbush available from McKell and others. The comparative advantages and relative resource requirements for these crops should then be evaluated as monocultures and polycultures. The large nitrogen fixing trees P. cineraria and A. albida should be evaluated in various spatial configurations with the staple crops millet, sorghum and peanuts. The short shrubby and herbaceous legumes of the genera Tephrosia, Zornia, and Dalea should be evaluated with jojoba, guayule, saltbush, and opuntia.

As with all crops, solutions to weed problems, insect problems and cultural practices will have to be developed for these ecosystems. Herbicide

and cultivation methods should be examined for weed control and insecticide, biocontrol, and integrated pest management should be evaluated for insect control. Harvesting, pruning, plant spacing, and planting methods also require development.

It has been the experience of Dr. Yermanos with jojoba and of this author with mesquite that once genetically superior strains have been produced the demand for the strains and the technology associated with them will greatly outstrip the supply. Elderly ladies with 100 square feet o desert in their backyard in Yucca Valley, California, business executives, and ministers of agriculture in arid developing countries will ask the project leader to visit their backyard or country from one day to six months to set up the appropriate technology. It is imperative to develop sufficient plant material for further multiplication and to train extension personnel who can assist farmers, businessmen, or government leaders to develop the appropriate technology. Short extension courses provided by staff involved in germplasm nurseries and evaluation centers would be an ideal method of disseminating the information that is developed.

The staffing of the germplasm nursery and evaluation centers would require a Ph.D. project leader for: 1) *Acacia tortilis* and *A. seyal*, 2) *Acacia albida*, 3) *Prosopis cineraria*, 4) *Parkia biglobosa*, 5) the American *Prosopis* species, 6) the shrubby and herbaceous legumes, 7) the cactus, 8) the atriplex complex, 9) quayule, 10) jojoba, and 11) other overlooked species. A central tissue culture and clonal propagation center should develop the techniques for clonal propagation and have at least two Ph.D.'s, six B.S.'s and/or master's level technicians and 6-8 support personnel

preparing media, washing dishes, etc. Each research center should have two B.S. or M.S. full-time personnel and 6 non-skilled laborers rooting cuttings and/or multiplying germplasm for research and/or further distribution. The availability of a statistician and computer for analysis of field experiments is essential.

A major effort will be required to develop support facilities for research in arid developing countries of Africa. Telephone service, mail service, ground transportation, and freight services to and from Europe are too unreliable to make effective research possible in East Africa and perhaps other countries. It is absolutely essential that the plant research be conducted in the climate and on the soils where it is to be utilized and this requires development of support services for the research.

VI. CONSTRAINTS FACING DEVELOPMENT AND IMPLEMENTATION OF ARID ADAPTED PLANT PRODUCTION TECHNOLOGIES

There are no major or theoretical scientific constraints to utilization of these technologies, but applied research efforts are required in several areas. Techniques need to be developed for clonal propagation of all materials described here by both rooting of cuttings and tissue culture. Planting techniques, and greenhouse and field cultural practices need to be optimized. A continued effort to identify and propagate better genetic selections is required.

Environmental constraints to development of these systems are minimal, as increased vegetation in arid developing countries has the effect of halting desertification.

There are serious cultural constraints to development of perennial production systems since the perennial vegetation in Sahelian Africa is viewed as community-owned (Thomson, 1980). Thus, the pods or fruits from trees can be taken by anyone, even if the trees are on privately-owned land.

Similarly, people can cut branches from non-protected species of trees for fuelwood even if the landowner planted the trees for his own fuelwood use. Freely-roaming goats which eat young seedlings constitute a major problem in the establishment of perennial production systems. Control of the movement of goats is probably an insoluble cultural problem and thus goat-proof devices for protection of young seedlings will have to be devised.

Political constraints for the development of these technologies stem from politicians' and bureaucrats' unfamiliarity with use of these perennial

crops. This is most accurately described in Pelissier's explanation of why Acacia albida is not more widely used in West Africa (translation from Felker and Bandurski, 1979).

"One cannot help but be astonished that an agronomic research center established to study the Serer people (in Senegal, West Africa) is not more interested in the methods and effectiveness of native farming systems. These researchers ignore the milieu of naturally-regenerating Acacia stands by which they are surrounded. This mark of indifference and incomprehension for African techniques is too often manifest by European specialists or those trained in Europe. In order to promote their own cultural values, these researchers use the terms 'modern' and 'scientific' as if laboratory and field techniques are completely inapplicable, for social or economic reasons, to the truly native farming systems. Acacia albida suffers from the division of the technical services. The agronomist regards the presence of the tree in the field as an adversary to be eliminated. The forester is not interested in the tree because Acacia albida does not grow in what could be termed a forest and is, therefore, not capable of being dealt with by standard sylviculture concepts. The role of Acacia albida, including its growth and germination conditions, illustrates its marvelous character which cannot be dissociated from its genuine agricultural setting and illustrates the necessity for deep-seated action to aid the farming population. At this time in our intimate knowledge of political techniques for rural management, an end must be placed to the absurd division of agriculturally-related disciplines which encloses agricultural development specialists. It is not lack of concern in the develop-

ment specialists which causes this problem but rather their over-specialized training, and above all the administrative structures which thwart their action and hinder an integrated development plan which alone can be effective."

VII. EFFECT OF TECHNOLOGY IMPLEMENTATION ON CAPITAL, LABOR, AND LAND REQUIREMENTS

The intial inputs required for these systems are low but the output/input ratio of the system is high, such that yield increases will tend to stimulate more investment of the technology. For example, assume a farmer will plant 1 ha with 200 *Prosopis* trees. The wholesale seedling cost should be approximately $0.15, requiring an outlay of $30. These seedlings could be planted on his own land with only a shovel, and some buckets for watering the seedlings after transplant. If planted in regions at 500 mm annual rainfall, at year 10 the tree should be producing 4,000 kg of pods per hectare (Felker et al., 1980). These pods typically have protein and nitrogen contents of 12.5 and 2.0 , respectively (Becker and Grosjean, 1980). Thus, the pods contain 80 kg of N which is worth $40 at today's price of $50 per 100 kg of N. To achieve capture of 80 kg of N in pods from chemical fertilization, at least double the amount of nitrogen in the pods, or 160 kg of N would have had to have been applied. Thus, the cost to provide the nitrogen found in the pods would have been $80 per year. Recalling that the farmer's cash outlay for seedings was $30, his annual return on the seedling investment from nitrogen alone is 270%. His $30 investment in seedlings probably would be returned from 60 kg of N fixed by the plants in 2 to 3 years.

Because most of these trees are outcrossed and planted only once every 30-50 years, it would be most advantageous to plant clonal material from outstanding individual trees. Thus, the commercial tree nurseries would be required to supply young trees to villages in the countryside.

Hopefully, farmers would recognize the importance of obtaining high quality clonally propagated seedlings for long-term plantings, and would support commercial village level nurseries that would be an effective vehicle for delivery of superior genetic stock to the local population.

Fertilizers other than nitrogen would be required. Phosphate and, to a lesser extent, sulfate fertilizers stimulate nitrogen fixation in legumes and would be a worthwhile investment. Phosphate fertilizers have approximately the same unit price as nitrogen fertilizers but only 10% as much phosphate as nitrogen fertilizers would be required. Annual crops such as maize may capture (Olsen _et al._, 1970) only 40-50% of applied fertilizer partially because of leaching beyond the root zone. Shrubs and trees such as _Acacia_, _Prosopis_, and jojoba commonly root to 10 meters (Felker, 1979) and would achieve higher capture ratios of applied fertilizer. There is no reason to suspect that pesticides would be required any more or less than other kinds of systems since insects would be just as likely to attack tree or shrub crops as annual crops. Due to the low till or no tillage requirement for many of these shrub and tree-based production systems, agricultural machinery requirements would be expected to be less than those of conventional plant production systems. The harvesting of the majority of plant production systems in arid developing countries is by hand. With increased yields of traditional crops stimulated by association with leguminous companion crops, the demand for labor at harvesting time

will increase. Production of large quantities of tree legume pods, jojoba nuts and fuelwood will also increase the labor demand for harvesting operations.

The low requirements for tillage machinery, and the lack of a nitrogen fertilizer requirement will greatly reduce credit requirements for these two traditionally high credit requiring areas. On the other hand, the several years' wait prior to harvest of perennial crops will require credit to pay for the seedling costs.

VIII. IMPACT OF WIDE-SCALE TECHNOLOGY IMPLEMENTATION ON THE SOCIOECONOMIC STRUCTURE OF AGRICULTURE IN DEVELOPING COUNTRIES

Most of the plant systems (technologies) discussed in this report are widely used by subsistence farmers in the developing countries. The plants currently used are primarily volunteer seedlings of unselected genetic stock which the farmers may prune and care for (Pelissier, 1967). This system is comparable to use of unselected races of maize and wheat, as would have been done in the late 1800s in the United States and Europe. Placing these widely-used, but scientifically unmanipulated plants into a research and development framework probably can be expected to give yield increases similar to that achieved by first inbred and then hybrid lines of maize and other cerals. Vigorous, naturally-occurring tree legume hybrids have been observed and clonally-propagated by this author and demonstrate the ease with which hybrids can be formed. Maize yields increased from less than 20 bushels per acre in the early 1900s to close to 100 bushels per acre at present. The plant systems described here probably have the potential of achieving the same yield increases. Perhaps a two- to three-fold increase in plant productivity can be expected in 5

to 15 years and a five- to ten-fold increase in 50 to 100 years. Unlike maize, these systems are based around nitrogen-fixers and will not require fossil-fuel-derived and energy-intensive nitrogen fertilizers.

Assuming these kinds of yield increases in tree legume pod production, fuelwood production, cash crop production, soil fertility and ensuing staple food production, returns to farmers can be expected to increase in the same approximate fashion. As the farmers income rises, his demands for goods and services will rise and stimulate the economy as a whole. A greater tax base will then be available to support more roads, schools, and health services, which will in turn decrease unemployment. The economy of a country with an agrarian society is inextricably tied to the primary productivity of the ecosystem. As long as substantial progress is being made towards achieving the economic goals of the rural population, the population probably will be satisfied and there will be no economic grounds fostering political instability. Past efforts to stabilize the political systems of arid developing countries, such as Iran, with military hardware systems have proven futile. It is imperative to develop plant systems which have the capability of directly impacting the smallest farmers on the local level to increase his well being and decrease economically fostered political unrest.

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PAPER NO. 1. MULTIPLE CROPPING SYSTEMS: A BASIS FOR DEVELOPING AN ALTERNATIVE AGRICULTURE

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ABSTRACT

A general discussion of the concept of Multiple Cropping is presented, including a description of the different types of systems, and the advantages and disadvantages of their widespread use, both biologically and socioeconomically. These systems are designed to achieve the intensification of agricultural production not only in terms of yields per unit area, obtained through the more efficient use of space and time.

Examples of yield increases with Multiple Cropping systems are expressed in terms of Relative Yield Totals (RYT) or Land Equivalent Ratio (LER) where the production per unit area with the multiple cropped field is greater than the sum of equivalent areas planted to the monocultures. This increase in production is explained in terms of higher overall efficiency of resource use.

Specific cases of the effects of multiple cropping systems on resource use, conservation, and management are discussed, including: light, soil, water, pests, diseases, weeds, crop interactions, and space and time. The special case for agroforestry as a multiple cropping system is discussed in more detail for the combinations of trees with crops and pastures.

In conclusion, the socio-economic implications, both

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advantageous and disadvantageous, are discussed, considering that the perspectives for multiple cropping systems in agriculture in the United States show great potential. Research needs to be oriented towards testing these alternatives.

MULTIPLE CROPPING SYSTEMS: A BASIS FOR DEVELOPING AN ALTERNATIVE AGRICULTURE

By: Dr. Stephen R. Gliessman.

INTRODUCTION

Multiple cropping is not a new form of agricultural technology but instead an ancient means of intensive farming that has been practiced in many parts of the world as a means of maximizing land productivity in a specific area in a growing season. Generally speaking we observe the practice of planting two or more crops on the same field in a year more commonly in tropical regions where more rainfall and higher temperatures spread over the year are more favorable for continual crop production. As population has increased, increasing the need for agricultural production, the use of multicropping systems is more prevalent. Though the history of multiple cropping is old, the concept has received very little attention from agricultural scientists, and what limited interest exists has come about very recently.

One may ask why this interest has begun to increase so dramatically in such a short time. Food shortages in many parts of the world, as well as the threat of insuficient supplies for others in the near future, continues to stimulate more intensive agricultural investigation in a search for more productive alternatives. As a consequence it appears that we are about to embark on a new phase of agricultural research. Exactly what form it will take is still not known, but the reasons for this new approach are rapidly becoming apparent.

First, we have recently begun to observe a leveling off in yield increases brought about by the types of genetic manipulation that gave us such rapid and impressive yield increases during the "Green Revolution". It is like we have reached a "yield plateau" with the current lines of research and crop selections. Large scale single varieties (for example, some of the International Rice Research Institute-IRRI- varieties of rice most widely utilized) with broad adaptability, produced major breakthroughs in yields, but it appears that such broadly adapted varieties have almost reached their maximum yield potentials. These varieties have been distributed widely, but in many areas with specific soil and climatic conditions, they have not performed as well as hoped, especially on land more difficult to mechanize or irrigate. Thus it is becoming obvious that we must begin to look for varieties with more specific adaptability and selected for specific environments, or else consider alternative cropping systems.

Second, most of the dramatic yield increases during the past few decades have been on the best agricultural lands where soils are good and water control is easily brought about. Future increases in production, therefore, will have to come about through a new and innovative way of managing these highly productive lands, as well as looking for methods of making more marginal lands increasingly productive. Only 20% of Asia rice land, for example, is irrigated, and the new high yielding rice varieties (and also high requiring of fertilizers, water use, and pest control) have not penetrated much beyond this boundary[1].

The third factor is the oil crisis. Oil prices continue

to soar, and with them, the cost of fertilizers, pesticides, - and fuel needed to build and run farm equipment and move irrigation water. Costs continue to mount for those inputs most - responsable for having been able to achieve such dramatic yield increases during the "Green Revolution", and we are faced with the necessity of having to consider other alternatives that -- might allow us to substitute these high cost inputs with innovative biological or agronomic practices and varieties. Multiple cropping offers one of the most important and promising of these alternatives.

CONCEPTS AND DEFINITIONS

Multiple cropping systems involve management practices where the total crop production from a single piece of land is - - achieved thorough growing sole crops in close sequence, growing several crops simultaneously, or combining sole and mixed crops in some sequence. The most important aspect of multiple cro -- pping is the intensification of crop production into aditional dimensions other than just the cropping area and the yield achieved there. Multiple cropping includes the dimensions of time - and space; for example when two crops share the same space at the same time. Based upon this idea of intensification, a classification of types of multiple cropping systems is presented in Table 1. It should be noted that special emphasis is placed on the distinction between intercropping, where two or more - - crops are grown at the same time, and sequential cropping, where two or more crops are grown on the same piece of land, but - one following the other. Some additional terms used in multiple cropping jargon are presented in Table 2. Agroforestry, as a - particular type of intercropping system , will be discussed in

more detail below. Also, it is understood that "mixed cropping", "polyculture," and "multiple cropping" are defined equally in this review and will be used interchagably. By combining different aspects of simultaneous and sequential cropping systems, it is possible to visualize a truly complex pattern of different multiple cropping systems. This classification will be used throughout the following discussion, based upon a recent symposium sponsored by the American Society of Agronomy, in support of the need that currently exists to standardize terminology[3].

THE BASIS OF MULTIPLE CROPPING

A. Yield advantages of crop mixtures

In areas on the world where multiple cropping is a common aspect of agroecosystem management, it has been shown generally that productivity is more stable and constant on the long term[1, 4].

The farmer is often able to achieve a combined production per unit area greater with a crop mixture as compared to an equal area divided among the separate crop units. In such cases the Relative Yield Total (RYT) is greater than 1.0. It may be that each crop in the mixture yields slightly less that the monocultures, but the combined yield of the mixture of crops on less total land area is the important aspect.

In a study by Trenbath[7], the results of 572 comparisons of crop mixtures demonstrate that the majority (66%) had RYT's close to 1.0, indicating no distinct advantage to the mixture (Figure 1). On the other hand, 20% of the mixtures had RYT's greater than 1.0, ranging up to 1.7, indicating advantages to the mixtures, and only 14% had less than 1.0, indicating distinct disadvantages. It must be remembered that most of the cases studied were experimental planting, and not many cases of actual multiple cropping systems. Farmers would tend to chose the systems which yield more, as we have observed in traditional agroecosystems in the lowland tropical areas of southeastern Mexico[5,6].

TABLE 1. Definitions of the Principal Multiple Cropping Patterns.

Multiple Cropping: The intensification of cropping in time and space dimensions. Growing two or more crops on the same field in a year.

Intercropping: Growing two or more crops simultaneously on the same field per year. Crop intensification is in both time and space dimensions. There is intercrop competition during all or part of crop growth. Farmers manage more than one crop at a time in the same field.

- Mixed intercropping: Growing two or more crops simultaneously with no distinct row arrangement.
- Row intercropping: growing two of more crops simultaneously with one or more crops planted in rows.
- Strip intercropping: Growing two or more crops simultaneously in different strips wide enough to permit independent cultivation but narrow enough for the crops to interact agronomically.
- Relay intercropping: Growing two or more crops simultaneously during part of each one's life cycle. A second crop is planted after the first crop has reached its reproductive stage of growth but before it is ready for harvest.

Sequential Cropping: Growing two or more crops in sequence on the same field per year. The succeeding crop is planted after the preceding one has been harvested. Crop intensification is only in the time dimension. There is no intercrop competition. Farmers manage only one crop at a time in the same field.

- Double cropping: Growing two crops a year in sequence.
- Triple cropping: Growing three crops a year in sequence.
- Quadruple cropping: Growing four crops a year in sequence.
- Ratoon cropping: Cultivating crop regrowth after harvest, although not necessarily for grain.

Source: Andrews and Kassam (1976)[2].

TABLE 2. Related Terminology Used in Multiple Cropping Systems.

Single Stands: The growing of one crop variety alone in pure - stands at normal density. Synonymous with "solid planting", - "sole cropping". Opposite of "multiple cropping".

Monoculture: The repetitive growing of the same crop on the same land.

Rotation: The repetitive growing of two or more sole crops or multiple cropping combinations on the same field.

Cropping Pattern: The yearly sequence and spatial arrangement of crops, or of crops and fallow, on a given area.

Cropping System: The cropping patterns used on a farm and their interactions with farm resources, other farm enterprises, and - available technology that determine their makeup.

Mixed Farming: Cropping systems that involve the raising of - crops and animals.

Cropping Index: The number of crops grown per annum on a given area of land x 100.

Relative Yield Total (RYT): The sum of the intercropped yields divided by yields of sole crops. The same concept as land equivalent ratios. "Yield" can be measured as dry matter production, grain yield, nutrient uptake, energy, or protein production, as well as by market value of the crops.

Land Equivalent Ratios (LER): The ratio of the area needed under sole cropping to the one under intercropping to give equal amounts of yield at the same management level. The LER is the sum of the fractions of the yields of the intercrops relative to their sole-crop yields. It is equivalent to RYT, expressed in commercial yields.

Income Equivalent Ratio (IER): The ratio of the area needed under sole cropping to produce the same gross income as is obtained from 1 ha of intercropping at the same mangement level. The IER is the conversion of the LER into economic terms.

Source: Sanchez (1976)[3].

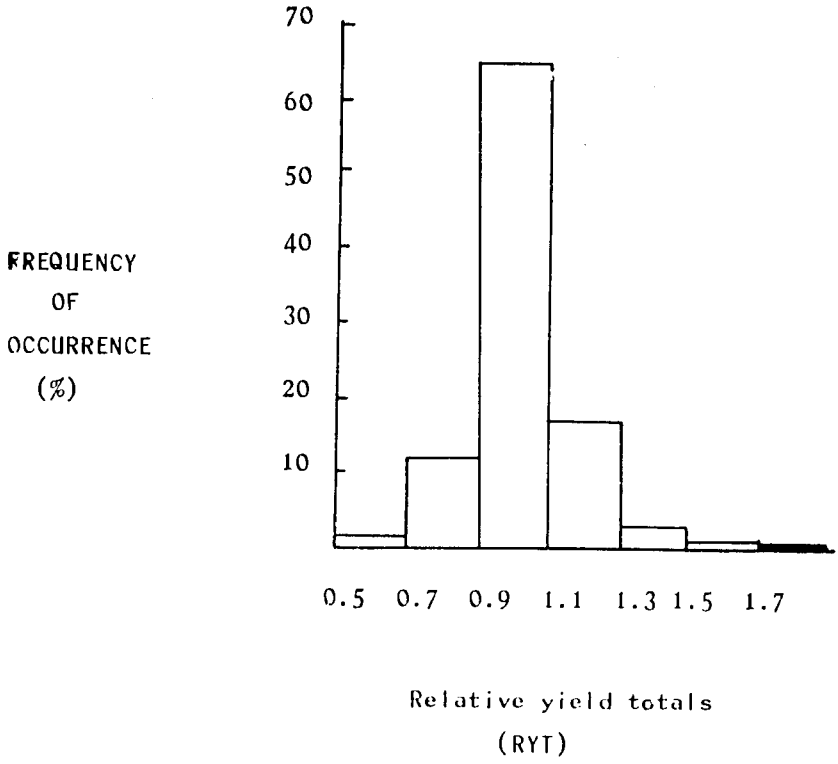

FIGURE 1. Distribution of the relative yield totals of mixtures based on 572 published experiments. From Trenbath (1974).[7]

The fact that advantageous mixtures do exist demonstrate the need for detailed research in order to take proper advantage of such systems as alternatives in the near future. But -- for such systems to be considered as actual alternatives we need to understand thoroughly the biological and agronomic basis responsable for the observed response, as well as the advantages and disadvantages to their use. Before beginning a discussion of each aspect, a basic outline of such characteristics is presented, separated broadly into biological and physical aspects on the one hand (Table 3) and socio-economic aspects on the -- other (Table 4). In many cases it is understood that there may be overlap between the two classifications, yet is is hoped -- that in the course of the following discussion that such aspects will be clarified.

B. General Resource Use:

The most commonly accepted reason for why it is possible to obtain better yields with crop mixtures is due to the fact that the component crops differ enough in their growth requirements that overlap does not take place, or at least is greatly reduced. Such combinations of components can be said to be "complementary"[9].

TABLE 3: Comparative listing of the advantages and disadvantages of multiple cropping systems as compared to sole-cropping - or monoculture systems, in regards to biological and physical - aspects of the agroecosystem (priority not established).

A. Advantages:

1) It is possible to obtain a better use of vertical space and time, imitating natural ecological patterns in regards to - structure of the system, permitting a more efficient capture of solar energy and nutrients.

2) Greater amounts of biomass (organic matter) can be returned to the system, sometimes even of a better quality.

3) There exists a more efficient circulation of nutrients, including their "pumping" from the deeper soil profiles when - deeper rooted shrubs or trees are included.

4) Damaging effects of wind can sometimes be reduced.

5) Systems very appropriate for (but not restricted to) marginal areas or areas with considerable variability, because multiple cropping systems can better take advantage of variable -- soil type, topography, and steeper slopes.

6) Multiple cropping systems are not as subject to variability in climatic conditions, especially extremes of rainfall, - temperature, or wind.

7) Reduction of evaporation of water from the soil surface.

8) Increase in microbial activity in the soil.

9) Avoidance or reduction of surface erosion of the soil -- through physical protection.

10) Fertilizer use can be more thorough by the more efficient capture of nutrients by a more diverse and deeper root structre in the system.

11) Possible to improve soil structure (more staple soil -- aggregates), avoiding the formation of a "hard pan", as well - as promoting better aeration and filtration.

12) Legumes (as well as a few other plant families) are - - able to fix and incorporate nitrogen into the system.

13) Heavier mulch cover over the soil aids in weed control, as well as different physical benefits.

14) Better oportunities for biological control of insects and diseases.

15) Crop mixtures better permit the functioning of complex mutualisms and beneficial interactions between organisms.

16) Better use of time, with more crops per unit time in -- the same area.

B. Disadvantages:

1) Competition between plants for light.

2) Competition between plants for soil nutrients.

3) Competition between plants for water.

4) Possibility for allelopathic influences between different crop plants due to plant produced toxins.

5) Harvesting of one crop component may cause damage to the others.

6) It is very difficult to incorporate a fallow period into multiple cropping systems, especially when long lived -- tree species are included.

7) It is sometimes impossible, and many times very difficult, to mechanize multiple crop systems.

8) Increase in evapotranspiration loss of water from the -- soil, caused by greater root volume and larger leaf surface area.

9) Possible over-extraction of nutrients, followed by their subsequent loss from the system with the increased exportation of agricultural or forest products.

10) Leaf, branch, fruit, or water-drop fall from taller elements in a mixed crop system can damage shorter ones.

11) Higher relative humidity in the air can favor disease outbreak, especially of fungi.

12) Possible to favor a proliferation of harmful animals (especially rodents and insects).

TABLE 4: Comparative listing of the advantages and disadvantages of multiple cropping systems as compared to sole-cropping monoculture systems, in regards to social and economic aspects of the agroecosystem (Priority is not established).

A. Advantages:

1) Dependence on only one crop is avoided, such that the great variability in prices, market, climate, and pests and diseases do not have such drastic effects on economic outcome of the cropping system.

2) Less need to import energy to the system, as well as pay for externally produced materiales or depend on machinery.

3) Wildlife is favored, such that with a rational exploitation it can constitute an important source of protein.

4) Reduction in the outlay for fertilizers.

5) There is much greater flexibility of the distribution of labor over the course of the year.

6) Possible to recover investments in much less time, especially in programs of tree production combined with short term agricultural crops.

7) Availability of harvest over a much longer period of time, if not one crop, at least of a series of crops in sequence.

8) In areas and times of high unemployment, multiple cropping systems can occupy much more labor.

9) The farmer of little economic resources can produce a -

large variety of useful products, thus lowering the outflow of funds, such as firewood, construction materials, flowers, honey, crops for home consumption, all of course depending on the type and complexity of the multiple cropping systems.

10) Certain multiple cropping systems permit a gradual change in more destructive farming practices to more appropriate - technologies, without a drop in productivity.

11) Promote a return to the land, as well as a maintenance there, of the agriculturalist.

12) In systems which include trees and/or animals, such components can constitute a type of "savings" for the future, while short term crops satisfy immediate needs.

13) Because of their diverse nature, multiple cropping systems - promote interdisciplinary activities, stimulating interchange and group activities, leading to more social cohesion on the long term.

B. Disadvantages:

1) The systems are more complex and little understood agronomically and biologically. Statistical designs for experimental analysis are much more complex.

2) In some cases yields are lower, obtaining only a subsistence level production.

3) In many actual economic systems, multiple cropping is not considered to be economically efficient, due to the complexity of activities necessary to make them function.

4) Normally a greater need for hand labor, which in certain economic systems, is considered to be a disadvantage.

5) Some mixed crop systems don't offer sufficient stimulus to lower income farmers to raise their standard of living.

6) For producers with limited economic resources, it may take longer to recover the entire initial investment.

7) In order to install multiple cropping systems, one encounters opposition from the prevalent social, economic, and political system. In order to permit the new focus in productions may result to be very difficult.

8) There is a shortage of trained personnel (technological as well as scientific) capable of installing and managing multiple cropping systems.

9) There is a general lack of knowledge or understanding of multiple cropping by "decision makers", affecting especially funding for research to make such systems viable alternatives.

A mixture makes better overall use of available resources. Negative influences (such as competition for light, water, or nutrients) between the component members of a successful multiple cropping system would be considerably reduced. In order to maximize the advantages of such a system, it is important to maximize as much as possible the degree to which one component complements another. With a greater range of requirements between different elements of the mixture, theoretically the greatest advantages would be achieved.

One of the principle ways to achieve such complementary is by varying the crop components temporally, using sequential planting to achieve a multiple cropping system which insures that antagonistic interactions between the components could be avoided. Following a crop with another that has different growth requirements would enable the maximum use of resources. This concept has been used for a long time and forms the basic rational behind crop rotations. The most advantageous use of soil, for example, would be to follow one crop with another that requires different soil nutrients. A subsequent crop would thus be able to absorb fertilizer residues left over by the previous crop, as well as reducing the need for fertilizer applications for the following. For the Eastern United States it has been concluded[10] that such double cropping systems as soybeans after wheat or barley, or the production of silage crops after grain corn or sorghum, can function well. Depending on the length of the growing season numerous sequential plantings can take place during a single year. Such systems require very special management, with timely harvest, use of proper varieties, alteration of the standard planting distance, special selection of herbicides so as to not create antagonisms or residual effects, and --

also the possibility of using no-tillage planting with certain of the row crops.

Another form of complementing different crop components is through an intensification of the sequential cropping system -- enough to achieve an intercropping system based on relay planting. The same avoidance of overlapping plant growth requirements is gained, as well as the avoidance of direct plant interference, by planting a second crop after the first one has completed the major part of its development, but before harvest has taken place. Relatively little research on relay cropping has been done in the United States, and most often has demonstrated little if any yield advantage (for example, corn into wheat or barley[10]).

On the other hand, in Mexico and Latin America, inumerable examples of relay planting with defintite yield advantages have been reported, especially for corn and beans.[3,11]

Again, the important, and as yet little studied, aspect of relay planting success depends on the correct combinations of timing and varieties so as to avoid shading, nutrient competition, or inhibition brought about by toxicity produced by the decomposition of a previous crop residue.[12]

Finally, the maximum complementarity is achieved by growing two or more crops simultaneously, either in rows, strips, or mixed, but taking advant-age of the spatial arrangement of the different crops, as well as knowledge of their individual growth requirements. Again, most examples of such systems come from outside the United States. One particularly well-documented example is a traditional corn, bean, and squash system in Tabasco, Mexico.[13]

Corn is planted at a density of 50,000 plants/ha, climbing beans in the same hole at a density of 40,000 plants/ha, and the squash intermixed among the rows of corn and beans at a density of 3,330 plants/ha. All are planted at the same time in this case. Beans begin to mature first, using the corn stalks for support; the corn matures second; the squash is the last to mature. Aerial space is divide such that corn occupies the upper canopy, beans the middle, and squash covers the ground in between. Better weed control is achieved, and insect pests are largely controlled by natural enemies (work in progress). Corn yield was significantly higher for the polyculture as compared to different densities of monocultures, but beans and squash suffered a distinct yield reduction (Table 5). Interestingly, the LER (Land Equivalent Ratio) value of 1.73 tells us that the sum of the yields in the mixture can only be equalled in monoculture by planting 1.73 times the area divided proportionally among the three sole crops. The advantage of producing a greater yield altogether on less land is obvious. The much higher total yield of biomass in the mixture is also very important, because much of this organic matter is returned to the soil, bringing important consequenses in soil fertility, humidity conservation, microbial activity, etc., all related to the success of the following crops. Currently, studies are being carried out to try to determine if the higher yields come about due to more efficient resource use, or if in fact some mutually beneficial effect between crop components is taking place, for example, the bean producing nitrogen that the corn can absorb.[14] This example demonstrates the enormous potential that multiple cropping systems offer for the future.

TABLE 5: Yields of corn, beans, and squash (kg/ha) planted in polyculture as compared to low and high densities of each crop in monoculture. Data are presented for grain or fruit yields, as well as for total biomass.

	CROP	MONOCULTURES				POLYCULTURE
Grain or Fruit Yields	Corn: Density	33,300	40,000	66,600	100,000	50,000
	Yield	990	1,150	1,230	1,170	1,720
	Beans: Density	56,800	64,000	100,000	133,200	40,000
	Yield	425	740	610	695	110
	Squash: Density	1,200	1,875	7,500	30,000	3,330
	Yield	15	250	430	225	80

	CROP	Total biomass dry weight				
Biomass Yields	Corn	2,822.9	3,119.4	4,477.5	4,870.9	5,927.2
	Beans	852.9	895.1	842.6	1,390.4	253.1
	Squash	240.9	940.9	1,254.0	801.9	478.3
					Total Polyculture Biomass	6,658.6

$$\text{LER (Land Equivalent Ratio)} = \frac{\text{Sum of yields of each polyculture}}{\text{Sum of highest yield each monoculture}}$$

$$\text{LER} = \frac{1720}{1230} + \frac{110}{740} + \frac{80}{430}$$

$$\text{LER} = 1.73$$

Source: Amador, 1980.[13]

C. Specific Resource Utilization, Conservation and Management:

A more intensified land-use system of agriculture will certainly put greater pressures on the available natural resources of our crop and rangelands. Considerable discussion exists at the moment as to the harmful or beneficial aspects of this intensification; and a review of some of the more important aspects can aid greatly in understanding this problem:

1) Microclimate and light: In any agroecosystem a very important aspect of productivity is related to the amount of light converted directly to carbohydrate, hence to vegetative material, through photosynthesis. Each cropping system has a photosynthetic potential, based upon its capacity of conversion[15]. Monocultures, especially of annuals, generally have a much lower potential, because either the plant cover is not complete, or else the soil is occupied only during the growing season, leaving the surface bare of photosynthetic capacity until the planting of the next crop. Light is not like other resources where a reservoir exists, and the plants tap it as the need arises. Rather, it has to be used when it is instantaneously available, thus leaf area becomes a very important factor. A multi-layered polyculture would be able to capture much more light energy, raising efficiency, and potentially, production.

Apart from the quantity of light absorbed, its quality is also important. Light that has passed through a leaflayer is altered as certain light waves are absorbed and others penetrate. Plants in the lower layers of the canopy need to be adapted to this alteration - an aspect well studied only in natual vegetation[16]. For cropping systems, light has been studied in detail only for monoculture systems[15] from the point of view of in -

creasing effective photosynthetic leaf area for the single crop. By manipulating species with different light requirements, greater phosynthetic potential can be achieved. This is made - - easier by using dominant species in the polyculture which do not develop a closed canopy, allowing considerable penetration to - the next levels, terminating with the most shade-tolerant plants in the lowest levels. In such a system, the soil surface is -- effectively covered completely by plants. This manipulation of plant architecture has been studied in detail ecologically[17] - and has considerable application in multiple cropping systems.

By insuring that a greater percentage of light is absorbed by the leaf canopy, other aspects of the crop microclimate are also affected. Crops in the lower layers would be subject to - less water stress, but care must be taken that root system competition for water does not become a problem. Water loss by - soil surface evaporation could be reduced, but transpiration - from leaf surfaces might be overly increased in the crop mixture. Soil temperatures would be lowered, an advantage especially in warmer and drier environments, aiding in the conservation and buildup of organic matter in the soil. Protection -- from wind would be provided for the lower canopy species. Care would need to be taken that the increased humidity in the lower canopies does not promote higher incidence of certain diseases, especially fungi, either of the roots or foliage.

2) Soil-Plant Relations in Multiple Cropping Systems:

Any time that we try to combine 2 or more crops simultaneously in one area, there exists the possiblity for complex - interactions between the plants and their soil environment[3].

When total complementarity is achieved, the roots of the component species occupy different soil horizons, reducing considerably the potential competition between species, and increasing the efficiency of total nutrient uptake. In combinations of deep-rooted with shallow-rooted species, especially when trees are planted with grasses or annual crops, the trees are capable of absorbing uncaptured nutrients as they are leached into the soil. Then, through their transport to foliage, they can be deposited on the soil surface again with leaf drop[18].

Intercropping systems have been shown to definitely extract more nutrients from the soil than do single crop plantings per unit area of land. In a very complete study with corn and pigeon peas in Trinidad[19] (see Table 6), various parameters of crop response were measured. Highest single crop yields of grain were obtained in the monocultures, but by summing yields of the two crops planted mixed or in intercropped rows, relative yield totals (RYT) were always higher. Total dry matter production was higher in the mixtures as well. The most interesting aspect is the uptake of nutrients (N, P, K, Ca, & Mg). The total uptake is based on the sum of the two crops together, and in all cases the total nutrient content of the dry matter production was higher for the mixtures, demonstrating the greater extractive capacity of the multiple cropping system. Apparently, for corn and pigeon peas, row intercropping gave the best results, demonstrating that at times two crops together can negatively influence each other, as described in Table 3, but the total yield summed makes up for the reduction. Each mixture needs to be examined in detail.

The greater uptake of nutrients in crop mixtures is said -

TABLE 6: Effects of mixed and row intercropping on yields and nutrient uptake of Corn (C) and Pigeon Peas (PP) in St. Augustine, Trinidad, expressed as relative yield totals (RYT).

Parameter	Sole Crop		Mixed Intercrop			Row Intercrop		
	C	PP	C	PP	RYT	C	PP	RYT
Grain Yields (tons/ha)	3.1	1.9	2.0	1.7	1.54	2.0	1.8	1.78
Total Dry Matter (tons/ha)	6.4	5.1	4.2	3.8	1.40	5.0	4.9	1.74
N uptake (kg/ha)	66	119	48	100	1.56	54	127	1.88
P uptake (kg/ha)	13	6	9	5	1.52	11	7	2.01
K uptake (kg/ha)	51	37	37	32	1.59	46	33	1.79
Ca uptake (kg/ha)	10	22	10	15	1.68	9	19	1.76
Mg uptake (kg/ha)	12	14	9	8	1 32	9	12	1.61

Source: Adapted from Dalal (1974)[19], cited by Sanchez (1976)[3].

to deplete the soil more rapidly, but an aspect that needs to - be considered is what proportion of this nutrient content is removed from the system with the harvest, as compared to the part reincorporated back into the system. In Table 7 an example is presented of a corn/bean polyculture as compared to the corn - monoculture. Total biomass production, as well as yield removed from the system is considerably higher from the mixture -- (10.24 tons/ha vs. 6.68 tons/ha total biomass). The percentage of this total which leaves the system is slightly lower for the mixture (61% vs. 66%), but the actual amount of organic matter returned to the soil in the polyculture (3.98 tons/ha) as compared to the sole crop (2.32 tons/ha) demonstrates that although more material is produced by the intercrop system, a greater - amount returns, possibly offsetting any increase in extraction- of soil nutrients and permitting the long term management of the system.

Another way to increase the return of nutrients to the system is to plant "nurse plants". These plants do not contribute directly to the biomass harvested and removed from the system,- but their capacity to capture nutrients and continually recycle them in the soil would be of definite advantage. Local farmers in Tabasco, Mexico, use this concept in the management of weeds,[20] leaving those that don't interfere with the crops and removing - those that are harmful. The constant cover over the soil gained by such a practice permits, apart from nutrient conservation, the maintenance of better soil structure, conservation of water, more microbial activity, and over the long run, less need for the - - application of chemical fertilizers. By including plants which "trap" nutrients, such as legumes, such benefits can be improved even more. The wide-spread use of legume trees for shade in - - coffee and cocoa plantations is a classic example[21].

TABLE 7. Biomass distribution (in tons/ha) of dry matter in a corn/bean polyculture as compared to a corn monoculture, in Tacotalpa, Tabasco, Mexico.

Crop	Roots	Crown	Leaves & Stem	Grain[a]	(A) Total	(B) Removed Matter	(B)/(A) %	(A)-(B) Total Reincorporated
Corn	0.49	0.60	2.29	4.76*				
+					10.24	6.26	61%	3.98
Beans	0.15	0.00	0.45	1.50*				
Corn Alone	0.34	0.41	1.57	4.36*	6.68	4.36	65%	2.32

[a] Weight of grain of corn is unhusked, including cob and husk, in the manner that the harvest is removed from the field in this region.

* Indicates the removed portion of the biomass.

Source: Adapted from Gliessman & Amador[5].

3) Water Use in Multiple Cropping Systems:

Any discussion of water use involves a consideration of rooting patterns. It can be supposed that in multiple cropping systems, especially with several crops with differently arrayed root systems, that a greater volume of the soil will be occupied and thus water use efficiency will be higher. This would be useful on the one hand in areas where water supplies are limited, and on the other to make more complete use of costly irrigation water. It has been proposed that cover crops in orchards stimulate deeper rooting by the trees[22]. Different peak periods of water use in the crop mixtures would avoid competition and increase over-all water use efficiency[23]. A crop such as corn which uses relatively little water in the early stages of development could be interplanted with an early maturing crop in order to take advantage of the unused moisture[24].

In areas where water is severely limiting, one would have to be careful not to plant crops with over-lapping water requirements, because in very dry years, one member of the mixture could be outcompeted by the other[25]. Combining two crops with slightly over-lapping water needs, on the other hand, could be used to an advantage in areas with widely fluctuating rainfall regimes. In a dry year, one component would be favored, and in a wet year the other, guaranteeing profitable harvests of at least one or the other every year. Studies on water availability in each region, coupled with studies of water needs of each component crop of multiple cropping systems are critical for proper management.

The important effects of multiple cropping on the conservation of water and soil are well known[26,27], primarily achieved

through the maintenance of a more complete vegetative cover over the soil. It is important to remember that apart from improving cover while the crop is growing, multiple cropping systems aim towards maintaining this cover between harvests. This is achieved by reducing the time between harvest and replanting in sequential systems, planting a new crop into another in relay cropping, and continually interplanting in an intercropped system. The use of trees, either as windbreaks, or for soil stabilization on eroded hillsides or in areas subject to desertification, can be enhanced greatly by combining them with crops or pasture grasses (see discussion on Agroforestry).

In summary, although it appears that multiple cropping systems use more water, their ability to obtain water not available to monocultures, use the water more efficiently, and contribute significantly to soil conservation, demonstrate a further potential for their more widespread use.

4) Pest, Disease, and Weed Relations:

As can be seen in Table 3, there exist possiblilities for multiple cropping systems to be both advantageous and disadvantageous in relation to problems of pests, diseases, and weeds.[28,29] The problem has to do with the great complexity of environmental factors and their dynamic interactions within the cropping systems, where capital is not available or technical assistance has not been accepted, we observe that the main means of control of pest, disease, and weeds is achieved on the one hand through biological control, and on the other through the management of a great diversity of cropping patterns, both in time and space[30].

It has been suggested that multiple cropping systems permit

such a control because they are much less subject to attack.[28,-31,32] This comes about because the mixed cropping system (1) - prevents spread of diseases and pests by separting susceptible plants, (2) one species serving as a trap crop, protecting the others, (3) associated species serve as a repellant of the pest or disease to which the other crops are subject, and (4), a greater abundance of natural predators or parasites of pests due to a higher diversity of adequate microsites and alternate prey. - However, we can site reasons for which a multiple cropping system may be more susceptible to attack: (1) reduced cultivation and - greater shading due to the presence of associated species, (2) - associated crops serve as alternate hosts, and (3) crop residues from one crop may serve as a source of inoculum for the others. All of these advantages and disadvantages can exist, and much - further study is necessary to achieve the combinations which give the most positive results.

A few examples might serve to demonstrate the specific potential of multiple cropping for biological control. In one study[34] it was shown that the planting of a locally used medicinal-herb (Chenopodium ambrosioides) in sequence with corn or beans, - reduced the incidence of nematode populations in the soil, demonstrating a potential for reducing attack on the roots of the bean and corn crops. Substances toxic to the nematodes were liberated into the soil by the herb, wherein the nematodes were inhibited. In another study, yields of cotton untreated with insecticides, but interplanted with sorghum, were 24 higher than the-sprayed monocultures. The reason was that sorghum served as microhabitats for cotton bollworm predators[35]. In another case - fall army worms on corn associated with bush beans were less a - problem than on pure-stand corn[36]. In an incidence in which - -

beans intercropped with corn were attacked less by rust as compared to beans in pure stands, it is felt that corn functions as a barrier to the dissemination of the fungal spores[37].

Weeds, on the other hand, present another problem. It has been reported that weeds are much less a problem in multiple cropping systems, especially in intercropping,[29] the idea being to occupy the space normally available to weeds, with other crops. The aggressive nature of weeds is well known[38], but recent work has begun to show that weeds can fill an important ecological role in cropping systems, by capturing unused nutrients, protecting the soil, altering soil fauna and flora, serving as trap plants for pests and disease, and changing the microhabitat to allow for high populations of pest predators and parasites.[39,40], The understanding and use of a "non-weed" concept by farmers in rural tropical Mexico[20], where each is classified according to positive or negative effects, demonstrates that we need to understand in more detail the biological functions of each component of the agroecosystem in order to establish the structure that will allow adequate weed, pest, and disease control. If part of this control can be achieved by merely manipulating the crop mixture in time and space, great strides towards a more efficient agricultural management can be made.

5) Mutualisms and crop coexistence:

In natural ecosystems it has become apparent that a great number of interactions between different species are mutually beneficial for those organisms involved, leading us to believe that there is a strong selective pressure operating to select combinations that coexist rather than compete.[41] On the long term, such a coexistence permits a more efficient use of resources, with the

component organisms aiding one another rather than interacting - negatively. More energy can be put into growth and reproduction rather than into direct competition.

To a certain extent, nurse crops or companion plants function in this way. Legumes, because of their symbiosis with nitrogen-fixing bacteria, can coexist with corn without competing for nitrogen. Infact, part of this nitrogen may be available for the corn[14], reducing overall need for fertilization. Studies with - coffee and cocoa shade trees have demonstrated the same relationship; the trees provide shade, nitrogen, and an organic mulch - over the soil[21].

As already mentioned in previous sections, the presence of - one crop may have beneficial effects on others through alteration in the microclimate, pest and disease protection, etc. Thus, apart from looking for crops that complement one another by avoiding - overlap in requirements, we need also to look for crops that are - interdependent to the extent of mutually benefitting from the - - association. Crop selection programs are faced with a very stimulating challenge in this respect.

6) Use of Space and Time:

As mentioned in the beginning of this review, one of the - most important aspects of the management of multiple cropping - systems is the facility they offer for the intensification of - production through manipulation of space and time. It is within this context that the previously mentioned aspects of resource - use takes place. By achieving the most ideal combination of the interaction of the two, we will achieve the greatest productivity. On the one hand we attempt to occupy the available resource

space as efficiently as possible, combining species that complement each other in relation to the availability of resources, - yet attempting to avoid overlaps that lead to negative interactions.

Resource use in space is then combined with its use in time, trying o achieve constant use of those resources available. For this reason multiple cropping systems are intensified by sequential, relay, and mixed planting, establishing constant resource use within the environmental limits imposed by the ecological - conditions of each region. In this sense, we can even visualize the possiblity of including cold resistant trees in association with annual crops or pasture, such that during the winter the - trees continue to occupy the area. Thus, any yield reduction - brought about during the normal frost-free growing season is more than compensated for by the long term tree production.

Additionally, multiple cropping systems permit greater stability in production, despite variability in climate or physical factors in the planting area. This is achieved by the security that the conditions in one location and for one growing season - will be adequate for at least one member of the multiple cropping system. Now that the more homogeneous, better drained and structured soils have been put into production, the more variable marginal lands will require a special technology in order to make - them produce. We cannot consider for the moment massive programs of soil and water manipulation in order to install mechanized - high-yielding monocultures. To do so is currently economically, if not ecologically, prohibitive. The basic framework in available with a focus on multiple cropping. Innovative combinations need to be searched for and tested.

D. Agroforestry: a Multiple Cropping System:

Agroforestry is a technology of land management that implies the combination of forest trees with agricultural crops, with - animal raising, or any combination of the two. Combinations can be simultaneous, or staggered in both time and space. The major- objective of agroforestry is to optimize production for each unit of surface area, keeping in mind the need to maintain long term - yield[42,43,44]. Small scale traditional agriculture has always - included trees as integrated elements of farm management, but only recently has interest been revitalized in the application of - agroforestry practices into modern agriculture.

The renewal of interest in agroforestry systems has its basis in many of the same reasons observed for multiple cropping - systems in general. The ever-increasing demand for production, - yet the rising cost of obtaining it, has forced us to look again to some systems used commonly in the past in developed regions,- and still in use in less developed areas. The explosive demand for firewood and lumber has placed incredible pressures on the - forested areas of the world, especially in tropical and subtropical regions. Deforestation continues at an accelerated rate.[45,46] But programs of reforestation or forest manipulation involving a multiple use focus, do not allow for the satisfying of basic needs for food, clothing, and other necessities which come - from our crop and range lands. Thus it would seem logical that pressure for both forest and agricultural products would stimulate their combination in agroforestry systems.

Agroforestry practices can be broadly classified into three types[47]: (1) combined agrosilvicultural systems, (2) combined fo

restry and grazing, and (3) simultaneous combinations of forestry with crops and grazing. Examples of each of these classifications are presented in Table 8. The focus varies from soil - improvement, erosion control, wind breaks, and shade on the one hand, and on lumber, firewood, and reforestation on the other. The combinations are essentially unlimited, depending on the demands and needs for each region. At first glance it might appear that agroforestry systems are most applicable on marginal lands, of steep slopes, poor soils, or areas with widely fluctuating - rainfall regimes. But we must also consider the widespread application of agroforestry even for prime agricultural or grazing land, because as mentioned before, production needs to be increased -- both by opening up new areas as well as by looking for innovative ways to increase productivity of already exploited lands.

The principle limitations to widespread use of agroforestry practices at the moment are economic and technological. Ecologically, the advantages are well known (Table 3), but technically we still do not have the information necessary to begin inmediate implementation. With the present focus in agriculture aimed at maximizing single crop yields, and therefore economic profits from their management, there is as yet a lack of acceptance of - the idea that yields need to be thought of more on a long term,- diversified basis. Agricultural research has not yet accepted - the challenge that such an integrated focus to forest and farm - management requires.

E. Socio-economic Implications of Multiple Cropping Systems: Perspectives for the Future:

In all of the aspects of multiple cropping systems that this review has considered - yield, resource use, pest and disease -

control, weeds, use of space and time, types of planting systems, much of the evidence indicates that generally there are more advantages than disadvantages of a biological, physical, or agronomic nature. But we need to consider the social and economic implications of the possible more widespread use of multiple cropping systems in presentday agriculture.

As can be seen in Table 4, the types of advantages derived from multiple cropping are many and varied. With a greater diversity of crops, a farmer is less effected by market fluctuations, being able to shift from one crop to another depending on price and demand, at the same time having the harvest spread out over a longer period of time. Less dependence on outside sources of energy for system management has obvious advantages , especially in areas where capital is limited. Labor, instead of having to be concentrated in certain specific periods of the year, can be more evenly distributed, an aspect very important in relation to the migrant farm worker problem. In times of higher unemployment, multiple cropping systems can offer more and steadier work.

Most of the disadvantages of an economic nature are derived from our lack of experience and knowledge with multiple cropping systems. Reported lower yields, complexity of activities involved in their management, the higher labor demands, and the difficulty in mechanizing such systems are all important components which discourage modern farmers from participating in multiple cropping practices. An important aspect of this hesitation or resistance comes from the emphasis on large profits that governs so much of modern agriculture today. Maximum profits on the short term, rather than being concerned with maintaining constant income on the long term, governs the decision making process on most American farms

today. But with the incredible rise in farm costs, a new focus is necessary. All of these increases cannot be passed on to the consumer. Many of the advantages listed previously of multiple cropping systems in this aspect definitely need to be stressed more for use on farms today. Smaller farms, with a greater diversity of products and activities can function quite profitably, due to less dependence on high cost energy inputs. Lower costs mean food can be produced at a lower price, the benefits being received in this case by the general population.

Socially speaking, with smaller farms, we need more farmers. To a certain extent multiple cropping systems mean a return to the land, with the incentives necessary to keep the farmers there. The great diversity of activities in multiple cropping systems will necessarily promote an increase in interdisciplinary activities in their investigation, installations, management, and amplification into present day agriculture. This stimulation of interchange and collaboration on the long term can lead to greater social cohesion. Rural regions once again take on the social importance they enjoyed in the past. The problems of lack of trained personnel, and social, political, and economic restrictions on multiple cropping systems, all can be overcome by thorough and conscientious programs of research aimed at determining the proper methods, varieties, and practices necessary. The belief that multiple cropping is only suitable for marginal or underdeveloped regions ignores the fact that just a relatively short time ago, such systems were the most common type of agriculture, but have been replaced by monoculture systems dependant on the use of massive quantities of inexpensive high energy inputs. For the moment, this time has passed, and the need to relearn from the past in order to reshape agriculture for the future, provides the greatest challenge for present agricultural research.

TABLE 8: Classification and Examples of Agroforestry Technologies, with a description of the benefits and aims of each system.

I. Combined Agrosilvicultural Systems (Trees with crops):

1. Agrosilviculture - establishment of trees, intercropped with agricultural crops during initial stages of tree growth, until tree canopies close and force the elimination of the cropping. Production available in early stages of tree development, and cultural activities simultaneously beneficial for both crops and trees.

2. Forest trees of commercial value in crop systems. Maintenance of trees in crop areas, either planted or natural, at low densities so as to not interfere, yet of value in the future.

3. Fruit trees in crop systems. A system that allows for fruit production and grain or vegetable production simultaneously.

4. Trees that serve as shade for certain crops or improve the soil through nitrogen fixation, organic matter incorporation, mulch, and microclimate modification.

5. Trees used as hedge rows, fence lines, or windbreaks around cropping areas, whose management is intimately linked with the needs of the crops.

6. Trees around rivers, lakes, or artificial reservoirs or tanks, integrated with fish or waterfowl management, providing shade, food, and roosting.

II. Combined Forestry and Grazing Systems (Trees with grasses):

1. Grazing or forage production takes place within forestry plantations, aiding in avoiding weed or brush build up, lowering fire risk.

2. Grazing or forage production in young natural forests, with same advantages as above.

3. Forest trees of commercial value in pastures, either planted or natural, at densities that do not interfere with the pasture species.

4. Timber trees in pasture, either planted or natural, with the capacity to fix nitrogen and improve soil, thus lowering the need to fertilize, at the same time of commercial value.

5. Trees in pastures that provide shade for the animals and aid in improving the soil through nitrogen fixation and nutrient extraction from deeper soil levels.

6. Trees, either in or around pastures, or in forests, that produce folliage of forage value for animal consumption. Can - allow the reduction of feed supplement for animals.

7. Fruit trees in pastures, allowing for commercial production of both fruits and animals.

8. Trees around pastures as hedgerows, fence lines, or wind -- breaks.

III. <u>Simultaneous Combinations of Forestry with Crops and Grazing</u>:

1. Forest plantations planted with crops and grasses, permitting the management of grazing animals, either free to - wander or enclosed in specific areas.

Especially adapted to smaller animals, such as ducks or - pigs. Requires close control of activities and use of - specific crops.

2. Trees associated with crops and grazing, either planted - or natural, in densities that will not adversely influence the crops. Example of scattered trees in and around - cropping areas that can be periodically pruned and used - as forage for animals, with the timber harvestable at some later date.

3. Hedge rows or living fence lines around rural communities, serving as shade, windbreak, property divisions, forage, - fruits, timber, and firewood. In this sense, the system - takes on a truly multiple use aspect.

Source: Combe & Budowski (1979)[47].

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APPENDIX

Photo 1. Example of a Corn/Bean Mixed Cropped System. Turrialba, Costa Rica.

Photo 2. Example of a Corn, Pineapple, watermelon relay intercropping system. Turrialba, Costa Rica.

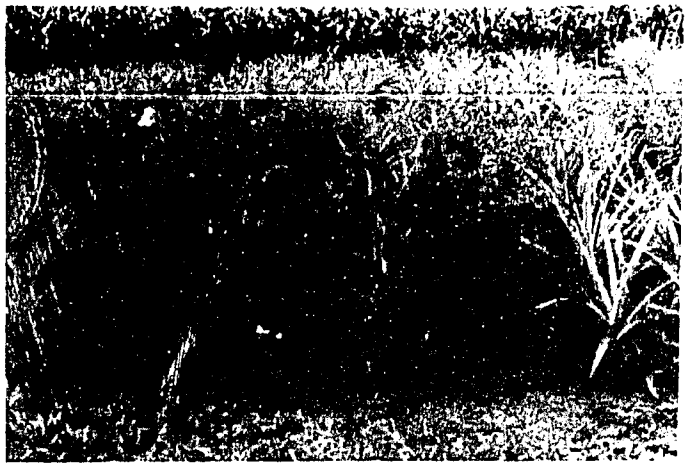

Photo 3. Example of a Pineapple/Pigeon Pea Intercropping System, Turrialba, Costa Rica.

Photo 4. Example of an Agrosilvicultural System of Agroforestry, with coffee, cocoa, bananas, and a legume shade tree. CATIE, Turrialba, Costa Rica.

PAPER NO. 5. AGROTECHNOLOGIES BASED ON SYMBIOTIC SYSTEMS THAT FIX NITROGEN

(By Dr. Jake Halliday, College of Tropical Agriculture, University of Hawaii)

Terms of Reference

Describe how the technology operates and its beneficial or adverse impacts, existing or potential, on the sustained production of food and forage from tropical and subtropical soils.

Describe where this technology is being used; describe whether the technology is being used on a commercial level, a subsistence level, as a pilot program, or is being applied only in the research state; describe who is conducting the major research on the technology; and describe what organizations (AID, FAO, and others using U.S. funds) are funding development of the technology and what organizations are implementing it on a project scale.

Explain in some technical detail how this technology increases or decreases the need for fertilizers, pesticides, irrigation, and machinery when applied to tropical and/or subtropical soils.

Discuss potential ability of this technology to restore, improve, or sustain in perpetuity the food and forage productivity of tropical and subtropical soils, and the likelihood that this technology will be used widely.

Describe a plausible research, development, and implementation scenario in which this technology realizes its potential in enhancing productivity of tropical soils. The contractor shall include responses to the following: What organizations would be involved? What levels of capital and trained personnel would be necessary? What degrees of attitudinal changes would be necessary for consumers, farmers, government agricultural experts, bureaucrats, politicians, foreign advisors, policymakers in foreign aid or lending institutions, etc.? What biophysical (soils, climate, topography), cultural, and socioeconomic conditions would be most conducive to successful implementation of the technology? Where do these conditions exist or where are they likely to develop? To indicate the priority of the various steps that need to be taken on this technology, the contractor shall discuss how he (if he were the head of a wealthy foundation) would spend $10 million on research, development, or implementation of the technology.

Describe the major scientific, environmental, cultural, economic, and political constraints on development and implementation of this technology.

Describe how implementation of this technology in a region would affect that region's need for inputs of capital (agricultural chemicals, machinery, credit, seed, and other materials from the implementing farm), labor, and land.

Describe the potential impact of wide-scale implementation of this technology on the socioeconomic structure of agriculture in the implementing regions. The contractor shall address the following: Does the technological implementation give rise to economies of scale, or diseconomies of scale, that would make large or small farm units more competitive? How would the technology either displace or create demand for farm laborers?

Abbreviations

ARC	Agricultural Research Center
BNF	Biological nitrogen fixation
BTI	Boyce Thompson Institute (Cornell University)
CB 81	CSIRO, Brisbane, *Rhizobium* strain 81
CGIAR	Consultative Group on International Agricultural Research
CIAT	Centro Internacional de Agricultural Tropical (Colombia)
CGIAR	Consultative Group on International Agricultural Research
CRSP	Cooperative Research Support Program
FAO	Food and Agriculture Organization (of the United Nations)
IARC(s)	International Agricultural Research Center(s)
IBIT	International Bean Inoculation Trial
IBPGR	International Board for Plant Genetic Resources
ICARDA	International Center for Agricultural Research in Dry Areas (Syria)
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics (India)
IITA	International Institute for Tropical Agriculture (Nigeria)
INLIT	International Network of Legume Inoculation Trials
INTSOY	International Soybean Program (University of Illinois)
ISRIE	International Soybean *Rhizobium* Inoculation Experiment
MIRCEN	Microbiological Resources Center (UNEP/Unesco project)
NGR 8	New Guinea, *Rhizobium* strain 8
NifTAL	Nitrogen Fixation by Tropical Agricultural Legumes (University of Hawaii project)
OTA	Office of Technology Assessment (U.S. Congress)
SEA/CR	Science and Education Administration/Cooperative Research (within USDA)
UNDP	United Nations Development Program
UNEP	United Nations Environment Program
Unesco	United Nations Educational, Scientific and Cultural Organization
USAID	United States Agency for International Development
USDA	United States Department of Agriculture

ABSTRACT

Legume crops are especially attractive when sustained productivity is sought from low-input farming systems in the tropics and subtropics because of their unusual ability to be self-sufficient for nitrogen supply. Life on earth is dependent on transformations of atmospheric nitrogen to a form in which it can be absorbed from soil by plants for protein synthesis. The process can be accomplished industrially but at a very high energy cost. Biological nitrogen fixation (BNF) by symbiotic associations of plants with microorganisms is economically more sound and environmentally more acceptable than nitrogen fertilizer use in agriculture.

Agrotechnology based on BNF by legumes has two facets, the use of legumes and inoculant technology. Currently legumes are used in many systems without any specific attempt to maximize their nitrogen fixation through inoculant technology. Yields can be increased and nitrogen fertilizer requirements reduced through implementation of appropriate inoculant technology. Maximum gains from BNF in agriculture will arise from innovative use of legumes in areas and in roles they have not occupied previously, provided that their nodulation and nitrogen fixation is assured. Most legumes in the tropics "fix" about 100 kg/ha/year of nitrogen with levels around 350 kg/ha/year common for the forage tree leucaena and fixation as high as 800 kg/ha/year within the potential of some species. Fertilizer savings through the use of legumes represent not only significant savings in foreign exchange but also reduced dependence on the oil-rich nations whose influence over the cost and availability of nitrogen fertilizer is increasing.

The use of legumes involves the management of legume species in farming systems not only for direct benefits accruing from the multiple uses of legume products and the greater stability of mixed-cropping, as opposed to monocrop systems, but also for indirect benefits arising from their ability in some circumstances to make a net contribution of nitrogen to the soil and thereby to companion or following non-leguminous crops.

The underlying objective of inoculant technology is to introduce sufficiently high numbers of preselected strains of rhizobia into the vicinity of the emerging root that they have a competitive advantage over any indigenous soil strains of lesser N-fixing ability in the formation of root-nodules. Inoculation technology involves: selection of strains of rhizobia that are compatible and effective N-fixers with particular legumes; multiplying selected strains to high population densities in bulk cultures; incorporating the liquid rhizobial cultures into a carrier material (usually finely milled peat) for packaging and distribution; and finally, coating the seeds of legumes with the carrier or implanting the soil with the inoculant directly into the seed drill.

Legumes are already used widely and consistently, but as minor crops, in farming systems of the tropics. Inoculant technology is in use on a meaningful scale only in a few countries other than the U.S. and Australia.

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Greatest future potential would appear to rest in the development of: legume-based pastures and viable multiple-cropping systems including legumes for under-utilized savannahs; agrofrestry systems that combine fast-growing, nitrogen-fixing trees, leguminous and other crops to meet the food and fuel requirements of the rural poor; fast-growing leguminous trees for reclothing water catchment areas following forest clearance; legume-based cropping systems to give sustained productivity in cleared jungle soils which typically exhibit a rapid decline in fertility under conventional cropping; selection of deep-rooted, drought-tolerant leguminous trees that can serve as browse species in the world's dry lands.

The major constraints to full implementation of legume-based BNF technology in the tropics relate to the delivery and acceptability of the technology at the farm level, and are political, cultural, socioeconomic and, to a lesser extent, scientific in nature. The major scientific constraint is inadequate understanding of host legume x rhizobial strain x environment interactions resulting in inability to predict whether a given legume will respond to inoculation in a particular region or not. A constraint to deriving a better understanding of these interactions is the lack of trained personnel in the tropical regions to execute legume inoculation trials for determining the economic yield benefit attributable to legume inoculation. A lack of domestic inoculant production plants in the majority of countries also constrains research, development and production enterprises with legumes.

The scenario in which legume-based BNF technology would realize its potential would include: increasing economic and political pressure for greater energy efficiency in agriculture; increased recognition, by decision makers in funding agencies and in governments, of the potentials for exploiting BNF in the agricultural sector of the economies of developing countries; an increase in the cadre of trained professionals and technicians in countries of the tropics; improved integration of legume germplasm improvement programs and legume bacteriology programs; concerted application of international funding to catalyze establishment of a BNF Resource Center staffed, equipped and budgeted to provide technical assistance, offer germplasm and information services, provide professional and technical training and conduct such research as may be necessary for adaptation of BNF technology to individual needs of developing countries but which is beyond the current capability of local researchers; improved opportunity for interchange of findings from field research programs; implementation of a competently executed sequence of standardized experiments designed to quantify the economic yield benefit attributable to legume inoculation under field conditions and followed up by studies to quantify the nitrogen balance in multiple cropping systems that include legumes.

Legume inoculation does not substantially affect the need for farm labor. The inoculation is accomplished as an integral part of the sowing method whether by hand or mechanized planter. If fertilizers are normally applied, elimination of the need for nitrogen reduces the capital cost but no substantial labor saving is realized as other fertilizers still need to be applied. The use of legumes to benefit companion or following crops is consistent with the farming systems already prevalent in the tropics. To use legume-fixed nitrogen for, as an example, cereal production in the U.S. would necessitate adoption of mixed-cropping systems that are not easily mechanized. Thus an increased demand for labor would be an impact. The major positive impacts of BNF technology are indirect through elimination of the multitude of negative environmental impacts associated with nitrogen fertilizer production, distribution and use in agriculture.

Introduction

Beans and peas are well-known examples of food products from the array of plant species that belong to the legume family. Legumes are especially attractive when sustained productivity is sought from low-input farming systems. This is because of their unusual ability to be self-sufficient for nitrogen supply.

Nitrogen is an essential component of all life forms, being a cornerstone in the chemical structure of proteins. Ironically nitrogen is abundant in the atmosphere and the air we breathe is 80% nitrogen. In its gaseous form, however, nitrogen occurs as dinitrogen molecules, each having two nitrogen atoms joined by a triple bond. This is among the most stable, inert molecules known and cannot be utilized directly. Thus life on earth is totally dependent on transformations of atmospheric nitrogen to a form in which it can be used readily by plants, and subsequently, by animals and man. This process is referred to as "nitrogen fixation" and involves splitting dinitrogen into two nitrogen atoms which are then reacted with hydrogen (generated by splitting water molecules) to form firstly ammonia and subsequently a range of nitrogenous compounds. Nitrogen fixation can be accomplished industrially, but the process is one of the most energy demanding in today's agriculture. The energy cost of fixing nitrogen in the form of urea, ammonimum sulphate or ammonium nitrate is compounded by the additional costs involved in its transport and application. Additionally, the rather small proportion of N-fertilizer actually taken up by the crop to which it is applied and the serious environmental pollution that can be caused by nitrogen lost from agricultural land through run-off are incentives for appraising alternate N-sources. Self-sufficiency for nitrogen supply as exemplified by the legumes is thus a highly desirable trait.

The biological nitrogen fi ation (BNF) process

Biological nitrogen fixation (BNF) in legumes is possible by virture of the mutually beneficial association (symbiosis) which can form between leguminous plants and certain microorganisms from a specific family of soil bacteria known as *Rhizobium*. Rhizobia can penetrate the roots of legumes and give rise to highly specialized organs referred to as root-nodules. These are quite different from tumors or other swellings that commonly occur on plant roots as a result of infection by disease-causing (pathogenic) organisms. The structure and function of nodulated legumes is modified in such a way that carbohydrates (sugars) produced in the leaves of the plant during photosynthesis are delivered to the nodulated root where they are respired to provide energy. In the nodules, this energy is consumed to maintain conditions under which nitrogen fixation can proceed and also to sustain the growth requirements of the rhizobia.

Gaseous dinitrogen enters the nodule from the air spaces in the surrounding soil. An enzyme, nitrogenase, which is the unique contribution of the microsymbiont, catalyses the splitting of dinitrogen molecules and the reaction of their component atoms to form ammonia. Neither the sequence of reactions and transformations that follow initial fixation nor the precise sites in the nodule where the events occur are fully understood. The steps involve very rapid incorporation of ammonia, which would ordinarily be toxic to both symbionts, into nitrogenous compounds such as amino acids, amides and/or ureides depending on the particular legume species. These are removed from the nodule in the plant's transpiration stream to be used throughout the plant as building blocks for plant proteins.

Agrotechnologies based on BNF by legumes

Most farmers in the tropics do not know that legumes fix nitrogen in their root nodules. Yet traditional and modern farming systems of the tropics almost invariably include legumes (1,2). Thus legume cultivation results from recognition by farmers over many centuries that legumes are valuable components in farming systems rather than from intentional exploitation of biological nitrogen fixation *per se*.

Agrotechnology based on BNF by legumes has therefore two major aspects. One relates to the deliberate inclusion of legumes in cropping systems to derive benefits from their nitrogen fixation. The other concerns the intentional use of specific practices to maximize nitrogen fixation by legumes. For convenience these two facets of BNF technology will be referred to as "use of legumes" and "inoculation technology". The distinction is drawn to emphasize that currently legumes are utilized widely with less than maximal benefits from BNF because of deficient symbiotic associations. Productivity could be increased through use of appropriate technology to assure effective symbiotic nitrogen fixation by legumes in the role they currently play in the agricultural sector. Much greater gains in productivity and economies of energy from reduced fertilizer requirements will be realized through innovative use of legumes in roles they have not occupied previously in production systems, e.g., the use of fast-growing leguminous trees in agroforestry systems. Production gains will be greatest if the use of legumes is always complemented by appropriate inoculant technology. This is because legumes can only benefit fully from biological nitrogen fixation if they encounter rhizobia with which they are genetically compatible, so that root infection and nodulation can occur and if the strain which forms nodules functions effectively in fixing nitrogen.

The use of legumes

The benefits from BNF through the use of legumes in farming systems are both direct, because the legume has an intrinsic value, and indirect, as inclusion of a legume affords greater yield stability in adverse growth conditions and can benefit companion or following non-leguminous crops.

Direct benefits from biological nitrogen fixation by legumes in cropping systems arise from the multiple uses of plants in the legume family. Though known primarily for grain, forage or feed production, legumes are also cultivated in the tropics for timber, fuelwood, green manures, oils, fibers, gums, drugs, dyes, and resins. Additionally they may be used as hedges, ground covers for weed, insect and disease control, as soil stabilizers on terraced slopes or simply for shade or as ornamentals (3).

Indirect benefits accrue from the stability of performance and assurance of some economic return for at least one component under unfavorable conditions when legumes are intercropped with other crops. Stability is afforded, for example, in erratic rainfall zones when the components in the intercropping system are separated in time such as with sorghum/pigeon pea and groundnut/cotton (4,5). When there is an outbreak of pests or diseases, maize/beans and other intercrops afford stability of yields and income (6,7). Other indirect benefits accrue from the ability of legumes to make a net contribution of nitrogen to the soil under some circumstances, thereby reducing the N-fertilizer requirement for a companion or following non-leguminous crop.

Inoculant technology

There is a commonly held view (8) that tropical legumes are much more promiscuous than temperate legumes in that they nodulate freely with a wide range of tropical rhizobia; and that tropical soils are laden with such bacteria to an extent which virtually guarantees effective nodulation without inoculation (9,10). This view is no longer well-founded. Some species and accessions from genera previously considered to be promiscuous (8) require specific strains of *Rhizobium* (11,12,13) or form highly effective symbioses with only a few out of the wide array of strains with which they nodulate (14,15,16). Recent intensification of interest in the tropical legumes and their rhizobia is revealing much greater variation in genetic compatibility and nitrogen fixation effectiveness among tropical rhizobia than has generally been acknowledged (17,18). A plea has been made for recognition that tropical legumes fall into one of three categories (18):

> Promiscuous effective (PE) group in which nodulation occurs with a wide array of rhizobia isolated from many legume genera and the resultant symbioses are predominantly effective in nitrogen fixation.
>
> Promiscuous ineffective (PI) group in which nodulation occurs with an array of strains of rhizobia isolated from many legume genera, but in which fully effective symbioses form with only a few of those strains.
>
> Specific (S) group in which only those strains from the same genus (or, commonly, a restricted number of other genera) form effective symbioses.

Just as with the temperate legumes, the likelihood that compatible effective rhizobia will not always be encountered already present in sufficient numbers in the soil microflora is the basis for inoculation technology for tropical legumes (19). When a tropical legume seed is sown uninoculated in a tropical soil, a native rhizobial population of strains differing greatly in their symbiotic effectiveness compete for the finite number of nodulation sites on the legume roots. Many forage legumes bear only 10-20 nodules on which they depend for nitrogen during the first three months of their establishment. Thus it becomes critically important that each of the nodules which form on the root contain a strain of *Rhizobium* that is fully effective in fixing nitrogen. The underlying objective in inoculation technology is to introduce sufficiently high numbers of preselected strains of rhizobia into the vicinity of the emerging root that they have a competitive advantage over any indigenous soil strains of lesser N-fixing ability in the formation of root-nodules.

Inoculation technology involves: selection of strains of rhizobia that are compatible and effective N-fixers with particular legumes; multiplying selected strains to high population densities in bulk cultures; incorporating the liquid rhizobial cultures into a carrier material (usually finely milled peat) for packaging and distribution; and finally, coating the seeds of legumes with the carrier or implanting the soil with the inoculant directly into the seed drill (20,21,16).

An inoculum strain of *Rhizobium* recommended for a particular host must be able to form effective N-fixing nodules with that host under a wide range of field conditions. Nitrogen fixation effectiveness is only one important criterion for an inoculant strain. Other criteria include: competitiveness in nodule formation, particularly against less effective strains; persistence in the soil in the absence of the host, especially for strains for annual species; promptness to form nodules; ability to fix nitrogen under a range of soil temperature conditions; tolerance to pesticides; tolerance of low soil pH; nodulation in the presence of high levels of soil nitrogen; and ability to grow and survive in peat inoculants.

The host genotype interacts with the infecting strain of *Rhizobium* in determining the level of nitrogen fixation with the host playing the dominant role. Thus two sources of variation (plant and *Rhizobium* strain) can be exploited in selection programs. Most commonly, though, the plant is selected independently and a suitable strain sought thereafter, thus allowing only for exploitation of strain variability. The range of specificities of host genotype interactions is well illustrated by soybean (22) and in the African clovers (23).

Such specificities give three options in the approach to selection of strains for inoculants: numerous inoculants, each with a highly effective strain for individual species; 'wide-spectrum' strains that vary from good to excellent in N_2 fixation with a range of legumes; or multiple-strain inoculants containing the best strain for each host species. There may be a conflict between the option that would be chosen for commercial expediency and that which is scientifically excellent (24). In Australia 'wide-spectrum' strains are used when these are available, but there is increasing use of specialized inoculants with specific strains for

individual hosts. Despite findings which suggest that multi-strain inoculant should be avoided because of possible antagonistic and competitive effects in culture (25) and the likelihood of competition in nodule formation from the less effective strains (26), this is the approach used successfully by the U.S. inoculant industry.

Strains for testing can be obtained from other laboratories working with the same species, from nodules on plants in the native habitat from which they were originally collected for plant-introduction/evaluation programs, and from nodules formed on the legume by native strains after sowing uninoculated seed in the region where the new species is expected to be used. None of these sources is invariably better than the other in screening programs.

Most legume inoculants are prepared by adding liquid cultures of *Rhizobium* to a finely-ground carrier base material such as peat. Although mixtures of peat with soil or compost mixtures, lignite, coir dust and some other organic materials have been used, peat has proven to be the most acceptable carrier worldwide. Agar, broth and lyophylized cultures are not recommended because of the very poor survival of these forms of the inoculum on seed (27,28,29).

Peat cultures can be prepared in two ways. Either ground (milled) peat is mixed with a high viable count (more than 10^9 rhizobia/ml) broth culture in sufficient volume to provide the minimum number of *Rhizobium* acceptable for use, or sterilized peat is inoculated with a small volume of culture and incubated to allow multiplication of the rhizobia in the carrier. The choice of method will depend on two main factors--the survival of the rhizobia in peat in numbers high enough to meet a minimum standard of quality, and the availability of suitable, sterilizable containers and sterilizing facilities. The two factors that most affect survival of rhizobia in peat are temperature of storage and sterility of the peat. There are differences among species and also between strains of the same species of *Rhizobium* in their ability to survive well in peat (30).

Like all biological products, legume inoculants are prone to loss of quality owing to variation in the organism concerned and from unforeseen factors affecting some aspect of growth or survival. It is therefore essential that a quality control system be established. In Australia large-scale manufacture of legume inoculants is by private enterprise, and a separate, official (government) control laboratory is responsible for maintaining a high quality product. The control laboratory maintains and supplies recommended strains of *Rhizobium* to the industry, checks strains annually for ability to fix N_2, assesses quality of cultures during and after manufacture, and conducts such research as may be necessary to overcome problems associated with production and survival in the final product. In the U.S. the industry is free to select its own strains and official control ensures that the product can form nodules on the legume for which it is recommended.

Although control of quality of inoculants is primarily in the manufacturer's interest and therefore his responsibility, power of control by external bodies provides protection from less scrupulous operators and genuine failure of a strain outside manufacturer control. Not all countries back their control labs with legislation. A control group requires suitably qualified and experienced personnel with facilities to permit normal aseptic culture transfer and plant growth facilities suitable for legumes over the range for which inoculants are manufactured. Methods of assessment involve both qualitative and quantitative tests. The number and extent of these may vary according to competence and experience of manufacturers and the standards desired. In Australia this control extends to holding stocks of the strains used in inoculants. This is not the case in the U.S. (13,31). In addition to assessment of quality throughout manufacture, it is important to monitor quality of product in retail outlets. Standards acceptable at this level may vary from that at manufacture and between countries. It is important that standards be realistic and within the capability of manufacturers yet ensure that sufficient viable rhizobia are applied to the seed to provide a satisfactory inoculation. In may instances this can be as few as 100 rhizobia per seed but in case of severe environmental stress as high as 10,000 or even 500,000 (32,33,28).

The prime objective of inoculation of legume seed with rhizobial inoculants is nodulation of the introduced legume host plant. Rhizobia introduced into new environments must live saprophytically in competition with other rhizobia and soil microorganisms in an environment which may be adverse for their growth and survival, until such time as the host seedling roots provide the ecological niche to which they are adapted. Thus steps should be taken to assist inoculant strains: remain viable until the host seedling is at the susceptible stage for infection; compete with any naturalized rhizobia for infection sites on the roots of the host legume and so form sufficient nodule tissue to permit maximum nitrogen fixation; nodulate its host promptly and effectively over a range of environmental conditions; and persist in the soil for at least several years in sufficient numbers to maintain nodulation of perennial legumes or to achieve prompt nodulation of regenerating annual species.

The first attempts at inoculation involved the transfer of soil from one field to the next, but with the isolation of the organisms responsible for nodule formation, artificial cultures soon replaced the laborious soil transfer technique. The usual inoculation technique is to apply the inoculant to the seed just before sowing either as a dust or as a slurry with water or adhesive solution. Adhesives such as gum arabic and substituted celluloses not only ensure that all the inoculum adheres to the seed surface but also provides a more favorable environment for survival of the inoculum. Pelleting of seed with finely ground coating materials such as lime, bentoninte, rock phosphate and even bauxite (32,34) have been used to protect rhizobia during their time on the seed coat. Pelleting is a simple on-farm technique (32,35) but custom-pelleted (by seedsmen at farmer's request) and preinoculated seed is now more popular. This latter procedure is potentially able to provide high populations of rhizobia on the seed for long periods of time (one growing season to the next) but has not yet been fully developed or exploited. Most preinoculation

procedures are based on multiple coatings, alternately of adhesive and finely ground pelleting materials as used in simple pelleting. The peat inoculant is included as one (or more) of these coating layers. Soaking seeds in a broth suspension and then exposing them to either high pressure or vacuum to impregnate the rhizobia into or below the seed coat has not proven successful. Theoretically, rhizobia introduced in this way would be protected from drying and other adverse environmental conditions, but the quality of products produced commercially has been variable to very poor (36,37,38). It is, in fact, an indictment of the research workers in this area that 25 years has yielded so little progress in an area that has so much to offer for those concerned with the practical aspects of agricultural microbiology. The technique is particularly applicable to the less well developed and inexperienced rural groups in that a high quality and reliable product could be marketed by a manufacturer or seeds distributor thus eliminating the need for farmer involvement in legume inoculation.

An alternative to pelleting and preinoculation in recent years has been the use of concentrated liquid or solid granular peat culture which can be sprayed or drilled directly into the soil with the seed during planting. Suspensions of rhizobia either as reconstituted frozen concentrates or suspensions of peat inoculant can be applied with conventional equipment. Similarly, granulated peat inoculants can be drilled in from separate hoppers on the drilling equipment. These methods have been especially successful for introducing inoculant strains into situations where there are large populations of competing naturally occurring soil rhizobia (39) or in cases of adverse conditions such as hot-dry soils (40) and where insecticide or fungicide seed treatment precludes direct seed inoculation (41,35). Solid inoculant, also known as granular or "soil implant" inoculum, is advantageous also, where seeding rates for crop legumes of 70-100 kg/ha make on-the-farm inoculation logistically impracticable.

Current use of legume-based BNF technology

(a) *The grain legumes*: The grain legumes are cultivated widely in a variety of agro-climatic zones in the tropics and subtropics. Total area in grain legumes in 1979 was 175 million hectares. Dry bean (*Phaseolus vulgaris*) is the most important grain legume in Latin America, groundnut (*Arachis hypogaea*) in Africa and collectively groundnut, pigeon pea (*Cajanus cajan*) and chickpea (*Cicer arietinum*) in Asia. These and other grain legumes have been consistent components of human diet in the tropics for centuries yet in quantitative terms they continue to be minor crops.

The use of legumes in mixed legume/grass pastures in the tropics is at present restricted to northern Australia, the United States (Hawaii, Florida), southern Brazil and northeastern Argentina. The total area in improved legume/grass pasture is insignificant compared to the area of native grasslands under grazing. The use of temperate forage legumes in mixed pastures at high altitude locations in developing countries within the tropics is frequent but is considered outside the scope of this report.

Production statistics for the tropical grain legumes are seldom accurate. Most of the production is on a subsistence scale on small farms and the yields are seldom included in official statistics. Thus a figure of 186 million tons (42) should be regarded as an understatement.

There are very many agencies supporting and conducting research related to the use of legumes. International agencies such as FAO, UNDP, IBPGR and the IARCs all have grain and forage legume programs. The USAID together with the governmental agencies of many countries engaged in foreign agricultural development support research on legumes. The World Bank and several private and public foundations also support legume research. The author is not aware of any country in the tropics that does not have a legume project within its official agricultural program. Additionally, universities and agricultural colleges in tropical countries usually have legume programs. These projects cover the physiology, plant nutrition, agronomy, pathology, entomology, breeding and seed production of legume crops. Insofar as BNF proceeds at a rate governed strongly by the plant's ability to deliver carbohydrate to its root nodules, most technologies that improve overall plant performance are likely to have a beneficial impact on nodulation and nitrogen fixation. Relatively few projects, however, give adequate attention to specific techniques for maximizing biological nitrogen fixation by the respective legume. In fact some research programs with legumes are conducted under nitrogen-fertilized contitions or in fertile, N-rich soils. Breeding for high-yielding varieties under such conditions has resulted in plant types which are only weakly symbiotic and heavily dependent on soil nitrogen; e.g. bush bean (*Phaseolus vulgaris*) varieties developed in the United States.

Given the important role of grain legumes as the major dietary protein source for low-income groups in the developing countries, it is hardly surprising that such a multitude of funding agencies and implementing organizations give attention to research on legume technology. Whilst it is to be expected that there will be overall gains in the quantities of nitrogen fixed from improved performance by legumes in the roles, and on the acreage they currently occupy, the major gains in BNF through the use of legumes will follow increases in the total land area in which legumes are grown and especially the innovative use of hitherto under-utilized legumes.

(b) *Inoculant technology:* Inoculant technology is implemented widely on a commercial scale mainly in the developed countries, the United States and Australia having substantial industries for the production, distribution and marketing of legume inoculants. There is also commercial-scale production in Brazil, Uruguay, Argentina, India and Egypt. Inoculants are available commercially in many other countries but produced in U.S. or Australian laboratories for importation and marketing by a subsidiary of the parent company or suppliers of legume seed, e.g. the Nitragin Company, Milwaukee, has subsidiaries in Mexico, Venezuela and Argentina and distributes inoculants worldwide. Some research centers, such as CIAT and the University of Hawaii NiFTAL Project produce inoculants in pilot-scale plants as a service mainly to researchers and occasionally

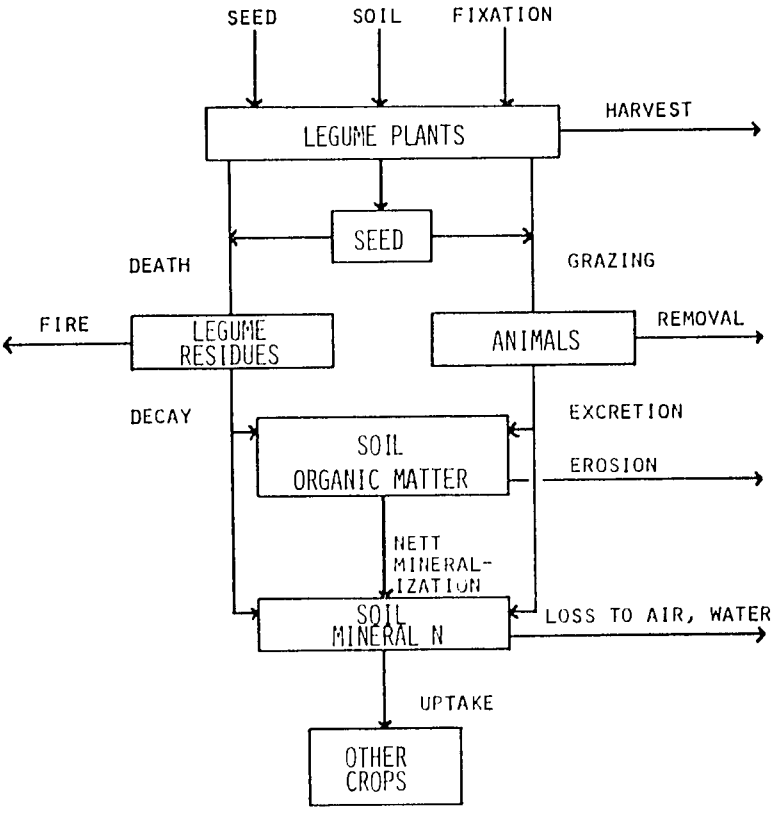
to legume growers. Demands for inoculation technology are increasing, associated mainly with the increased use of soybeans. There are dangers in trying to satisfy this demand by importation of inoculants developed in the U.S. or elsewhere. This is because inoculation technology as presently practiced has not proven transferable. That is to say, strains of *Rhizobium* and inoculation methods developed for conditions at one location in a particular farming system do not perform equally well at another location in a different farming system. Furthermore, the viability of rhizobia in legume inoculants is greatly affected by storage conditions during shipment. Since producers are unable to control such factors, no guarantee can be given that the inoculants are of merchantable quality on arrival at their destination. For both these reasons inoculation failures are a common occurrence and this is affecting adversely consumer acceptance of the technology. An ideal scenario for improved implementation of BNF technology is described in a later section.

Those organizations funding research to adapt inoculant technology to the circumstances in which it will be used in tropical countries are: UNDP by its support to the IARC's through CGIAR and for a specific research program involving IITA and BTI/Cornell University; UNEP and UNESCO support inoculant technology under the MIRCEN Project. FAO is actively considering the role it might play in the adaptation of inoculant technology of use in developing country agriculture (inoculantcy reports have been prepared and a planning workshop held during 1980). USAID through its contracts with University of Hawaii (NIFTAL Project) and USDA, Beltsville ARC (World *Rhizobium* Study and Collection Center) through grants under Section 131-(d) to the U.S. Universities' Consortium on BNF in the tropics, and through a portfolio of small grants administered by USDA SEA/CR, USAID and several governmental and non-governmental agencies who support the CGIAR are thereby sponsoring work at CIAT, IITA, ICRISAT and ICARDA on the adaptation of inoculant technology for use in the tropics.

How BNF by legumes increases crop yields and soil fertility

Consideration of the possible pathways for transfer of N from legumes to other crops (Fig. 1) affords a model around which estimates of the relative importance of the pathways of transfer of N from legumes to other crops and/or the soil can be attempted. Nitrogen gains per hectare per year entering the cycle as seeds, 1.2 kg (4%) and in acid rainfall, 1.9 - 3.3 kg (6%) are small compared to the nitrogen accumulated from the soil fixed biologically. About 50% of the nitrogen accumulated in legumes in fertile soils is estimated to BNF (45) though the proportion from fixed nitrogen will be greater in impoverished soils and lesser under nitrogen fertilization. Nitrogen accumulation in legume monocrops ranges from 20 - 350 kg/ha/year. It is generally accepted that N fixation of around 100 kg/ha can be expected from the majority of grain and forage legumes. High levels are typically those of lucerne and other forage legumes with a twelve-month growing season. Low levels are typically those of pulses and nitrogen fixers with short growing seasons (e.g. Phaseolus vulgaris). As an illustration, the fate of, say, 100 kg of biologically fixed N entering the cycle will now be followed. Between

Figure 1. Pathways for flow of N from legumes to other crops (from Henzell, 1977)



60 - 90% of the nitrogen accumulated in legumes is removed as grain depending on the species, harvest index and harvesting practice, or as animal products depending on the intensity and selectivity of grazing. Thus in an intercropping system only 10 - 40 kg nitrogen could potentially benefit other crops. Some of the organic nitrogen of the legume residues is mineralized rapidly and the rest is added to the soil organic matter pool from which it is mineralized slowly over a much longer period. In the studies that have been performed, 60% is probably the maximum portion of the nitrogen in the organic residue of a legume crop that could be mineralized in time to benefit a following crop.

Using 50% initial mineralization for the purposes of these calculations, in a cropping system in which the legume fixes 100 kg/ha/year only 5 - 20 kg of nitrogen is likely to benefit the following crop. One practice that would substantially increase the contribution is green manuring. On the basis of the level of nitrogen fixation cited above (100 kg/ha/year), a residual benefit of 50 kg/ha/year to a following crop could be anticipated after incorporation of one year's production into the same area prior to raising the following crop. Greater benefits still can be contemplated if the green manure from a large production area is carried for incorporation into a smaller crop production area. Experience has shown, however, that crops do not necessarily respond to exaggerated applications of green manures. There are few farming systems in which green manuring is economically feasible (43,46) since land is tied up without immediate economic return. Where green manuring is practiced, 5 tons of green matter per hectare is an accepted application rate (47). This would represent an addition of only 40 kg/ha of nitrogen to the soil, of which only about 20 kg would mineralize to the benefit of the crop. Real data, though limited, supports such an estimate. Green gram contributed 22 kg of nitrogen to following crops and calapo/stylo green manure contributed 15 kg (48).

Moving on to consider the nitrogen economy of mixed cropping systems in which the legume and non-legume are growing concurrently, the situation is more complex. Legumes usually take up less soil nitrogen in competition with non-legumes and a greater fraction of the nitrogen they accumulate in mixed crop is from fixed nitrogen. Somewhat surprisingly the nitrogen fixation of intercropped beans (*Phaseolus vulgaris*) per hectare is not significantly different from beans raised in monoculture (49). This is attributed to competition between the maize and the bean for light and nutrients beginning after the decline in nitrogen fixing activity in the root nodules of the beans. Not all legumes shut down nodule function as early in the growth cycle as *Phaseolus vulgaris* and the effect of intercropping on nitrogen fixation may be detrimental in other intercropping systems.

It is a common misconception that there is substantial direct transfer of nitrogen from the legume to a non-legume companion species in a mixed cropping system. There is no convincing evidence that actively growing, healthy legumes, whether grain or forage, excrete significant amounts of nitrogen from their roots or nodules.

The hypothesis orginally proposed by Virtanen and co-workers (50,51,52) that surface excretion of simple amino compounds from healthy, functioning legume root-nodules resulted in direct ransfer of significant quantities of nitrogen to non-legume companion species has found little support from other workers (53,54,55,56,57).

Subsequent research under carefully controlled conditions using the 'fox box' technique (58) indicated that excretion of a wide range of substances from plant roots does occur, but that the quantities involved are small, being less than 0.5% of the plant's nitrogen (59). Stated differently, a crop fixing 100 kg of nitrogen a year would excrete only 0.5 kg to the soil.

Nitrogen benefit to non-leguminous crops through association with companion legume species is considered to be of an indirect nature through loss and decay of shoot, root and nodule tissue, or by recycling *via* the grazing animal, rather than by a direct pathway (60,61,62,63).

Clearly then, mixed cropping systems that aim to utilize legume-fixed nitrogen for the benefit of a companion non-legume species must match species such that the non-legume is longer-lived than the legume because nitrogen will be released in significant amounts only after cessation of active growth and decomposition of tissues of the legume. The maize/bean association used widely in Latin America exemplified this principal. Estimates place fixation by beans at 20 - 40 kg of nitrogen per growing cycle (64). Assuming 70% removal of nitrogen as protein in the legume grain, this leaves only 6 - 12 kg in legume residues of which 3 - 6 kg (assuming 50% mineralization) will be mineralized in time to benefit the maize. Some estimates place the mineralization that can benefit a companion species as low as 20% and consistent with this it is not uncommon for there to be no detectable nitrogen benefit in companion crops that are intercropped with legumes.

From the preceding quantitative considerations, it is clear that the biological nitrogen fixation benefit to non-legumes due to inclusion of legumes in a cropping system is small indeed compared to the level of nitrogenous fertilizer use in the more intensive cereal production systems of the developed world. Thus the principal contribution of biological nitrogen fixation to human nutrition will continue to be *via* the protein in legume grains. An important implication of the data discussed here is that any suggestion of substantial replacement of nitrogen fertilization of cereals and root crops by biologically fixed nitrogen is unrealistic as these crops are known to respond to levels of nitrogen fertilizer far in excess of those which could currently be supplied through BNF by legumes. Thus there is an urgent need to devise ways of increasing the contribution which BNF by legumes can make to cropping systems as a complement to N fertilizer-based production rather than as an alternative to it.

Legumes can be managed to increase their nitrogen contribution to companion or following crops. They vary in total nitrogen fixed, the proportion retained in non-harvested residues, the percentage nitrogen level in residual tissue and the facility with which the organic nitrogen is mineralized. The greater are these parameters, the greater will be the residual nitrogen benefit. Given this situation, the priority given in legume breeding programs to improving their harvest index, i.e maximizing the fraction of each plant's total production that is removed as grain, should be called into question.

In summary it can be said that the principal benefits from BNF through the use of legumes in farming systems of the tropics are derived from the dietary protein of the legume grain, the multiple uses which legumes serve for the subsistence farmer, and the greater stability of yield and financial return of intercrops over monocrops. The indirect benefits from contribution of biologically fixed nitrogen to companion or following

species are small but are significant at present in the context of input levels in subsistence farming in the tropics.

At present there is insufficient reliable data on the benefit to be derived from enhancing, through inoculant technology, the nitrogen fixation in tropical legumes over and above the level which would be anticipated from spontaneous nodulation with native strains already present in the soil to advocate that rhizobial inoculation always be performed. It is tempting to recommend rhizobial inoculation of all legume sowings as an insurance measure against the risk of nodulation failures that would otherwise occur. However, inoculant technology does represent a cost, albeit small, and does add a degree of complexity to the sowing practice. Thus inoculant technology should only be advocated when there is known to be a need-to-inoculate and a demonstrable benefit therefrom. Additionally the concept and practice of inoculant technology is so foreign to farmers' normal practices that it should not be recommended lightly. A subsistence farmer can be forgiven for not comprehending nor accepting a technology that involves sticking black powder containing bacteria to his seeds. This contradicts concepts about which he has only recently become educated, namely, that bacteria are bad and clean seed is important. It is to be questioned whether inoculant technology in this form will ever be accepted widely among subsistence farmers in the tropics and subtropics. Further discussion of this topic follows later.

Unfortunately many trials peformed to evaluate inoculant technology with tropical legumes under tropical conditions have been performed with imported inoculants which may not have contained acceptable levels of viable rhizobia at the time of use. Lack of response to inoculation in such trials does not preclude the possibility that the legume could potentially benefit from inoculation. More recently coordinated networks of trials have been initiated to determine whether there is an economic yield benefit from inoculation of legumes or not. INTSOY conducts international Soybean *Rhizobium* Inoculation Experiments (ISRIE) throughout the tropics. CIAT distributes an International Bean Inoculation Trial (IBIT) throughout Latin America. The University of Hawaii coordinates an International Network of Legume Inoculation Trials (INLIT) offered for 13 agriculturally important legumes and involving a 3-stage experimental program in which cooperators throughout the tropics select strains specifically for their legume variety and local soil conditions thereby maximizing the opportunity for a yield response following inoculation.

Future potential of legume-based BNF technology

Despite their seeming atttractiveness for sustained productivity from low-input production systems, and despite also their consistent strategic use in many farming systems of the tropics, legumes have remained minor crops in the systems in which they occur (65).

Why is this the case, and what factors would lead to greater use of nitrogen fixed biologically by legumes? A small-scale, subsistence farmer elects to raise those crops that best meet the various needs of his household but also chooses one crop, at least, to sell or exchange for goods or services

for which he is dependent on others. Large-scale farmers consider primarily the economic return and facility of management associated with the crops they will choose to plant. A grower preference for cereals over legumes, when the grain is to be marketed, would be understandable. It is usual for yields of cereal grains to be as much as four times higher than legumes (typically 3.0 t/ha *vs.* 0.7 t/ha). Although the protein content of legumes is much higher in legumes (30%) than in cereals (6%) the market value of legume grains, albeit higher than for cereals, does not compensate the grower for their low relative yield.

Many factors will contribute to an increase in the use of legumes. Cereals will continue to be the major source of protein and calories for human nutrition on a worldwide basis but an increase in importance of root and tuber crops and plantains over the next two or three decades is anticipated (66). Legumes can be expected to be one means of complementing the dietary quality of these starchy foods that are deficient in protein.

Another factor that has already caused a re-appraisal of biologial nitrogen fixation through legumes is the cost and availability of energy for production of nitrogen fertilizers. Already 20% of N fertilizer production in the U.S. is cost-ineffective because of the cost of energy (in the form of natural gas) for the process. Producer costs have been calculated as $160 per ton (67) whereas the selling price is in the range of $85 - $105 per ton. It is predicted that by as early as 1984, 60% of the world's ammonia production will be by the USSR, Eastern Europe, and the developing countries, and that ultimately N-fertilizer production will be economically feasible only in those countries with huge surpluses of natural gas (mainly Mexico and Indonesia).

Thus biological nitrogen fixation through the use of legumes may be resorted to increasingly, not only to reduce the cost of on-farm inputs, but also to save foreign exchange and avoid over-dependence on foreign powers.

But economic pressure alone will not guarantee adoption of biological nitrogen fixation-based technology without compelling demonstration of greater benefits from BNF by legumes than are currently recognized. The dramatic increase in interest in BNF since the energy crises of 1973/4 and 1979 has brought it under the scrutiny of agencies and individuals whose concern is its viability as a productive agricultural technology now rather than its often acclaimed potentials for the future. This should encourage the agricultural research community to undertake a comprehansive program of technology development in which the relative distribution of funding and manpower investment is realistically prioritized. Thus research aimed at stabilizing grain legume yields is likely to increase the contribution of biological nitrogen fixation in tropical farming systems to a greater extent than much of the research on the BNF process *per se* in grain legumes. Similarly, research involving selection of forage legume germplasm that is adapted to the soils and climates of the world's under-utilized savannahs, and development of appropriate legume-based pasture management and utilization technology can be expected to bring about a major increase in the use of biological

nitrogen fixation even without further research on the BNF process *per se* in those legumes. These statements assume of course that those BNF components of each legume production package that are acknowledged to be indispensable can be guaranteed, i.e. effective nodulation. Since this is not always the case, those specific aspects of BNF research which tackle the factors which limit nodulation and nitrogen fixation by legumes in tropical soils should be singled out and given highest priority. Unless pursued concurrently and with an intensity that assures that outputs on the BNF component for each legume are in synchrony with other advances in the use of those legumes, performance of the legume "package" will be seriously impaired.

Constraints to implementation of BNF technology

There are still many unknowns in the scientific understanding of BNF, and research into the biochemistry and genetics of the process is particularly intense and competitive.

But few, if any, of these unknowns are really constraining the implementation of legume-based BNF technology. The basic principles of inoculant technology have been known for many years and have already made major contributions to agricultural production initially in Australia and, more recently, worldwide as soybean cultivation has been increasing. The real constraints to fuller implementation of BNF technology relate to delivery of the technology, both to potential inoculant producers and to farmers, and acceptability of the technology, again by both the inoculant producers and farmers.

There has not been adequate demonstration, under realistic, farm-relevant conditions in the developing countries, of the yield increases and/or reduced fertilizer needs that are repeatedly stated to be the benefits of BNF technology. In some cases, inoculation trials have been performed and no response obtained. But these trials have been mainly with imported inoculants, the quality of which at the time of their use was not or could not be verified. Thus a related constraint is the lack of trained personnel with the essential combination of agronomic and microbiological skills for executing production-oriented research on BNF technology. Such research is necessary for adaptation of BNF technology including development of appropriate *Rhizobium* strains and inoculation procedures for use under the variety of circumstances encountered in the tropics and subtropics. It must be remembered that current inoculation technology as used in the U.S. and Australia is suited to legumes grown under favorable conditions with relatively high complementary agronomic inputs. Transferability of this technology to situations where the legumes are grown usually in marginal conditions with minimal inputs, and confronted with one or more soil and climatic stresses is in some doubt (68).

It is the genotype of the legume which is to be inoculated that is the prime determinant of the strain used in rhizobial inoculants, rather than the characteristics of the soil into which the inoculant will be introduced. This is contrary to what is expected by many first-time users of inoculants.

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For example, in providing inoculant services in Latin America and Hawaii, it has been common to receive data from soil analysis together with requests for inoculants. This illustrates that farmers expect that the selection of legume inoculant is made after consideration of local soil and climate, just as would be the choice of crop variety. Yet there is only one instance in which an inoculant strain recommendation for an inoculant in commercial production takes into consideration the soil characteristics into which it will be introduced. *Rhizobium* strain CB 81 is recommended for *Leucaena leucocephala* sown in acid soil and NGR 8 for alkaline soils (69).

When soil characteristics are very different, the response to inoculation and the relative performance of rhizobial strains is also different. Even when soils were selected for their apparent similarity, the performance of rhizobia in those soils was very different. It is not surprising therefore that some authors have advocated that simple "need-to-inoculate" trials always be performed at the local level due to the unpredictability of the response to inoculation (32,16,18). If carried to its conclusion, this suggestion would result in legume inoculation being tested, essentially by trial-and-error, at every site where legumes are to be grown. It is certainly to be hoped that inoculation technology is more transferable than this, otherwise its value as an agrotechnology is questionable.

It is well known that there are significant differences between sites in the size of their indigenous rhizobial populations (70,71) and in the range of strains of *Rhizobium* in the indigenous microflora (72,71). Such differences have been attributed to the effect of soil factors (72,73) though the possibility of widespread correlations between specific soil characteristics and rhizobial occurrence in tropical soils has not been critically examined.

It is also acknowledged that the response by tropical legumes to inoculation with rhizobia varies from site to site (32,16,74,75,15). Such variation has been attributed to: differences in number, effectivenss and competitiveness of native strains (76,77,71,17); variation in quality of the inoculant at its time of use (78); and to variation in soil nitrate levels (79). The possibility that the response to inoculation could be predicted on the basis of a more thorough description of soil and environmental characteristics has not been tested.

It is also known that the relative performance of strains selected under optimal conditions for a specific legume is variable, depending on the site to which they are introduced (15). With inoculants that contain a mixture of strains of *Rhizobium*, it is common for one strain to dominate in the nodule population that results from the inoculation (80,81). The possibility that rhizobial strains might be selected for adaptation to particular soil and environmental conditions is not presently exploited in tropical agriculture.

A serious constraint to fuller implementation of BNF technology is non-availability of domestically-produced, high quality inoculants within each of the countries of the tropics and subtropics. Thus factors

which deter government organizations or private enterprise from undertaking inoculant production in a particular country are also constraining BNF technology. Among these are: high capital cost of inoculant production plant (of type used in the U.S. and mistakenly assumed to be a prerequisite for any production plant); high operational cost associated with retaining a professional and well-trained staff to run the plant; operational risks associated with losses due to such factors as contamination; absence in most developing countries of an adequate infrastructure that would permit marketing and distribution of a biological production with notorious vulnerability to damage by high temperatures; reticence to embark on an enterprise in advance of official control standards being established (confounded by official reticence to set standards until there is an industry to be controlled); insufficient present demand and uncertain future demand for inoculants.

As has been referred to already, the present nature of the technology meets considerable farmer resistence, i.e. the coating of seeds with peat inoculant. In Brazil, packets of inoculant are included "free" by some seed distributors with all seed sales. However, the inoculant is frequently discarded by farmers not only because of the nuisance associated with use of the inoculation on a field scale, but also in part because of an unfortunate impression that if inoculant is "free" it is suspect and of little value.

The cost of inoculants is not usually a constraint to the use of inoculant by farmers who outlay capital for seed. Inoculant will seldom exceed 1% of the seed cost. For subsistence farmers who do not ordinarily purchase seed off-the-farm, the capital outlay for incoulant, albeit small, may be a disincentive to the use of inoculants. Cost becomes a more important consideration with granular forms of inoculant in which the rate of application is much greater than with seed-applied inoculant.

BNF technology is a difficult technology to deliver by normal extension mechanisms. Thus a lack of illustrative and explanatory pamphlets and other aids both for extension agents and the farmers with whom they have contact is also a constraint on implementation of BNF technology at the farm level.

Furthermore, few of the senior administrators and decision makers who determine agricultural policy in the developing countries are fully aware of the applications for legume-based BNF technology in the agriculture section of their countries. Most policy makers are aware of some of the attributes of legumes. Relatively few of those individuals appreciate the role played by biological nitrogen fixation in legumes and among those few an even smaller proportion recognizes that it may be essential to employ specific technologies to ensure that nitrogen fixation occurs at all, let alone at a maximal rate. Thus there is a need for educational material, specifically developed for this clientele group, bringing to their attention the real need to adapt currently available technology to the particular circumstances in which it is to be employed in their country.

As BNF technology is being implemented, new constraints are emerging that are best described as "scientific" and are researchable. For example, some countries do not have peat deposits suitable for carrier materials for inoculant production and alternate materials must be identified and validated. Also, specific soil and climatological stresses such as extreme soil acidity and the associated high levels of toxic elements like aluminum and manganese may require selection of strains of rhizobia tolerant to those conditions for use in inoculants.

It could be suggested that the large number of researchers with the competencies required for BNF research but who expend their energies and resources researching aspects of BNF other than limiting factors such as the examples cited above is also a constraint on fuller implementation of BNF technology. Funding agencies do not always recognize a distinction between applied and less useful research that competes for resources under the general subject matter area of biological nitrogen fixation. Biological nitrogen fixation has great pertinence to agriculture production in developing countries but not all research conducted under the BNF umbrella is applicable in agriculture.

Scenario for full implementation of BNF technology

Given that the constraints on fuller implementation of BNF technology are not solely scientific but include cultural, socio-economic and political factors, the scenario in which BNF might realize its potential would necessarily be multi-faceted and comprehensive.

The current trend toward energy-efficient farming systems to reduce capital outlay for fertilizers that must be imported can be expected to continue and intensify. Because of the high energy consumption during manufacture of nitrogen fertilizers, their price and availability is influenced increasingly by oil-rich nations. There is added attractiveness in alternate nitrogen sources to avoid even further dependence on foreign powers. Legume-based BNF technology is the major option available and is likely to be resorted to more and more. As has been described, the use of legumes and appropriate inoculant technology has the potential to increase the amount of biologically-fixed nitrogen entering agricultural production systems. Given that the main value of legumes is their high-protein grain, rather than their nitrogen contribution to non-leguminous food crops such as cereals and root crops, the scenario for full realization of BNF technology's potential would need to include a swing in consumer preferences away from crops that depend so heavily on nitrogen fertilizer. Thus, in the gambit of BNF research priorities, attention will need to be given to learning the cultural and scientific bases for these preferences and to alleviating where possible the constraints to greater consumer acceptance of legumes.

As explained earlier in this report, the major increases in benefits from legume-based BNF technology will arise through: an increase in the total acreage in legume production; innovative use of legumes in roles they have not previously occupied; and by ensuring that biological nitrogen fixation

in those legumes is maximal through appropriate inoculation technology. Much remains to be done to improve the biological nitrogen fixation components in the technology package for legumes in the role they currently play in agriculture. There is a wide discrepancy between farmers' yields and the known yield potential of the grain legumes. Furthermore, it is disconcerting that in the majority of reports of legume trials that included rates of nitrogen fertilizer application, the legumes responded to nitrogen fertilization--disconcerting because this means that even when legumes were grown under favorable management in experiment stations, let alone in farmers' fields, the symbiotic association of the legume with *Rhizobium* was defective. There is therefore the potential to double or triple the nitrogen benefits described in this report through development of technology that would assure establishment of maximally effective rhizobial symbioses in tropical legumes under tropical conditions.

Greatest future potential would appear to rest in the development of: legume-based pastures and viable multiple-cropping systems including legumes for under-utilized savannahs; agroforestry systems that combine fast-growing, nitrogen-fixing trees, leguminous and other crops to meet the food and fuel requirements of the rural poor; fast-growing leguminous trees for reclothing water catchment areas following forest clearance; legume-based cropping systems to give sustained productivity in tropical soils following jungle clearance which typically exhibit a rapid decline in fertility under conventional cropping; selection of deep-rooted, drought-tolerant leguminous trees that can serve as browse species in the world's dry lands.

Reference has already been made to the need to exploit fully the variation in host plant x rhizobial strain x environment interaction in selection of the optimal BNF package for each circumstance. This would require that all current legume programs retain the services of a trained professional microbiologist, a suggestion that is just not practical. Firstly, few legume programs can afford the luxury of a full-time microbiology position and secondly, there is currently a worldwide shortage of professional soil microbiologists that is unlikely to be alleviated significantly for about ten years. The world's major multidisciplinary legume programs should, however, have their own microbiologists. This is already the case with the IARC programs for beans, cowpeas, pigeon peas, groundnuts, chickpea, and the tropical forages. INTSOY, working with soybean, has its own soil microbiologist. Also there are several national legume programs into which microbiological support is integrated through a participating institute with expertise in the BNF area (e.g., Brazil, India).

The needs of the multitude of other legume programs for BNF expertise could be met through the provision of one (or more) BNF Resource Center(s) established to provide technical assistance, offer support services (germplasm and information), provide professional and technical training, and conduct such research as may be necessary for adaptation of BNF technology to specific local conditions but which is beyond the capability of local researchers. Such centers would require a critical mass of BNF researchers to be able to carry out a comprehensive support program and

still retain a capability to respond to technical assistance requests that are sometimes difficult to anticipate. The BNF Resource Center(s) would best be located at universities in developed countries and preferably in the tropics. Location of a BNF Resource Center at a university facilitates provision of professional training, an important output for assuring that ultimately national institutions in developing countries can sustain their own BNF programs. Short-term, non-degree training programs in BNF technology should be offered to key personnel responsible for providing bacteriological backstopping to production-oriented research programs involving the legume/*Rhizobium* symbiosis. This is more effective in the short-term than Ph.D. or M.S. programs which tend to be a passport out of research into better paid administrative positions for many graduates returning to their home country. The short courses should be mounted in cooperation with developing country institutes to generate a regional capability for offering such courses. They should be complemented by on-the-job training tailored to the needs of selected individuals that would be conducted at the BNF Resource Center and include visits to pertinent industry facilities.

Such BNF Resource Centers would engage information specialists for development of communications materials suitable for the many clientele groups to whom BNF technology has to be delivered. This would range from newsletters for administrators to pamphlets for extension agents and include updating developing country researchers, who often do not have access to libraries, on progress in BNF research.

There has been an increased tendency in agricultural research to focus manpower and resources on improvement of single commodities. Thus the IARCs are characterized by multidisciplinary teams with specific crop and/or geographic mandates. Similarly in the CRSP activities under Title XII a commodity approach has emerged. The suggestion for establishment of a BNF Resource Center would be considered by some as going against this trend and viewed as a return to discipline-oriented research. This author contends that the key element in the acknowledged success of commodity programs such as some of those in the IARCs has been that they are highly focused and actively managed in pursuit of well-defined research priorities rather than attributable to the commodity approach *per se*. A program investing manpower and financial resources in an actively managed, carefully prioritized BNF program sharply focused on the constraints to full implementation of BNF technology can be expected to make real progress toward that end. The specialized and sophisticated nature of *Rhizobium* bacteriological expertise and the scarcity of experienced manpower is further justification for assembling a critical mass of rhizobiologists in a single BNF Resource Center.

An additional advantage in the existence of such a BNF Resource Center would be a capability to extend BNF technology developed at a particular IARC to crops and regions outside the crop and geographic mandate of that IARC but in which there is a strong likelihood that the technology is immediately utilizable. Staff of the BNF Resource Centers would travel as required and undertake short (1-3 months) or longer (3 months - 3 years) assignments in support of specific outreach activities when warranted. Conceptually the personnel of the BNF Resource Center would have their

attention drawn to researchable constraints on BNF technology in real agricultural situations in the developing countries when interacting with local cooperators during duty travel. The BNF Resource Center would embrace within its research program specific projects aimed at resolving those constraints. Additionally, the Resource Centers would work closely with other universities and research organizations to which specific research on factors limiting BNF utilization could be referred under sub-contract when those institutions are recognized centers of excellence in the pertinent sub-discipline and have a comparative advantage to provide the required support.

The BNF Resource Center would need to develop links with commercial inoculant producers to mount appropriate assistance programs for government organizations or private enterprise in developing countries contemplating inoculant production. Such programs would cover not only technical aspects of the production of inoculants but also the business aspects of small enterprise production, marketing and distribution of inoculants. The BNF Resource Center should develop specifications, including sources of all equipment items, for inoculant production facilities that would be feasible at levels of capital investment ranging from $50,000 to as high as $1 million. The Center should also advise governments on an appropriate mechanism for quality control.

The Center would also need to develop strong links with major legume germplasm centers and those involved in legume improvement to encourage simultaneous exploitation of host legume and rhizobial germplasm in selections for particular soils and climates.

The BNF Resource Center would take a major organizational responsibility for calling such workshops and scientific meetings as may be necessary to coordinate international experimentation and provide for dissemination of results.

The major activity to be undertaken by the BNF Resource Center would be the coordination of a competently executed sequence of standardized experiments designed to generate the data necessary to quantify the economic yield benefit attributable to legume inoculation under field conditions. Such trials would also serve as local demonstrations of the benefits from legume inoculation.

The core budget for such a BNF Resource Center should be guaranteed by the host government through its agency responsible for international development. The host insitution (university) cannot realistically be expected to provide direct financial support for such a Center given that the Center staff will not have substantial conventional instructional responsibility and that the research ouput will aid mainly foreign nations with only minor spin-off benefits for agriculture in the state or province where the Center is located. The mandate of a BNF Resource Center is international and therefore the support should be international.

There is understandable reticence on the part of international funding agencies to expend resources in a center located in a developed country.

This author contends that it is in the best interests of the developing countries that they be supported in their BNF programs by a Center located in the tropics but sited in a developed country where it can receive unimpeded logistic support for its sophisticated operations and enjoy continuity of service from high calibre professional staff. Such a Center would be ultimately more cost-effective than fragmented support to a myriad of in-country programs, an approach that often causes wasteful duplication of effort. Furthermore, support of a BNF Resource Center, for example in the U.S. with funding by USAID, would be prudent use of public funds. A maximum share of the Center budget would be expended in the U.S. sustaining employment of U.S. residents and strengthening a U.S. institution without lessening the level of development support for the developing countries. Additionally, a greater degree of control could be exercised over the activities of a U.S.-based Center than is possible with grants to foreign institutions.

Agencies that could be anticipated to be in the portfolio of contributors to a BNF Resource Center would be: FAO, UNEP, Unesco, and UNDP. Technical assistance on a continuing basis to any specific country ought to be funded externally as a special project with funding arranged by that country drawing on whatever national budget and international development assistance grants or loans are accessible to it.

At the request of OTA the author suggests the following distribution of $10 million in furtherence of the implementation of legume-based BNF technology. In proceeding it is assumed that the $10 million is additional to current support for BNF.

A five-year period is judged sufficient to expect an impact among the clients for BNF technology. Distribution of $10 million in support of a five-year program would be as follows:

BNF Resource Center

Salaries (6 professional and 12 subprofessionals)	$ 3,000,000
African network of trials/demonstrations	200,000
American network of trials/demonstrations	200,000
Asian network of trials/demonstrations	200,000
Training programs in technology	500,000
Professional (M.S., Ph.D.) training	150,000
Information services	120,000
Germplasm services	100,000
Workshops/conferences (3 regional, 1 global)	270,000
Research	
Simplification of inoculant production	90,000
Innovative inoculation methods	90,000
Stress tolerance in inoculant strains	150,000
Quantifying N fixation/cycling in cropping systems in the tropics	220,000

Necessary services	$ 280,000
Contingency fund	60,000
Indirect costs	1,160,000
BNC Resource Center sub-total	$ 1,500,000*

Pilot Demonstration Plants

Zambia (small-scale)	750,000
Lower Coast (medium-scale)	550,000
Offshore (beginning pilot scale)	1,700,000

Strategies Flowing From Research Initiatives in Metals/Materials/Energy | 500,000

Socio-economic Evaluation of BNC Technology | 250,000

Network Programs of BNC Resource Center Beginning Scale In:

Zambia	500,000
Bangkok	500,000
Peru	500,000
Grand Total	$11,000,000

*These figures do not cover the costs of operations overhead and do not fix the cost of a Resource Center appropriate equipment and buildings. Two already have been established and are operating in the proposed BNC Resource Center mode (Lima, Universidade de Ouro Preto, Brazil).

Impact of scale-specific implementation of BNC technology

The use of engineers to operate either high-technology large-scale plants or low-technology or intermediate-scale plants. The production process and therefore labor requirements and, in the case of medium-scale, the capital requirements. Hence, while the economics of mass production in developing countries are superior to Lowtech. If BNC technology were to be employed in the U.S. for example, this would necessitate a swing away from the highly mechanized mass-production technology employed and a return towards the Lowtech labor-intensive technology in semi-manual use the use of hardware as power assistance or as multiple-tools and operations in one. Such predictions are more difficult to make than large-scale.

Hightech technology does not necessarily mean dependence upon the domestic big labor. The international and intra-regional division of labor, which the technology involves, serve different or stage that can not easily be mechanized.

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PAPER NO. 6. A LOW FERTILIZER USE APPROACH TO INCREASING TROPICAL FOOD PRODUCTION

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ABSTRACT

Low fertilizer use in the tropics appears to be a desirable goal involving several strategies aimed at increased crop production with minimal use of inputs.

Due to the nature of the general response curve from added nutrients, the use of small amounts of an input may result in substantially increased production. The philosophy employed here is to use less than maximal inputs in order to achieve the highest output:input ratio or to make maximum use of inputs rather than to maximize yields which often requires a much greater use of scarce inputs such as fertilizer, capital, etc.

Because of their inherent high fertility, limited inputs are necessary on the high base soils (18% of tropical soils) when there is sufficient water. Small amounts of nitrogen, phosphorus and/or micronutrients are sufficient. High yielding varieties should be used on these soils to take advantage of the naturally high soil fertility.

On the low base soils (51% of tropical soils) which have high soil acidity and aluminum and the associated phosphorus deficiency, the production package should be considerably different. Lime may be necessary to reduce the availability of toxic aluminum. This will also increase the availability of phosphorus. However, additional phosphorus and/or sulfur will probably be necessary for increased yields.

The use of crops which will tolerate adverse soil conditions should also be employed on these soils. This reverses the philosophy of changing the soil to fit the crop (an expensive procedure on these soils) to one which takes the soil as it is or changes it only minimally and uses crops which grow well under these conditions. Examples of such crops are upland rice, cassava, sweet potatoes, cowpeas and some grass and legume pasture crops.

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With both high and low base soils, nitrogen is probably the most limiting element. Low yields in many tropical areas reflect a low level of nitrogen availability. Low yields and the lack of nitrogen result in low levels of protein for local human consumption, resulting in malnutrition. An excellent source of protein and of nitrogen are leguminous crops. These crops have the potential to biologically fix nitrogen from the atmosphere when growing in association with the correct bacteria. When these crops are used, the nitrogen input into the cropping system can be increased several fold. This technology is inexpensive, easy to use and available. Most important, it can substantially increase the yield of crop plants as well as meat and milk production to the benefit of the small farmer and the landless poor.

The Tropics

The tropics are that area of the world located between 23.5 degrees north and south of the equator. Thirty-eight percent of the earth's land surface (about 5 billion hectares) and 45 percent of the world's population (about 1.8 billion people in 1975) live in this area. Most of the world's developing countries lie in the tropics, although some areas in the tropics are not considered developing and many developing countries are outside the zone.

Because of the proximity to the equator, the tropics experience little change in temperature during the year. Variation of daylength is also relatively small compared to temperate zones. Rainfall is the variable which differentiates tropical areas. About one quarter of the tropics mostly near the equator, have a rainy climate. Seasonal climates - those with a distinct wet and dry period - cover about one-half of the tropics. Dry climates, usually having a short wet season, cover 16 percent of the tropics. Tropical deserts comprise the remaining area, about 11 percent.

In 1960, the world's population reached three billion; by 2000 six billion will inhabit the globe. Much of this population increase is taking place in the tropics, primarily in Asia. This population explosion will place a much greater strain on the resources of the tropics. Presently malnutrition, particularly protein deficiency, is widespread throughout the area. Protein deficiency, a lack of high protein food, is more specifically, a lack of nitrogen in the soil-plant system.

Protein synthesis in the plant only occurs when there is sufficient nitrogen in the soils, therefore, a lack of soil nitrogen decreases the rate of protein production in plants and hence, in the food supply. Inexpensive and efficient means to increase nitrogen in the tropical system are presently known. Use of these simple technologies could increase protein production and eliminate much of the misery and suffering in the

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tropics caused by poor nutrition.

Land Use

About ten percent of the tropics are cultivated for food production and pastures and meadows account for an additional 20 percent. The President's Science Advisory Committee estimated that only 500 million hectares were cropped in 1967 even though the potential for cultivation was 1.7 billion hectares. Grazing occupied one billion hectares although the potential was 1.6 billion hectares. These figures indicate that there is potential for much expansion in agricultural production for the tropics.

The use of land will vary depending on soil factors, climate, economic, social and political factors. In general, the farming systems are vastly different than those practiced in the United States.

Farming Systems

Farming systems according to Sanchez (1976) are:

1. Shifting cultivation, where the land is cropped and then abandoned when yields fall, cover 45 percent of the tropical area;
2. Settled subsistence farming, comprise 17 percent of the tropics;
3. Nomadic herding, covers 14 percent of the area;
4. Livestock ranching, make up 11 percent, and
5. Plantation systems, which cover 4 percent of the tropical area.

If food production is to be increased and the majority of people benefit, programs must be aimed at the small farm rural population since small farms are the most numerous. In tropical Asia, 75 percent of all farms are smaller than 2 hectares (5 acres), (Harwood and Price, 1976). Sixty-nine percent of Central American farms are smaller than 5 hectares (12 acres) according to calculations from data presented by CATIE, (1974). The average farm size for twenty tropical African countries reporting such data in the 1973 FAO Production Yearbook was 5.4 hectares. Studies by CATIE

(1974) and Pinchinat et al. (1976) showed that about 70 percent of food consumed in Columbia and Central America is produced on small farms. Therefore, any strategy dealing with food production in the tropics must deal with the small farmer.

Tropical Food Crops

Most frequently named tropical crops are sugarcane, pineapple, bananas, coffee and tea. These crops, however, contribute little to the nutrition of people in the tropics since they are exported, largely to the temperate zone. The major food crops consumed by tropical people are rice, cassava (root crop), corn, sweet potatoes, yams, wheat, sorghum, peanuts, potatoes, and dry beans in order of decreasing importance.

The total area cultivated for these twelve crops is only 300 million hectares compared to one billion hectares of pasture and meadow. In summary, we can characterize the tropics as a region where population pressures are often highest and likely to remain that way in the near future. On the positive side, there is a resource base in the soils and climate to expand production and meet population food needs. The introduction of simple technologies could greatly increase food production, helping to stabilize these countries in many ways.

Much of this increase must come from a better utilization and understanding of the tropical soils' capacity to produce. Therefore, the bottom line question becomes a question of soil fertility.

Soil Fertility Concepts - A General Statement

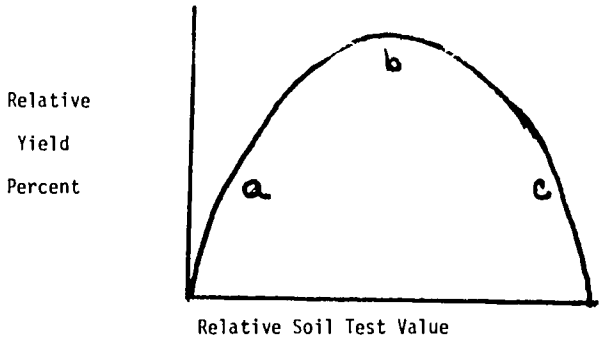
A fertile soil has the capacity to produce a high yielding and high quality crop. More specifically, it is a soil which does not limit production due to physical, chemical or biological constraints.

Numerous essential elements are required for crop production, including carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, calcium, magnesium,

sulfur, iron, copper, boron, zinc, manganese and molybdenum. The first three are obtained from water and the carbon dioxide of the atmosphere. The rest must be taken up from the soil by the plant's root system. Another important element is aluminum. Although not considered essential to growth, if excessive, it is severely toxic to plants, reducing plant growth and crop yield.

Soil tests attempt to predict crop yield for a number of elements. These tests determine as nearly as possible the soil's capacity to supply the elements necessary for plant growth. Where the soil's supply is considered insufficient for a desired yield, additional amendments are supplied to the soil increasing its "fertility", or ability to produce.

A typical soil test crop response curve follows:



The response curve has three general areas. Area "a" is the part of the curve where small inputs of nutrients result in increasingly greater production, i. e. the output:input ratio is favorable. Area "b" is a relative plateau where increasing fertilizer inputs do not result in increasing yields and the output:input ratio is poor since yield can be maximized at a lessor input rate. Area "c" represents the portion of the curve where additional nutrients actually reduce yield because of excessive or toxic concentrations.

Obviously this is a situation to be avoided. This is the situation with aluminum in many unlimed soils of the tropics. A few simple equations help to explain the relationship between the soil and plant nutrients. The general relationship between elements in the soil and plants may be seen in the following where E represents an element used in plant growth.

$$\text{Soil Solid phase}_{(E)} \rightleftharpoons \text{Soil Solution phase}_{(E)} \rightleftharpoons$$

$$\text{Plant Root}_{(E)} \rightleftharpoons \text{Plant Top}_{(E)}$$

As the above equation indicates, an element is taken in by plant roots and moved to the plant top as a soluble element dissolved in the soil solution. Elements are generally considered to be available when they are in the solution phase of the soil. In many instances an element is unavailable to the plant because it is not in a form the plant can use, that is, not in solution. Another equation helps to explain the soil fertility - plant nutrition relationship. Again, E represents an element necessary for plant growth.

$$\text{Unavailable}_{(E)} \rightleftharpoons \text{Available}_{(E)}$$

This simple equation shows the equilibrium in the soil which determines if the nutrient can be used by a plant. This equilibrium is controlled by the soil environment - soil pH, microorganisms, oxygen, water, temperature.

Soil Acidity and Liming

Soil pH is a term used to delineate the relative acidity or alkalinity of soils. It is important because soil pH affects the availability of most nutrients. The soil pH scale follows:

1 2 3 4 5 6	7	8 9 10 12 13 14
More Acid	Neutral	More Alkaline or basic

Early in history, man learned to cultivate high base soils (soils high in calcium, magnesium and potassium and low in aluminum) because they are naturally more productive. The majority of cultivated soils of the tropics are not acid, (Sanchez, 1976) although the majority of soils of the humid tropics are acid. Soils of tropical America are more acid than those of tropical Africa and Asia.

Liming of acid soils has been a long standing practice. For a long time, the practice involved adding sufficient lime to raise the soil pH to 7 (neutrality). However, in the early 1950's soil chemists showed that exchangeable aluminum, so toxic to plants, was the predominate element in acid mineral soils, as contrasted to organic soils, with a pH of 5 or less (Coleman and Thomas, 1967). Exchangeable elements such as calcium, magnesium and potassium are positively charged and are held in the soil by negatively charged sites. Strongly acid soils (pH less than 5.0) favor aluminum availability to plants, whereas above pH 5.5, calcium, magnesium and potassium prevail.

High soil solution aluminum, the available form for plants, causes reduced plant growth because aluminum is toxic to plants. Evans and Kamprath (1970) found that an exchangeable aluminum saturation of 60 percent (% of negative sites with aluminum) was required before a large amount of aluminum was present in the soil solution. Work in Guyana showed that an aluminum saturation of less than 60 percent resulted in less than one ppm -one part per million - in the soil solution (Cate and Sukhai, 1964). Increasing fertilizer results in an increase of aluminum in the soil solution (Fried and Peech, 1946). Therefore, use of high amounts of fertilizer could increase aluminum toxicity if the soil is sufficiently acid. Available aluminum in the soil solution decreases with increasing organic matter since aluminum forms very strong complexes, making it unavailable.

Research by Kamprath (1970) showed that elimination of all the exchangeable aluminum was not necessary to obtain maximum yield in field and greenhouse studies. Maximum yields of corn, soybeans and cotton were achieved with aluminum saturation values of less than 45, 20 and 10 percent respectively where soil pH was low. Growth of sugarcane was severely depressed on a soil with an exchangeable aluminum saturation of 70 percent. Addition of lime to reduce the aluminum saturation to 30 percent resulted in a four-fold increase in sugarcane growth (Abruna and Vicente-Chandler, 1967).

Finding the Correct Lime Level

The work cited above, plus other work, has shown that lime should be added to reduce the toxic levels of aluminum. This results in a much lower soil pH and the use of much less lime than the traditional approach of liming to neutrality. Liming beyond this point has resulted in reduced yields on soils of the tropics due to deficiencies of manganese, zinc and/or iron. Like aluminum, manganese becomes available as the soil becomes more acid (Block, 1967). Some soils are low in aluminum but high in manganese. In either case, liming will reduce the availability of manganese. However, since manganese is an essential element, liming must not be so high as to make the element unavailable and reduce the soils productivity.

Our liming philosophy, therefore, should be to add sufficient lime to decrease the availability of aluminum without limiting manganese to the point of deficiency where that is a problem. According to Sanchez (1976) the factors to be considered are (1) the amount of lime needed to decrease the percent of aluminum saturation to a level at which the particular crop and variety will grow well, (2) the quality of lime and (3) the placement method. Kamprath (1970) suggests that lime recommendations be based on the amount of exchangeable aluminum and that lime rates be calculated by multiplying the

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and soil-incorporated lime applications.

When very acid leached soils are limed to pH 5.5, most of the root development occurs in the top soil. The highly toxic aluminum in the subsoil prevents deeper root development. In such cases, plants suffer from water stress during short term droughts even though the subsoil is still moist. Gonzales and Kamprath, (1973) as cited by Sanchez (1976) incorporated lime at 0 to 6 inches and 0 to 12 inches in a Brazilian soil having excellent granular structure which permits deep incorporation with a roto-tiller. Deep placement of lime resulted in deeper root development, diminished water stress during drought and increased corn yield of 20 to 25%.

Nitrogen

As previously mentioned, nitrogen is very crucial to crop production and the availability of protein to tropical people. Acid soils contribute to that problem largely because nitrogen fixation by leguminous plants is reduced by soil acidity. In nitrogen fixation, the nitrogen of the atmosphere is made available to plants. Next to water, nitrogen is the most limiting factor in crop production in the tropics. It is necessary for protein synthesis and production. Plant-available nitrogen is derived from organic matter, leguminous nitrogen fixation, fertilizers and animal manure. The main source of nitrogen in the tropics is organic matter decomposition. Therefore, practices which maintain organic matter in the soil are essential. Organic matter not only provides nitrogen, but it improves the soil's physical condition and water-holding capacity increasing water to plants and decreasing the soil temperature.

Nitrogen Supply Process

Nature has provided the nitrogen for crop production since the beginning of time through natural processes. However, seldom has it provided

an abundance of nitrogen for long and sustained periods of crop production on the same land area. Moreover, natural supply processes at their best have seldom provided enough plant-available nitrogen to achieve the level of food and fiber production needed to meet the demands of present day crop production. Bartholomew (1972), states the natural supply processes include (1) mineralization of nitrogen from soil organic matter and from crop residues and the reverse process of immobilization in the decomposition of plant and animal debris and soil organic matter; (2) fixation of nitrogen from the atmosphere, largely through biological processes; (3) addition of nitrogen through rain and other forms of precipitation.

The nitrogen in soil organic matter is an important source of nitrogen for crop production. However, soil nitrogen is not inexhaustible, it declines in quantity in the soil as it is used by crops grown on the land, harvested and consumed. Nitrogen in soil is largely organic, replenished by periodic additions of fresh plant or animal residues.

Under normal conditions, nitrogen is added to the organic supply in soil each year through crop residues, (immobilization) but it is unavailable to plants. Also through biological decomposition, organic nitrogen in the soil is continuously converted to the inorganic form, (mineralization) which is available to plants. Under any sustained system of crop and soil mangement, these two processes tend to approach each other in magnitude so that mineralization balances immobilization, (Bartholomew and Kirkham, 1960). When this balance is attained, the system is considered to be in equilibrium.

The implications and consequences of an equilibrium in the soil's organic nitrogen need to be emphasized. At equilibrium, the amount added to the supply of organic nitrogen is essentially balanced by a like amount of decomposition. The total quantity of soil nitrogen remains unchanged and the net amount that can be and is supplied to a crop is zero (Bartholomew, 1972). During periods of virgin or noncultivated conditions, such as a forest,

certain soils tend to build up organic matter, accumulating as much as 10,000 kg per hectare of nitrogen under virgin conditions. During the first years of cultivation, these same soils may supply as much as 400 kg per hectare of available nitrogen per year to crops (Schreiner and Brown, 1938). As cultivation continues and the organic nitrogen declines, the quantity of nitrogen becoming available each year also declines. After long periods of cultivation, the soil's organic matter becomes exhausted since it is the major source of available nitrogen and, unless legumes are grown, or the soil fertilized with nitrogen the annual available nitrogen is depleted except for the limited amount from rain water and nonsymbiotic nitrogen fixation.

Many of the major land areas of the tropics have now been cropped for extended periods and the organic matter stored under virgin conditions has been dissipated. With little or no use of nitrogen fertilizer, tropical crop yields reflect the paucity of the natural nitrogen supply from rainwater and nonsymbiotic nitrogen fixation.

Yields of corn of 600 - 1200 kg per hectare and of wheat of 400 - 800 kg per hectare require a nitrogen supply only a little larger than could be expected from rain and from nonsymbiotic fixation. Yields this poor remove no more than 15 kg per hectare of nitrogen from the land in the harvested grain products. Such minimal yields can be sustained for a long period of time without fertilizer or legumes but do little to sustain the protein needs of animals or humans.

However, with inclusion of legumes in the rotation either as a primary food crop or as a green manure, the nitrogen supply in the soil-plant system can be increased substantially. This will result in increased crop and protein production, meeting the primary malnutrition problem of the tropics.

Biological Nitrogen Fixation

Despite the great use of chemical fertilizer today, biological nitrogen fixation processes have been responsible for providing most of the nitrogen currently used by and tied up in plants and animals and in the decomposed residues found in soil, supplying the major part of the nitrogen for crop production in world agriculture (Bartholomew, 1970).

According to reviews by Henzell and Norris (1962) and Jones (1972), Rhizobium bacteria fixation accounts for 100 to 300 kilograms of nitrogen per hectare a year. Whitney (1975), however, in tropical research reports an annual range of 47 to 905 kilograms of nitrogen per hectare for pure stands of an improved variety of Leucaena leucocephala.

Obviously, the potential to increase the nitrogen in a cropping system several fold (15 kg/ha vs several hundred kg) using legumes in crops or pastures is possible. Jones (1972) found that differences among adapted species within a specific environment were closely related to dry matter production (total growth). This suggests that there is little difference in the capacity of legumes to fix nitrogen as long as they are adapted to the environment. Factors affecting dry matter production, such as moisture or nutrient stress, solar radiation, diseases, and other factors will determine nitrogen fixation.

Pastures and meadows make up the greatest portion of the land which is managed for food consumption, therefore, potential increases in food are large if this segment of tropical production could be increased. Another important factor to consider is that production from pastures and meadows results in increased meat and milk, both high in quality proteins.

Some individuals consider cattle to be a very inefficient source of protein for humans in the food chain. This is true when animals and humans compete for grain. It is not true when cattle convert forage from pasture and meadow lands into meat and milk. The determining factor will be how

how much and what kind of land is available for cultivation.

Productivity of Improved Grass-Legume Mixtures

Beef production will normally increase by a factor of two to four (Jones, 1972) due to establishment of grass-legume mixtures. Few experiments provide long term data. Sanchez (1976) cites Shaw and Mannetje (1970) who introduced a legume, Stylosanthes humilis into a Queensland pasture and followed beef production for seven years. The following table summarizes the results:

Beef Production Systems in the Tropics

Treatment	Beef kg/ha
Grass alone	24
Grass & fertilization 1/	62
Grass & legume	93
Grass & legume & fertilization 1/	148

1/ Annual application 10 kg P/ha as 0-20-0 and 40 kgK/ha plus Mo.

It is interesting to note that the grass-legume treatment produced more beef than did the fertilizer treatment. The grass-legume mixture plus fertilizer more than doubled the beef produced by grass alone plus fertilizer, demonstrating the effect of adding nitrogen to the system via the legume.

Another plant, a fern, Azolla, grows in association with rice, the major crop of Asia. Azolla does not fix nitrogen itself, however, it grows in symbiotic association with blue green algae Anabaena azollae (Clark, 1980). About ten percent of China's rice (3.2 million acres) are grown with Azolla. He states that yields of rice of six tons per acre have been reported along with 60 tons of Azolla. Rice with conventional fertilizers yields about four tons per acre. Preliminary experiments indicate that Azolla will produce 50 to 180 pounds of nitrogen per acre, making it highly attractive as a natural nitrogen source.

Another nitrogen fixing system has been reported by Dobereiner and her associates in Brazil (Dobereiner, 1961; Dobereiner et al., 1972; Dobereiner and Day, 1975). Their work has focused on nitrogen fixation by nonleguminous plants. This work has a great potential if efficient strains of bacteria can be found. At present, this rate of asymbiotic fixation contributes only about ten kg nitrogen per hectare per year.

Recent evidence by Dobereiner and Day (1975) suggests that symbiotic nitrogen fixation takes place in some tropical grasses. The nitrogen fixation takes place in the rhizosphere (soil close to root), however, since this nitrogen is taken up directly by plants. it is considered symbiosis. Laboratory experiments suggest that the magnitude of this mechanism may be on the order of 1 kilogram of nitrogen per hectare per day. This system needs to be taken out into the field in order to determine nitrogen fixation under more realistic conditions.

Field beans, Phaseolus vulgaris, a staple in many Latin American Countries, appear to fix little nitrogen (Sanchez, 1976). This is attributed to poor nodulation characteristics which may be due to low phosphorus or high aluminum which inhibit Rhizobium activity. When these legumes are grown, they contribute nitrogen to the system, in an organic form becoming part of the organic matter and eventually available via mineralization or the breakdown of complex nitrogen compounds into simpler nitrogen compounds.

Nitrogen Release from Organic Matter

Plant-available inorganic nitrogen in most tropical areas shows a marked seasonal fluctuation (Sanchez, 1976). This is characterized by a slow nitrate (available form to plants) build-up during dry season. There is a large, but short-lived, increase at the beginning of the rainy season, and a rapid decrease during the rest of the rainy season due to leaching.

Since the level of plant-available nitrogen in many tropical soils is

low, the use of extra nitrogen (green manure, animal waste or fertilizer) will almost always increase yields of crops if these crops can make use of the extra nitrogen. Therefore, if nitrogen fertilizer is to be added, it should be at rates which can be justified economically.

Since most nitrogen fertilizer is very transitory due to its soluble nature, the use of nitrogen in particular, should be timed to the needs of the plant in order to avoid excessive loss due to leaching rain or denitrification, the loss of nitrogen as a gas. Numerous experiments in both temperate and tropical climates have shown that the application of nitrogen soon after planting when demand is highest will result in higher yields and more efficient use of the applied nitrogen.

This is not a serious problem with organic nitrogen from legumes or animal waste since these complex organic materials are not subject to leaching like the more soluble inorganic fertilizers. This suggests a greater efficiency for organic forms in high rainfall areas. In some cases nitrogen addition alone will not increase productivity substantially as other elements may be deficient or toxic. Such is the case with acid soils. Lime will promote legume establishment and growth by reducing aluminum availability and increasing the availability of phosphorus. Phosphorus deficiency is a serious problem in many tropical soils and must be considered in the fertility regime.

Phosphorus

Following water and nitrogen, phosphorus is probably the most limiting nutrient in the tropics. This is particularly true in the acid soils of the humid tropics since the high aluminum and iron concentrations render phosphorus unavailable to plants. The term used to denote this is phosphorus fixation. When phosphorus is added as soluble monocalcium phosphate ($Ca(H_2PO_4)_2$) the soil pH is reduced to 1 to 1.5 (very acid).

The acid dissolves aluminum, iron, potassium and magnesium compounds and unsoluble phosphates of iron and aluminum are formed. The higher the phosphorus - fixing capacity of the soil, (Sanchez, 1976), the higher the content of iron and aluminum oxides. Higher exchangeable aluminum also increases the soil's phosphorus fixation ability. Because of the fixation process, higher rates of phosphorus must be added to achieve the same level of plant-available phosphorus compared to a soil which does not fix phosphorus. The amount of phosphorus added to a soil to get 0.2 ppm phosphorus (adequate level) in the soil solution can vary from 20 to 30 pounds per acre to as much as 1500 pounds per acre. A general recommendation for corn and rice in Latin America is 100 to 150 of kg P_2O_5 per hectare for corn and from 0 to 60 kg for upland rice. In many cases soils respond only slightly to phosphorus unless they are first limed (CIAT, 1971). In an experiment, limed corn plots showed a marked response to 50 kg P_2O_5 per hectare with a yield increase from 0.8 to 3.2 tons per hectare. In limed plots rice did not respond to phosphorus.

Management of Phosphorus Fertilizer

Phosphorus responses are common in many tropical soils. Well calibrated soil test procedures can identify the soils with a high probability of phosphorus response. Phosphorus management in soils with moderate fixation capacity is usually a simple procedure: Small annual rates of superphosphate can be broadcast (spread over top of soil) and incorporated or banded (placed in a band near the seed).

In soils with high phosphorus fixation capacity economically sound phosphorus management involves several approaches (Sanchez, 1976). Two general approaches are used to deal with high phosphorus fixing soils: One is to apply small to moderate rates in bands near the plant. The other is to apply a large amount at one time saturating the soil's fixation

capacity, eliminating the problem right away. However, there is a disadvantage, the very high initial investment and need for adequate financing. In a high-fixing soil from North Carolina, Kamprath (1967) studied the residual effect of massive initial applications versus small annual maintenance rates applied in bands. The data follows below:

Yield of corn as affected by phosphorus application seven years after the initial application

Initial application kg P/ha	Yield tons/ha Annual Maintenance applications (banded) None	22 kg P/ha
0	1.7	5.7
168	3.9	6.2
337	5.5	6.8
673	7.0	7.1

$LSD_{0.05}$ = 1.3 tons/hectare

It is clear in this case, that the small annual banded application is superior to the massive single dose.

Applying phosphorus fertilizers in bands is a simple practice that satisfies the phosphorus fixation capacity of a small soil volume, making the fertilizer directly available to plants. In using a system of minimal inputs, banding is very appropriate since the goal is to increase crop production with minimal inputs without changing the inherent fertility of the entire soil volume. Sanchez (1976) cites Yose (R. S. Yost, North Carolina State University, 1974) who studied banded versus broadcast applications in a high phosphorus-fixing soil of Brazil. The results showed that broadcast-incorporated applications were superior to banded applications in the first crop. Banded applications concentrated corn root development around the band. When a temporary drought struck, these plants suffered more than those of the broadcast plots, which had a more extensive root

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system. In time, however, the effectiveness of the banded treatments increased while the broadcast treatments decreased. Annually banded treatments began to approach the broadcast treatments as the phosphorus became mixed in the soil.

Sources of Phosphorus

Research in temperate regions indicates that phosphorus fertilizers should have at least 40 to 50 percent phosphorus in water-soluble form to insure an adequate supply at early growth stages (Englestad, 1972). Ordinary and triple superphosphate and monoammonium and diammonium phosphates meet this requirement and can be used effectively in soils with low to moderate fixation capacities.

In acid soils which fix large quantities of phosphorus, application of less soluble phosphorus sources such as rock phosphate may be more effective and economical than the slightly soluble forms. Rock phosphates are more reactive in acid soils and usually cost one-third to one-fifth as much as superphosphate per unit of phosphorus (Sanchez, 1976).

The literature on tropical agriculture is full of research indicating the desirability of high-quality rock phosphate sources over superphosphate in acid soils (Motsara and Datta, 1971; Awan et al., 1971; Englestad, 1972) and the poor performance of low-citrate-solubility rock phosphate sources in acid soils (Alvarez et al. 1965; Viegas et al. 1970; Miranda et al. 1970). Studies at TVA by Lehr and McCellan (1972) indicate that when rock phosphate deposits (North Carolina and Tunisia) are given an index of 100, rock phosphates with a solubility index of 70 percent or greater can be recommended for direct application without testing. These are largely concentrated in North Africa, the Soviet Union and the southeastern United States.

The effects of rock phosphates of varying citrate solubility on flooded rice yields in an acid sulfate soil from Thailand was studied by Englestad et al., (1974). The initial and residual effects of the rock

phosphates were highly dependent on their absolute citrate solubilities. The yield responses of the North Carolina and Florida rocks approximated those of triple superphosphate.

In the tropics high-citrate solubility deposits are limited to relatively small areas in Peru and India (Sanchez, 1976). The majority of the deposits in most tropical areas, including significant ones in Brazil, Columbia, Venezuela, Togo and India have relative solubilities lower than 40 percent. Most are unsuitable for direct applications, but their reactivity can be increased by fine grinding or by thermal alteration and fusion with silica sand, sodium or magnesium carbonates. These silicophosphates, called, "Rhenenia" or thermophosphates appear to have promise for acid soils that fix large quantities of phosphorus because of the blocking effect of silicen on phosphorus fixation sites (Olson and Englestad, 1972; Fassbender and Molina, 1969).

The potential effectiveness of these cheaper forms of phosphorus in acid soils is illustrated in the following table:

Behavior of different fertilizer sources on wheat grown in Oxisols of southern Brazil.

Phosphorus Source	Relative yield 5-year average
No phosphorus	100
Olinda rock phosphate 1/	179
Simple superphosphate	206
Thermophosphate	218

Source: W. J. Goedert (personal communication) as cited by Sanchez (1976)

1/ Low citrate solubility

The low citrate solubility Olinda rock phosphate was inferior to ordinary superphosphate; but when thermally treated wilh silicates and carbonates to produce a thermophosphate, its effectiveness was superior to that of ordinary superphosphate. In view of the substantially lower costs of the rock phosphates and some thermophosphates, both seem desirable alternatives for soils with high fixation capacities.

An additional strategy, sometimes feasible for managing soils with high phosphorus fixation capacities, is to reduce their fixation through amendments that will block some of the fixing sites in the soil. This can be accomplished in some soils through liming or silicate additions (Sanchez, 1976).

Liming soils to pH 5.5 generally increases the availability of phosphorus by precipitating exchangeable aluminum and hydroxy aluminum. This has also been observed by Fox et al. (1964) in high fixing Hawaiian soils.

Applications of silicon or sand (an unessential element), usually as calcium silicate, sodium silicate or basic slag, are known to decrease phosphorus fixation and increase phosphorus uptake by crops. Suehisa et al. (1963) reported that grass yields increased from 2 to 7.6 tons per hectare and phosphorus uptake rose from 4 to 15 kg phosphorus per hectare when one ton of silicon per hectare was applied without added phosphorus.

Silicon is generally not considered to be essential to plant growth, however, positive yield responses have been achieved on highly leached soils of the tropics under intense cultivation of sugar cane or rice. Soils having low contents of soluble silicon are most likely to show response to silicon applications. Fox et al. (1967) suggested that the critical level is 0.9 ppm silicon in water extracts. Responses have been obtained on the leached soils of Hawaii, Maurituis and the rice soils in Japan, Korea and Sri Lanka.

In these rice soils, silicon applications increased yields because of a

more erect leaf habit, greater tolerance against insects and disease attacks, lower uptake of iron and manganese when present in toxic concentrations in the soil, and perhaps a rise in the oxidizing power of rice roots (Okuda and Takahashi, 1965). An element with plant requirements very similar to phosphorus is sulfur. Sulfur deficiency results in a reduction of growth and protein deficiency, often resembling nitrogen deficiency.

Sulfur Deficiency

Wide spread sulfur deficiencies and responses have been reported all over the tropics. McClung et al. (1959) observed sulfur responses in the Brazilian Cerrado in both savannas and recently cleared forests. In Central America, sulfur deficiencies are also widespread, (Muller, 1965; Fitts, 1970). Sulfur deficiency has also been found in sub-Saharan Africa and the sandy soils of central Africa according to a review by Bolle-Jones (1964). They have been reported in Asia by Olson and Engelstad (1972) and in Australia and Hawaii by Williams (1972) and Fox et al. (1971). Sanchez (1976) summarizes sulfur deficient soils as high in allophane or oxides, low in organic matter and often sandy. Soils subject to repeated annual burning are often sulfur deficient since about 74 percent of the sulfur is volatilized (goes off as a gas) by fire. Sulfur-deficient soils occur in unpolluted, inland areas where the atmosphere is low in sulfur.

Sulfur requirements are similar to phosphorus in tropical conditions ranging from 0.1 to 0.3 percent of plant tissue. A sulfur deficiency at early growth stages may disappear later when the roots come in contact with the sulfur-bearing subsoil.

In general, small rates of sulfur (10 to 40 kg per hectare) will overcome sulfur deficiencies. Sulfur as part of either nitrogen or phosphorus fertilizer, is usually sufficient to take care of sulfur problems. If not,

any soluble source containing sulfate will work as will flowers of sulfur which is oxidized to sulfate. The last major element to be considered, of less importance than the other nutrients considered here is potassium.

Potassium Deficiency

Potassium deficiencies do occur in the tropics, however, lack of potassium is not nearly as widespread as nitrogen and phosphorus deficiencies. Boyer (1972) in a review article suggests that the absolute minimum requirement of exchangeable potassium - the amount considered to be available to the plant - is close to 0.10 meq/100 g of soil but that this may vary between 0.07 and 0.20 meq/100 g depending on the kind of crops grown and the soils.

In Africa the most severe potassium deficiency appears in the savanna on sandy soils. In the lower Ivory Coast, potassium application resulted in very substantial yield increase with oil palm (Boyer, 1962). Potassium deficiencies have occurred in the southwestern Cameroon (Valet, 1967) in Madagascar (Vely et al., 1965) and in Brazil on sandy soils (Van Wambeke, 1970). Laudelot (1954) in the Congo (Zaire) showed that the exchangeable potassium increased from 0.067 meq/100g to 0.325 meq/100 after burning a forest. Thus clearing a forest by burning substantially increases the potassium content of soils. Busch (1958) found that the increases in bases (calcium, magnesium and potassium) persists for a number of years after burning.

When soils are potassium deficient, fertilization with moderate amounts of potassium usually corrects the problem. High yield crops which contain high carbohydrates such as potatoes have a higher potassium requirement than a grain crop such as wheat or rice.

Rice

Since rice culture differs from other crops due to the flooding requirement, it must be considered separately. Regardless of their original pH values, most rice soils reach a pH of 6.5 to 7.2 within a month after flooding and remain at that level until dried (Sanchez, 1976). This increase in soil pH is a result of the release of OH^- (base) ion when $Fe(OH)_3$ is reduced. Consequently, liming is of little value in flooded rice production. If low pH is a problem, flooding two to three weeks prior to transplanting may eliminate this danger.

In flooded soils oxygen is consumed, therefore, nitrates will be lost via denitrification. Since ammonium is already reduced, it is stable in reduced (flooded) environments. Organic matter decomposition proceeds at a slower rate without oxygen, however, materials such as rice straw which has a high carbon to nitrogen ratio may mineralize more rapidly under these anaerobic conditions thus providing a source of plant-available nitrogen. Soil solution phosphorus increases upon flooding (Sanchez, 1976) explaining why additional phosphorus in flooded conditions is rarely needed.

Nitrogen use in rice is very critical. An ammonium source is generally used when fertilizer is used. It is incorporated in the soil before seeding or transplanting, or broadcast at different stages of growth. Incorporations of two inches are usually sufficient for constant flooding conditions. This places the nitrogen below the oxidized layer, a necessary condition to prevent denitrification (Mickklesen and Finfrock, 1957). Nitrogen uptake proceeds throughout the growth cycle of the rice plant but it is particularly critical during two physiological stages: at the beginning of tillering and at the panicle (grain head) initiation stage (Matsushima, 1965). Adequate nitrogen at tillering increases tillers which is closely correlated with yield in short varieties. However, excessive nitrogen after maximum tillering and before panicle initiation may result in a large proportion of unproductive

tillers and premature lodging in tall varieties. Excessive nitrogen after flowering may extend growth duration and increase susceptibility to some diseases. The efficient use of nitrogen is very important economically. Scientists at International Rice Research Institute (1975) have almost doubled the efficiency of nitrogen fertilizer by either mixing it in mudballs or making urea briquettes. Fifty pounds of nitrogen per acre in this fashion was equal to 100 pounds per acre applied on the surface.

Rice rarely responds to phosphorus fertilizer except in highly weathered leached soils (Sanchez and Briones, 1973). Traditional soil tests for phosphorus do a poor job in predicting the need for phosphorus under flooded conditions.

Zinc deficiency is probably the most widespread micronutrient disorder in tropical rice, occurring in parts of India, Pakistan, the Phillipines and Columbia under low lowland conditions (Tanaka and Yoshida, 1970; Yoshida and Forno, 1971; CIAT, 1971 IRRI, 1971, 1972). It also occurs throughout the Cerrado of Brazil under upland conditions (De Souza and Hiroce, 1970). In lowland rice, zinc deficiency is associated with calcareous (high base) soils and is accentuated by prolonged flooding. Deficiency can be corrected by applications of 5 to 15 kilograms of zinc per hectare as the sulfate or oxide incorporated into soil before seeding (Giordano and Martvedt, 1973). An alternative is dipping the transplant seedlings in a one percent zinc oxide suspension before transplanting and mixing zinc oxide with pre-soaked rice seeds before direct seeding (Yoshida and Forno, 1971, CIAT, 1971). Yield increase of two to three tons per hectare have been achieved with one to two kilograms of zinc oxide per hectare (Brady, 1977). This again is an example of fertilizing the plant and not the soil, a much more economical and easy approach than treating the whole soil.

Potassium deficiency is rare in lowland rice as these soils are usually adequate in exchangeable potassium and receive potassium in the irrigation water when flooded. Soil tests are good for estimating potassium deficient soils (Sanchez, 1976).

Up to this point this paper has concentrated on soil modification in order that crop production might be increased. Another approach is to select or breed crops which will tolerate and produce well under natural conditions considered to provide a hostile environment for plants.

Plants Which Tolerate Adverse Conditions

Certain crops grown exclusively in the tropics normally grow at pH levels which would kill corn or soybeans (Sanchez, 1976). Pineapple is perhaps the best known example, but coffee, tea, rubber and cassava also tolerate very high levels of exchangeable aluminum. Among the pasture species, several grasses and legumes are apparently very well adapted to acid soil conditions. Tropical grasses such as guinea grass, *Panecum maximum*; jaragua, *Hyparrhanea rufa*; molasses grass, *Melinia multiflora*, and several species of the genera *Paspalum* and *Brachiaria* grow well in very acid soils.

Legumes are considered very susceptible to soil acidity because of their high calcium requirements for nodulation, however, several tropical pasture legumes are strikingly well adapted to acid conditions. *Stylosanthes* spp. *Desmodium* spp, *Centrosema* spp, *Calopogonium* spp, and tropical Kudzu, *Pueraria phaseoloides* are the principal ones (Sanchez, 1976). Among the grain legumes, cowpeas and pigeon peas are more tolerant of acidity than field beans and soybeans.

Many of these species have evolved in acid soils and have genetic properties which tolerate conditions associated with high aluminum levels.

On the basis of their research, Spain et al. (1975) have produced a list of species adapted to high soil acidity and aluminum:

Crops and Pasture Species Suitable for Acid Soils with Minimum Lime Requirements

Lime Requirement (tons/ha)	Al Saturation (%)	pH	Crops (Using Tolerant Varieties)
0.25 to 0.5	68 to 75	4.5 to 4.7	Upland rice, cassava, mango cashew, citrus, pineapple, Stylosanthes, Desmodium, kudzu, Centrosema, molasses grass, jaragua, Brachiaria decumbens, Paspalum plicatulum
0.5 to 1.0	45 to 58	4.7 to 5.0	Cowpeas, plantains (?)
1.0 to 2.0	31 to 45	5.0 to 5.3	Corn, black beans

In a review of tolerance to aluminum, Foy (1974) concluded:

1. Some aluminum-tolerant varieties keep developing and are not injured.
2. Some aluminum tolerant varieties increase the pH of growth medium which reduce availability of aluminum whereas sensitive ones decrease soil pH compounding the problem.
3. Some tolerant species accumulate aluminum in their roots or translocate (transport) aluminum at a slower rate to the top.
4. Aluminum in roots does not inhibit the uptake and translocation of calcium, magnesium and potassium in tolerant varieties, whereas it does so in sensitive varieties.
5. High plant silicon is associated with aluminum tolerance in certain rice varieties.
6. Aluminum tolerant varieties do not inhibit phosphorus uptake and translocation as much as susceptible varieties or species. Also many aluminum tolerant species or varieties are very tolerant of low phosphorus levels.

Cassava Manihot sp., a tropical root crop growing widely on very infertile soils that are frequently acid, has acquired the reputation for being a crop that yields well under very low fertility conditions (Cock and Howeler, 1978). They conclude that cassava tolerates low soil pH and high levels of aluminum and manganese as well as low levels of soil calcium, nitrogen and potassium better than many other species. While it has a high phosphorus requirement for maximum growth, it can utilize phosphorus sources that are relatively unavailable to other plants. It is highly tolerant of uncertain rainfall patterns and is an extremely efficient carbohydrate source on low fertility, acid soils with low levels of fertilizer applications. Cassava yields of 36 metric tons per hectare per year have been obtained under conditions that are suboptimal for many crops.

Rachie (1978) states that an estimated 1.57 million people live in the tropics and this number is likely to expand to five billion in fifty years. This rapidly growing population will have to increasingly rely on plants as sources of both energy and protein. In the semiarid to subhumid climates, two-thirds of dietary calories come from cereals while in the humid tropics the bulk of dietary carbohydrate comes from roots and tubers. The production of starchy root and tuber crops is inherently more efficient than the production of cereals, expecially on marginal lands and/or land with minimal external inputs. It is estimated that with roots and tubers, at least two to three times more caloric energy can be produced per unit of land and time and with only one-third to one-half the production cost of cereals. It is, therefore, suggested that an increasing proportion of human energy needs will be derived from starch roots and tubers. The tropics have a large amount of infertile lands, ill suited for many crops with moderate to high nutrient requirements. One of the most serious problems of some tropical soils is phosphorus deficiency and fixation which seriously limit crop production.

Plucknett (1978) in a review article suggests that sweet potatoes (*Ipomoea batatas* (L.) Lam.), long associated with poor people and less productive soils, may be one solution. There is good reason that the sweet potatoe is grown so widely under such difficult conditions.

Fox et al. (1974) found that sweet potatoe had one of the lowest phosphorus requirements of the crops studied (Lettuce, *Lactuca sativa*; corn, *Zea mays*; and Chinese cabbage, *Brassica pekinesis*).

The International Rice Research Institute (IRRI) 1972, classified varieties of rice that are tolerant to sensitive to low phosphorus. They are also selecting varieties for tolerance to iron deficiency or toxicity and the presence of toxic soil reduction products.

In summary, it is apparent that high production can be achieved on rather hostile soils with selection of tolerant species or varieties of plants. This would be a stratagem which relies on no or minimal inputs and yet can increase food production substantially.

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PAPER NO. 7. AZOLLA, A LOW-COST AQUATIC GREEN MANURE FOR AGRICULTURAL CROPS

(By Thomas A. Lumpkin[1] and Donald L. Plucknett[2])

A. Introduction

The air we breathe is 79% nitrogen. Plants need nitrogen to make the proteins that allow them to harvest sunlight and carry on natural processes. Unfortunately, nitrogen in the air is in an inert N_2 form which cannot be utilized by plants. Only two kinds of organisms have the ability to convert inert atmospheric nitrogen to a usable form such as ammonia. These two organisms are blue-green alga (cyanobacteria) and certain species of bacteria. Rhizobium bacteria are the nitrogen-fixing partners of the well known legume/Rhizobium symbiosis of soybeans, alfalfa, etc., while the blue-green alga, Anabaena, are the nitrogen-fixing partners of the virtually unknown Azolla/Anabaena symbiosis.

Until this century, nitrogen-fixing bacteria and blue-green alga, existing under freeliving or symbiotic conditions, produced most of the new nitrogen entering the cropping system. Almost all farmers had to include legumes in their crop rotation in order to maintain soil fertility. This traditional practice continued until the discovery of fossil-fuel-dependent methods of producing nitrogen fertilizer which radically changed the economics of agriculture. The use of legumes in crop rotation was soon considered to be too expensive and troublesome, and fell into disuse, except when grown as a cash crop.

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The change was most apparent in developed countries, and in developing countries that adopted the "green-revolution" technology.

However, during the 1970's, this change began to reverse itself. The rapidly rising price of fossil-fuel-dependent nitrogen fertilizers caused the economics of agriculture to shift again. The rising prices are causing researchers to seek alternative methods for producing synthetic fertilizer, and causing farmers to reconsider traditional methods for maintaining soil fertility.

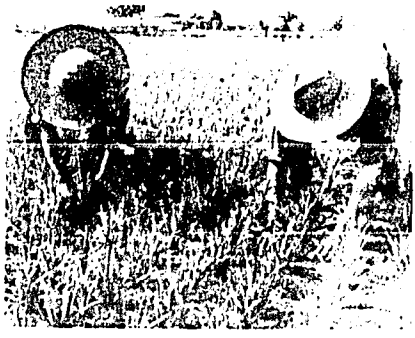
The traditional legume crops are and will continue to be the most commonly used nitrogen-fixing green manures, especially for upland crops. However, they have certain weaknesses for rice farmers. One of these weaknesses is that rice is traditionally grown on the most fertile and, consequently, intensively managed land. Rice farmers are reluctant to use part of the valuable growing season on a relatively slow-growing legume green manure crop. Another problem is that many rice paddies are flooded or waterlogged, particularly during the potentially productive early part of the rice season when most of the transplanted rice is still in the nursery beds. Unfortunately, under waterlogged or flooded conditions, most legumes can not grow or fix nitrogen, so usually the paddy fields stand idle for a month or more while the rice seedlings mature in the nursery beds.

The fast-growing aquatic Azolla has neither of these two weaknesses.

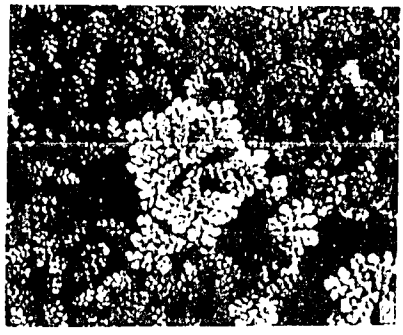
1. What is Azolla (Figure 1.)

Azolla is a genus of small aquatic ferns that are native to Asia, Africa and the Americas. Three Azolla species are native to parts of

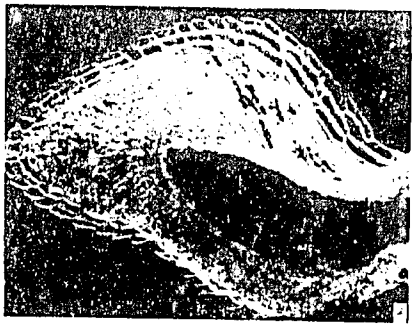
Figure 1



Azolla is a delicate nitrogen-fixing aquatic fern which can be used as a green manure for rice and other paddy crops. It can even be grown as an intercrop with the paddy crop. When the azolla dies, it becomes fertilizer for the rice.



Most azolla species are only a few centimeters in diameter and each leaf is only a few millimeters long. Azolla can double its weight every [illegible] days and provide enough organic manure for a high yielding crop of rice.



There is a dark green cavity in the center of every azolla leaf which is inhabited by a species of blue-green algae. The algae takes nitrogen from the air and makes nitrogen fertilizer for the azolla.

Cells of the nitrogen-fixing blue-green algae, Anabaena, look like a string of beads. The larger egg-shaped cells specialize in producing nitrogen fertilizer while the more numerous smaller cells harvest sunlight.

the USA. They live naturally in lakes, swamps and streams and other large and small bodies of water. Some have been spread by man or natural means to various parts of the world. Some are strictly tropical or sub-tropical in nature, while others grow and thrive in either temperate or tropical climates. Azolla has been of interest to botanists and agriculturists for years because of its symbiotic relationship with a nitrogen-fixing blue-green alga, Anabaena. Recently it has come under scrutiny as a green manure for flooded crops, particularly rice, since it is already used in rice in China and Vietnam.

The Azolla/Anabaena relationship (Figure 1, photographs 3 and 4.)

The most remarkable feature of azolla is its symbiotic relationship with the blue-green alga, Anabaena azollae. The delicate fern provides nutrients and a protective leaf cavity for the Anabaena, which in turn provides nitrogen for the fern. Under suitable field conditions the fern/alga combination can double in weight every 3-5 days and fix atmospheric nitrogen at a rate exceeding that of the legume/Rhizobium symbiotic relationship. Azolla can accumulate up to 2-4 kilograms of nitrogen/ha/day (equivalent to 10-20 kg of Ammonium sulfate), and since the Azolla/Anabaena combination grows in aquatic conditions, it can provide a potential nitrogen source for flooded crops such as rice. The exploitation of this potential is a challenge to agricultural scientists.

2. What are the benefits of using Azolla?

a. Producing nitrogen fertilizer for increasing crop yields.

Azolla plants are described by the Chinese and Vietnamese as being miniature nitrogen fertilizer factories. Indeed the Vietnamese

call them indestructible fertilizer factories, since azolla continued to produce nitrogen fertilizer for Vietnamese rice paddies even during the height of the Vietnam war.

The nitrogen fertilizer fixed by azolla becomes available to the rice after the azolla mat is incorporated into the soil and its nitrogen begins to be released through decomposition. In 25 to 35 days azolla can easily fix enough nitrogen for a 4 to 6 ton/ha rice crop during the rainy season, or a 5 to 8 ton/ha crop under irrigation during the dry season.

b. Maintaining soil fertility.

As a green manure, azolla's influence on the fertility of soil is due to its organic matter and nitrogen. A humus compound is formed as a result of the incorporation and decomposition of azolla. Humus increases the water holding capacity of soil and promotes aeration, drainage, and the aggregation essential for highly productive soils. Organic matter can bind together soil particles, and makes clayey soils more friable.

In addition to its influence on soil physical properties, azolla is important in the cycling of nutrients. While azolla is growing in the paddy, it fixes nitrogen and also absorbs nutrients out of the water that might otherwise be washed away. When the azolla is incorporated into the soil and humus is formed, these nutrients are slowly released into the soil as decomposition progresses.

Even though azolla appears to be a rather delicate plant that would rapidly decompose, it actually takes six weeks or more for most

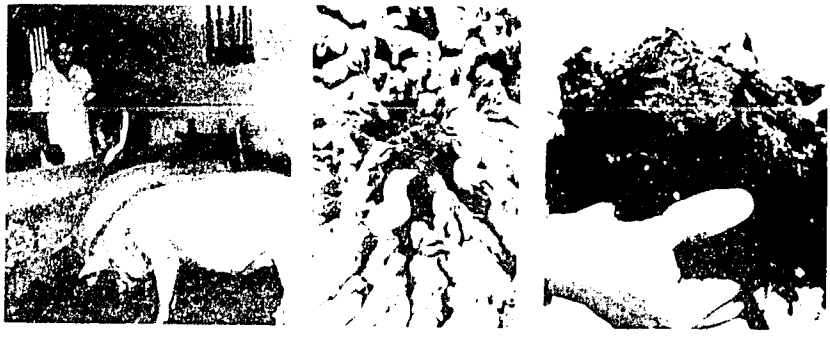
of the nutrients to be released because of its rather high lignin content. Slow decomposition gives a natural slow release effect which is ideal for efficient absorption of released nutrients by the developing rice crop. Another factor in azolla effectiveness as a green manure is its low carbon to nitrogen ratio of about 10:1. This high ratio ensures that azolla nitrogen will not be tied up by bacteria that are involved in decomposition of an over abundance of carbonaceous plant residues.

c. Producing fodder for pigs, ducks, and fish (Figure 2.)

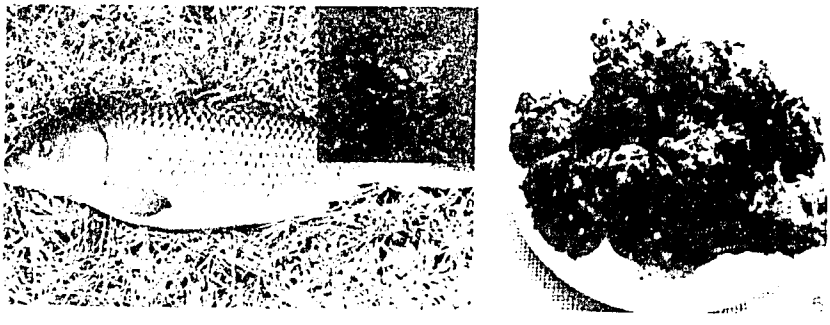
Azolla has traditionally been used as a fodder throughout Asia and parts of Africa. It is fed to pigs, ducks, and fish. The grass carp, (*Ctenopharyngodon idella*), Israeli Carp (*Cyrinus carpis*) and *Tilapia rossambica* prefer azolla over most other aquatic weeds as a source of food. Small plots of azolla growing in canals and ponds as food for pigs and ducks are ubiquitous throughout southern China. Azolla as a fodder probably has a longer history than as a green manure. There may even be potential for direct consumption by man. The wife of Dr. P. K. Sinch in India makes a tasty deep fried dish of azolla mixed with batter.

On a dry weight basis, azolla has a protein content between 13 to 24%. One hectare of azolla can produce 1 to 2 tons of fodder per hectare per day, equivalent to 10 to 30 kilograms of protein per day. When these statistics are considered, azolla has a tremendous potential as a fodder crop in developing countries and also in the U. S.

Figure 2



Although azolla is most commonly used as an organic fertilizer for rice, it can also be used as a fodder for pigs (1), ducks (2) and fish and as a compost (3) for upland crops. Many of the pigs which are grown to produce China's famous Hinhua hams are fed on a diet which includes azolla.



Azolla is a preferred forage for many species of herbivorous fish. The insert in the top right corner of photo 4 shows the carp grazing on azolla just prior to being netted. Azolla may also have potential for direct consumption by man if attractive uses can be developed. Photo 5 shows a deep fried dish of azolla mixed with batter.

Recent work in India at G. B. Pant University indicates that azolla may be useful as a fodder for cattle. In trials there growing heifers gained 0.33 kg/day when fed 0.9 kg of dried azolla with 2.1 kg of a 2:1 ratio of dry wheat straw and sugarcane tops. Control animals that were fed the same amount of wheat straw: sugarcane tops, but also received 1.5 kg of a concentrate feed gained only 0.14 kg/day (Dr. Frands Dolbert, DANIDA, personal communication).

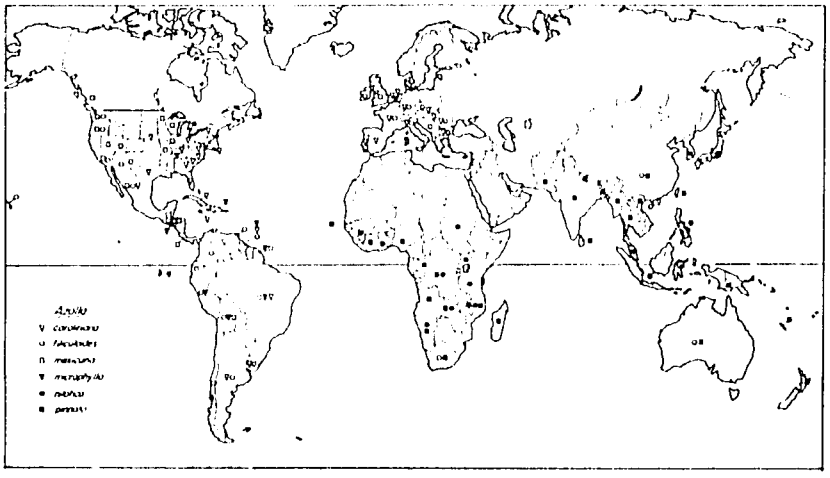
d. Suppressing the growth of aquatic weeds.

Agricultural economists have estimated that Asian farmers, particularly women, spend more time weeding than on any other activity required for rice production. Although research has been insufficient to date, it is commonly believed that azolla suppresses the growth of certain aquatic weeds. Weed growth is suppressed when azolla forms a thick, virtually light-proof mat. There are probably two mechanisms for this suppression, the most effective being the light-starvation of young weed seedlings by the blockage of sunlight. The other is the physical resistance to weed seedling emergence created by a heavy interlocking azolla mat. In some weed infested rice fields, the benefit from azolla weed suppression may even surpass its benefit as a nitrogen source. Rice seedlings are not affected by azolla's weed suppression effect because, when transplanted, they stand above the azolla mat.

B. The Present Status of Azolla

1. Where Azolla is being used in agriculture (Figure 3.)

Azolla is already being grown commercially in China and Vietnam, where its usefulness has been known for years. Once restricted in use



Distribution of *Azolla* species.

Figure 3. Distribution of Azolla species throughout the world. This distribution map is rapidly becoming outdated because many azolla species and varieties are being moved about and introduced into new places as research on azolla grows.

because of azolla propagation problems, the fern is now being used in larger crop areas.

Chinese use of azolla goes back hundreds of years, at least to the Ming dynasty. Its use in Vietnam dates to the 11th century. These two are the only countries with a long history of azolla cultivation. The practice probably began with recognition that the spontaneous growth of wild azolla in rice fields had a beneficial effect on the crop. Organized use of the fern could not occur, however, until reliable methods were developed to overwinter and oversummer the fern. Since azolla can only be grown from vegetative material, it must be protected during seasons that are too severe for its survival.

The original sites of azolla cultivation are thought to have been Zhejiang Province in China and Thai Binh Province in Vietnam. Until recently certain villages in these places had temples dedicated to the mythological discoverers of azolla. At the end of the 19th century azolla was being cultivated at favorable sites along the east Asian Coast as far south as 20°N latitude on the Red River delta in Vietnam and northeastward through Guangdong and Fujian Provinces to Wenzhou District near 28°N latitude in Zhejiang Province, China.

A major push for expanding the use of azolla began in China and Vietnam in the early 1960s. Before that time it was common for certain families or villages that had mastered the intricate techniques of oversummering and overwintering azolla to control the supply of azolla-starter-stocks in the spring. Peasants had to travel to these villages to purchase their spring plants.

After the revolutions in China and Vietnam, the new governments eventually recognized the worth of azolla, and began officially promoting its use and organizing the construction of propagation centers.

During colonial days in Vietnam, French scientists reported on the use of azolla and did some preliminary research, but its cultivation was never promoted officially. At the end of the colonial period, azolla was grown on about 40,000 hectares[1/] as a green manure during the winter for the spring rice crop. In 1958 the new government established an azolla research center at the Crop Production Research Institute and set up an extension network with over 1,000 inoculum production bases to stimulate utilization.

Despite this promising beginning, however, the big push in azolla research, as in China, did not come until the early 1960s. Articles on azolla began appearing in 1962, culminating in several articles and a 171 page book by Vo and Tran in 1970.

Since the introduction of high yielding rice varieties to Vietnam in the early 1960s, most azolla has been grown as a monocrop before the spring rice and reportedly doubled in cultivated area from 1965 to about 700,000 hectares in 1978. As in China, azolla cultivation is seldom practiced in summer because of the high temperatures and insect susceptibility of the A. pinnata var. imbricata native to the Asian continent.

Vietnamese scientists have collected over 30 varieties of local azolla and have selected superior strains for heat, cold, salt, and acid tolerances. Despite these advances, reportedly most communes and cooperatives have not adopted these improved azolla varieties.

The Chinese story is much the same as that of Vietnam, although much more was known of the Vietnamese experience because of the availability of publications in English and French as well as in Vietnamese. Recently, information from China has become available (Guangdong Acad. Agric. Sci., 1975; Guangdong Bur. Agric., 1975; Zhejiang Acad. Agric. Sci., 1975; FAO, 1978; Lumpkin and Plucknett, 1980).

1/ 1 hectare = 2.47 acres.

Today, azolla is grown as a green manure on about 1.3 million hectares of rice in China. Research and development activities have increased significantly, as have extension activities to promote its use. Large posters have been produced to inform the public of azolla's usefulness and of its management requirements.

How Azolla is used as a Green Manure (Figure 4.)

Azolla can be used as a green manure:

(1) by growing it as a monocrop and then incorporating it as a basal manure before the rice is transplanted; or transported to another site for use on upland crops;

(2) growing it as an intercrop and incorporating as a top dressing manure after the rice is transplanted; or

(3) by growing it both as a monocrop and an intercrop.

All three systems can be successful but, as is common in agriculture, use of the green manure crop requires some adjustments in management of both the green manure and the main crop.

(1) Monocrop Azolla is used in China and Vietnam during winter and spring to produce nitrogen for the spring rice crop. The same technique is used to produce nitrogen for the early summer rice crop, but this is less common since the growth of Azolla pinnata is affected by high temperature and heavy pest attack during mid - to late summer.

(2) Intercropped Azolla is usually grown with the rice in places where there is no time available in the cropping system for the monocropping of azolla. As an intercrop azolla will be initially incorporated by hand or rotary rice weeder and then later killed by heavy shading and/or high temperatures -- with subsequent decomposition and release of nitrogen to the crop -- at the stage of maximum rice tillering.

Figure 4

Two of several methods for soils incorporating a monocrop of azolla as a basal green manure for rice. Both photos 1 and 2 were taken during the spring of 1980 in Guangdong province, China. Photo 1 is A. filiculoides, Photo 2 is Azolla imbricata.

Photo 3 shows an azolla beater being used to spread inoculum azolla after it was introduced into the field of a second late summer rice crop to grow with the rice as an intercrop.

Photo 4 above shows an azolla pusher which is used to spread inoculum azolla if it is applied to a rice crop after the rice is transplanted, or is used to concentrate and collect azolla in a nursery. The illustration below shows a bamboo pole being used to collect azolla growing in a canal.

(3) Growing both monocrop and intercropped Azolla is a technique that is designed to use the growing period for azolla before the planting of the rice crop, plus production of added nitrogen for the crop through cultivation of intercropped azolla. In this system two different varieties of azolla may be used in each of the different periods. Different temperature and light sensitivities of azolla varieties make this possible.

2. Who is doing Azolla research?

A number of centers are conducting azolla research. Most of this work is less than 5 years old. Both China and Vietnam are studying *Azolla pinnata* var. *imbricata* under their own conditions. Recently, the Zhejiang Academy of Agricultural Sciences has had an opportunity to evaluate the other *Azolla* species (*caroliniana*, *filiculoides*, *mexicana*, *microphylla*, and *nilotica*) for use in China.

Many developing country rice research centers have begun azolla research, but with little success to date. Probably the most successful program is in Thailand, where the Ministry of Agriculture has been sponsoring an azolla program that has progressed through the regional extension stations and has now reached the stage of demonstration plots in the fields of progressive farmers.

The International Rice Research Institute started an azolla research program nearly eight years ago (Watanabe *et al.* 1977). IRRI is studying the use of several azolla species for use in flooded rice.

There are three major centers of azolla research in the USA. One is the University of Hawaii, where agronomic and physiology studies are underway to characterize and understand the usefulness of all azolla species in tropical crop production systems, including rice and taro

(Lumpkin and Plucknett, 1980). The work is led by T. A. Lumpkin who was selected by the National Academy of Sciences to conduct research on azolla in the People's Republic of China in 1979 and 80 at its foremost azolla research center, the Zhejiang Academy of Agricultural Sciences at Hangzhou.

Studying azolla management to fit temperate broadcast-sown production systems is the focus of the research program at the University of California at Davis (Talley and Rains, 1980). Research objectives at UC-D include use of A. filiculoides as a monocrop basal green manure crop for springsown rice, and A. mexicana as an intercrop in rice. The work is led by S. N. Talley and D. W. Rains. The UCD program received a grant from the USDA Competitive Grants Program in 1980 and a grant from the National Science Foundation.

Basic physiology studies are the focus of the program at the Fettering Laboratory where Dr. Gerald Peters has focused on understanding the Azolla/Anabaena relationship (Peters, 1977). The program has been supported by a grant from NSF and a grant in 1979 from the USDA Competitive Grants Program.

Another azolla research program that we know less about is at Virginia Commonwealth University, where the isolation and reconstitution of the Azolla/Anabaena association are being studied. This work has been supported by a grant from the USDA Competitive Grants Program; the first grant was made in 1979.

Dr. Jack Newton of the USDA in Peoria, Illinois has done some research on isolation of Anabaena from Azolla.

Countries that have initiated or plan to initiate azolla research include: India, Nepal, Thailand, Bangladesh, Burma, Indonesia, Malaysia, The Philippines, Sri Lanka, Egypt, Peru, and the West African Rice Development Association, headquartered in Liberia.

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In addition, several other countries have expressed an interest in the fern and its uses.

3. What Organizations are Financing Azolla Research?

Current financial support for azolla research in the USA comes from AID (a small 211-d grant). the National Science Foundation (2 grants) and the USDA (Section 406 and Competitive Grants). The USDA Competitive Grants office has made three grants totalling $278,000, to the University of California at Davis, Kettering Laboratory and Virginia Commonwealth University. National Science Foundation has made two grants; one each to University of California at Davis and Kettering Laboratory. In all probability, less than $300,000 per year is now being invested in azolla research in the USA. The work at Hawaii is sponsored by small 211(d) grant for nitrogen fixation from the Agency for International Development and by a research grant from the U.S.D.A. under the Section 406 program of the 1966 Food for Peace Act, and by Hawaii Agricultural Experiment Station funds.

C. Azolla's Effect on the need for Agricultural Inputs

1. Fertilizers

Successful cultivation of azolla requires the application of a certain amount of phosphorus fertilizer (0.5 - 1.0 kg P/ha/week), but this does not necessarily mean an increase in the amount of phosphorus fertilizer required to produce a crop of rice. The application of phosphorus is usually necessary for a good crop of rice,but instead of applying it directly to the rice, the phosphorus can be given to the azolla first in small weekly applications. Once the azolla is incorporated into the soil and begins to decompose, the phosphorus becomes available for the rice crop. Thus phosphorus originally intended for the rice crop is first cycled through the azolla. The phosphorus enables the azolla to grow and fix nitrogen that will be used by the rice. One kilogram of phosphorus applied to azolla results in the fixation of 5 kilograms of nitrogen. North Vietnam is deficient in petroleum products for the production of nitrogen fertilizer, but has sufficient phosphate deposits to fuel its miniature azolla nitrogen factories.

In certain deficient soils, azolla responds to the applications of other nutrients such as potassium, but these usually must also be applied for a high yielding rice crop. In some rare deficient soils, the addition of small amounts of molybdenum and/or iron have proved useful to increase azolla's rate of nitrogen fixation. The Chinese often apply river mud, ash and animal manure to supplement the phosphorus given to azolla.

2. Pesticides

Azolla is attacked by larvae of several species of moths and midges and by certain kinds of snails and beetles. These pests are especially destructive during the summer season, and must be carefully controlled or the azolla can be devastated. However azolla is usually not cultivated on a large scale during the seasons when insects are rampant but is maintained in over-summering nurseries. In addition, even when azolla is cultivated in the field during the summer season, the pesticides normally used on rice crops, such as diptenex, sumithion, malathion and carbofuran are usually adequate for controlling azolla insects.

3. Irrigation

Azolla is a delicate freefloating aquatic plant. Although it can last for months in a refrigerator, it can not survive for more than a few hours on a dry soil surface under direct summer sunlight. Since technology has not been developed for the use of azolla seeds (spores) in cultivation, a small amount (1-10% of inoculation requirements) of azolla plants must be maintained through the seasons when azolla is not being cultivated in the fields. This means that in tropical and subtropical areas a certain amount of water must be available throughout the year either to maintain azolla in nurseries or to cultivate it in the fields. The oversummering maintenance of azolla should not be a problem in regions where standing water is present throughout the year, such as in Bangladesh, or in regions where azolla can be maintained in small nurseries beside mountain springs.

The period when irrigation is most critical is when azolla is to be grown in the fields as a green manure. If azolla is cultivated as a monocrop before the rice, which is the most effective way, water must be available for flooding the fields. If water is not available, azolla cultivation will have to be delayed until it can be grown as an intercrop with the rice. Azolla grows as an intercrop with rice during the first 20-30 days after transplanting. In this period, the paddy fields must remain flooded with at least a few centimeters of water. Although some species of azolla can survive on mud, as is commonly seen in Hawaiian taro fields, they need standing water for good growth. Thus rice paddies dependent upon rain water, where short periods of drought often occur during the first month of rice cultivation, will not be suitable for azolla cultivation. Also, if extremely hot periods occur when water temperatures exceed 40°C, cooler water must be available for pumping into the fields to prevent the azolla from dying from heat stress.

Even though azolla cultivation require some extra irrigation water, it must be remembered that in fields where little or no nitrogen fertilizer is used, the cultivation of azolla will significantly increase the efficiency of water use. If azolla increases the yield of rice from 2.5 tons to 5 tons, than the efficiency of water use has nearly doubled.

4. Machinery

The need for machinery is not a handicap to successful azollo cultivation. Even the most primitive villages can manufacture the basic tools required for the cultivation of azolla. These are made from such locally available raw materials as bamboo and wood. A simple metal/wood tool, costing a few dollars, for soil incorporating intercropped azolla can be manufactured in villages by a black-smith. This tool is not

essential, but is more efficient than soil incorporation by hand. An even more efficient multiple row incorporating machine, with a small gas engine, would have to be manufactured commercially.

D. The Potential Use of Azolla

1. How does azolla affect the productivity of tropical soils?

Azolla affects soils in the same way as any other nitrogen-fixing green manure. It contributes nitrogen, which, after water, is the most common limiting factor to higher crop yields. The application of nitrogen to increase crop yields is the corner stone of the"green revolution". All new rice varieties are bred for high yielding response to nitrogen fertilizers.

The loss of organic matter is a primary cause of decreasing crop yields in the tropics. A decrease in soil organic matter results in soil structure deterioration, lower plant nutrient reserves from the organic matter, and a lower cation exchange capacity. Cultivated tropical soil tend to have lower organic matter contents and soil nitrogen than undisturbed tropical soils. This is especially true with Oxisols and Ultisols.

2. The potential use of Azolla.

What is the likelihood of its widespread use?

Azolla is cultivated as a green manure on about 2 per cent of the harvested rice area of China and about 5 per cent of the spring rice crop. In Vietnam, azolla is grown as a winter green manure for 8 to 12 per cent of the country's total harvested rice area, and about 40 to 60 per cent of the irrigated spring rice in the Red River delta. Estimates of China's terrestrial green manure crop (mostly legumes) are as high as 7 million hectares, or about 5 times the total estimated cultivation area of azolla

As strains or species of azolla are found that are less sensitive to high water temperatures during summer, the areas of azolla in China and Vietnam will probably expand.

The major areas where azolla should prove useful in rice production in the tropics are those where: (1) rice is transplanted, (2) labor is plentiful, and (3) some control of irrigation water is possible. Also, countries with effective research and extension services may have more success with popularization of azolla.

Azolla technology is not applicable yet for areas where rice is broadcast-sown, except as a monocrop, preplant, basal green manure. An azolla mat can cause suppression of tiny broadcast-sown rice seedlings; for that reason, intercropped azolla will probably not be successful in broadcast-sown rice, unless it is inoculated in the fields after the rice seedlings have become established and are growing well above the water surface.

With the above criteria in mind, the most likely countries to adopt azolla include parts of India, Bangladesh, Thailand, Indonesia, Philippines, Nepal, Peru, and the Dominican Republic.

E. A Research, Development, and Implementation Program

1. The Program Elements.

There are two basic azolla management systems that need research attention; these are:

(a) tropical, labor intensive systems and (b) temperate, capital intensive systems.

(a) The Tropical systems will be focused mainly on developing countries, and will follow the principles:

- labor intensive
- land intensive
- small farm based
- crop intensive
- maximizing opportunities for year-round production
- first priority to more intensive use of azolla in transplanted rice systems
- second priority to use in broadcast-sown systems.

The tropical program should set the following objectives:

(1) To find azolla varieties that are less sensitive to high water temperatures (above 27°C) and pest and disease attack. [This would have the effect of expanding azolla use from its present primary role as a spring green manure and its secondary role as a fall green manure to the point where it could be a primary green manure in summer in transplanted rice].

(2) To collect and characterize all of the six known azolla species, and to evaluate them for use year-round in tropical transplanted rice production systems. [Note: in 1980 preliminary studies by Lumpkin and his

Chinese co-workers in China, A. microphylla shows great promise as a summer green manure in south Central China, and a winter green manure in the south. Also, A. nilotica shows promise as a fall green manure in China. Neither of these species has ever been tested in rice before. Further mission-oriented research could have high payoff in the near future].

(3) Following characterization and early testing, to distribute promising strains to national program centers for synthesis, design, and testing of new rice cropping systems based on azolla as a green manure.

b. Temperate, capital intensive rice production systems, primarily centered on broadcast-sown or drill-sown rice. This work should focus on developed countries, and on middle-income countries (e.g. Brazil and Colombia, and other countries, primarily in Latin America where similar rice production systems are used).

2. What organizations should be involved?

In the U.S.A. there are two places where azolla is being studied for use in agriculture. The University of California at Davis is already conducting research on azolla for use in temperate zone, broadcast-sown rice, and would the logical leader for the temperate rice work. The University of Hawaii has a program on evaluation of azolla for use in tropical production systems, and would be the logical leader for the tropical efforts. Kettering Laboratory Virginia Commonwealth University and USDA have specialized programs that could play supporting basic research roles for the temperate and tropical programs.

Linkages to developing countries will be necessary. Important programs elsewhere include the Zhejiang Academy of Agricultural Sciences, Hangzhou People's Republic of China, (the University of Hawaii has a cooperative program there already); the Fujian Province, PRC (IRRI has links with this group); IRRI, and national programs in Thailand, India, and Nepal. Several national research programs were initiated after in FAO-sponsored azolla training mission by T. A. Lumpkin in 1977. Also T.A. Lumpkin and J.L. Walker of the University of Hawaii, on behalf of the Inter-American Development Bank, visited Uruguay, Brazil, Peru and Colombia in 1979 to assess the potential for azolla in those countries.

The West African Rice Research and Development Association (WARDA) is also interested in establishing an azolla research program, and they should be tied into the tropical network.

3. What is the necessary level of financial support?

We will speak first of priority areas of research. There is need to carry out several priority activities soon. These include:

(a) More extensive and complete collection of azolla species and varieties, for evaluation in agriculture. Indeed, collection should take precedence over efforts to breed azolla, for the array of variability available in nature is clearly great, and this should be collected, and characterized before consideration should be given to support of breeding programs.

(b) Characterization of azolla varieties as to tolerance of high and low temperature, phosphorus levels in water, pH, light and other growing conditions should be of high priority.

(c) Testing and fitting existing azolla varieties into rice production systems should receive high priority.

These three priority areas should receive first attention for funding. Related basic research on physiology of the Azolla/Anabaena symbiosis, biochemistry of the association, etc. can probably be funded through basic research grants from NSF or USDA.

The applied aspects of collection, characterization for use in agriculture, and fitting into rice production systems could be done for the tropics for about $400,000 to $600,000 per year. This would allow funds for collaborative collecting trips to assemble a wider germplasm base, to conduct screening trials for tolerance to the physical and growing environment, and to run first assessments of potential usefulness in production systems. Such funding would also allow some limited funds for working with collaborators in a tropical azolla network. It would be desirable to have some funds for assisting, through small subgrants, the conduct of specific desired research programs in cooperating countries. Training, both non-degree and degree, should receive attention early in the program. The first training should emphasize azolla research techniques (e.g., many programs have failed because researchers did not know how to keep azolla alive during hot or cold weather). Later, training could begin to stress field management. We believe the general principle to follow in funding azolla research is probably that continuity of funding over the first several years will be more effective than heavy funding over a shorter time. Collecting, characterizing and evaluating in production systems needs to be done by a team that will require continuity for effectiveness. Such a team should include an algologist or cyanobacteria specialist. It should have access to laboratory, greenhouse and field facilities. The tropical leading institution should be able to grow azolla in the field at any time of the

year, and to grow azolla in such a way that all growth stages can be available at any time.

The temperate program will probably require funding in the same order of magnitude as the tropical program. The temperate network may be easier to establish because (1) the potential countries involved are either in the developed or middle income categories, and therefore may have more resources at their disposal, and (2) the countries' institutional research capacity will be much stronger than those of the tropical LDCs.

Some savings may be made and efficiency gained through close cooperation between the temperate and tropical programs. Joint collection trips and close adherence to jointly - determined protocols for testing and evaluation within the networks should save both time and funds.

4. What are the personnel requirements?

We believe the major research networks should be oriented toward practical adaptation of azolla to agricultural production. Therefore, agronomists with strong physiology and field production backgrounds will be required. As was previously stated, specialists in blue-green alga should be available in the parent institution or nearby.

The program should provide for laboratory and greenhouse assistance, as well as field workers for the field experiments. It is probable that some of this work may be provided by graduate students and student help and by existing institutional farm staff, but some full time assistance will be needed.

Research assistantships should be provided in the program, in order to get the training program going as early as possible.

5. What are the attitudes of those who would be affected?

Most research organizations have become aware of azolla and have some idea as to its potential. A few extension specialists (notably in rice) probably also know something about it. Beyond that, except in the PRC and Vietnam and a few individuals in developed countries, the farmers would know nothing of the plant and its potential use in rice.

It may be that since azolla is already used successfully in China and Vietnam it may be easier to popularize elsewhere.

6. What are conducive conditions for implementation of the technology?

As has been mentioned before, for the tropics these are:

a. transplanted rice

b. rural labor supply

c. assured water supply and some control of water

d. also: as of now - places that grow spring or late summer/ fall rice crops - because of the high temperature susceptibility of A. pinnata in summer.

For temperate rice, the conducive conditions are much less certain, because success has not yet been conclusively demonstrated. Factors thought to be important include:

(a) for broadcast-sown rice;

1. growing cold-tolerant azolla (such as A. filiculoides) as a monocrop green manure to be incorporated into the soil before sowing;

2. growing heat-tolerant, shade-sensitive azolla as an intercrop with the broadcast sown rice during the summer.

3. Having an assured source of water to grow the monocrop azolla before planting of rice.

7. Where do conducive conditions exist and where are they likely to develop?

Most of the countries of Asia have conducive conditions for use of azolla. Special opportunities for success seem to be present in Thailand, Bangladesh (aus crop) and the Philippines (irrigated dry season crop).

In Latin America, Peru and the Dominican Republic would appear to have the proper rice production systems to make Azolla use a possibility.

8. What is the sequence of steps leading to successful implementation?

The first two things a country much learn to do are how (1) to keep azolla plant materials alive year-round and (2) to multiply azolla stocks in order to have inoculant materials available for use in the rice crop. Principles for such techniques can be learned in training programs at the network headquarters or azolla research centers. Such techniques need to be taught widely to extension workers and to innovative farmers.

In some conditions in Asia, A. pinnata, A. pinnata var. imbricata and perhaps A. filiculoides could be used now as a monocrop basal fertilizer before transplanting of rice. This should be easy to popularize for the late winter or early spring rice crops.

Before azolla is used in rice, however, it should be tested under local conditions. As was stated, keeping azolla alive throughout the year and finding ways to multiply it for field use are the most important steps in beginning a program. The next step is testing under local conditions,

to find ways to fit it into the existing production system. Use as a basal fertilizer before transplanting is probably easiest, but if the crop cycle doesn't allow for time to grow an azolla green manure crop between rice crops, then it will be necessary to grow it as an intercrop. In that case the rice must be grown in rows, in order that incorporation of the azolla can be done. This is just an illustration of some of the considerations to be dealt with in using azolla in agricultural production systems.

F. Constraints to the Development and Implementation of Azolla Technology

1. Scientific Constraints

The global azolla research effort is disorganized and much of the work is repetitious and often useless. There has never been an international discussion of research priorities in azolla research. Certain problem areas, such as those involving agricultural engineering, have been totally ignored. Much of the support is going to finance work which is of an esoteric nature, while many of the people doing the research have little or no understanding of the problems which prevent azolla's widespread use by peasant farmers. Much of the work is involved in trying to improve laboratory specimens of azolla, while the vast differences in wild varieties remain unexamined.

Many of the problems preventing the widespread use of azolla require a multidisciplinary research approach, but so far azolla research has been cloistered into individual departments, even in the international institutes.

Funding agencies can assist in ensuring that azolla research will be directed toward real problems and needs, by requiring multidisciplinary,

linked efforts that focus on use of azolla on farms. This does not mean that basic research will be precluded, but it will ensure that practical, mission-oriented research will not be neglected.

2. Environmental constraints

a. Water is the primary environmental constraint to the cultivation of azolla. Azolla is a freefloating aquatic fern and is therefore limited to locations that have an abundant, stable water supply during field cultivation.

b. Temperature and humidity. For practical purposes, azolla survives within the water temperature range of 0 to 40°C; beyond this range, death will result. During field cultivation, for adequate growth, the daytime water temperature should stay within the range of 15 to 35°C. Humidity and temperature interact in their effect on azolla. Very high humidity and high temperature or very low humidity and low temperature are both detrimental to the growth of azolla.

c. pH. The pH of the paddy water plays an important part in the ability of azolla to survive. Besides affecting directly the growth of azolla, pH also affects the availability of nutrients, especially phosphorus. Low pH and high pH can cause formation of insoluble compounds that tie up available phosphorus; the phosphorus in such insoluble compounds is unavailable to azolla.

Azolla grows best within a pH range of 5 to 7, and can survive a range of 3.5 to 10.

d. Available nutrients. Azolla growth is dependent upon an adequate supply of essential elements in the water or in the surface layer of mud.

These elements must also be relatively balanced. Usually the addition of phosphorus and sometimes potassium is all that is necessary to ensure good growth.

3. Cultural and Economic Constraints

For most farmers, azolla cultivation would be an entirely new concept in green manuring. The idea of using an aquatic plant for such purposes is not part of most agricultural heritages. Farmers in tropical Asia traditionally have grown upland legume crops, such as milk vetch or lentils (as a catch crop), after harvesting the monsoon rice crop. Most have never grown an aquatic green manure, and many have rarely grown a legume that is not a feed or forage crop. To some, especially the hungry, growing a crop that is to be plowed under as a green manure seems impractical.

Azolla can be used as a forage for pigs, ducks and fish. However, the raising of swine, ducks and fish is uncommon in some places. Also, it is generally believed, although untested, that cattle and water buffalo will not eat azolla.

The year-round cultivation of azolla is more complex than the cultivation of rice. Without support, many poor uneducated rice farmers probably would not or could not grow azolla. Diligent rice farmers, such as those in Nepal or Thailand, probably could master azolla cultivation techniques, just as farmers in China and Vietnam have. As a result of unfavorable land ownership patterns, low grain prices and other social or economic difficulties, some peasant rice farmers do little more than haphazardly plant their fields and then wait for harvest time. For them, meticulous

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farming does not yield sufficient benefits to their family. Also, much transplanted rice in some parts of Asia is not even planted in rows, a necessary measure for azolla to be incorporated as a basal fertilizer. Also, many farmers who could not be convinced to use nitrogen fertilizer in the 1960s when it was inexpensive, will be unlikely to cultivate azolla. The exceptions might be peasant farmers who want to improve their crop yields but do not have the capital to purchase nitrogen fertilizers. Also, farmers who have given up using nitrogen fertilizer because of the high cost might be convinced to use azolla as long as they can afford the cash outlay for relatively small amounts of phosphorus fertilizer and pesticides. They would have to purchase about 100 kilograms of single superphosphate to grow one hectare of azolla for 4 to 5 weeks. If properly applied, the phosphorus would result in as much nitrogen as 500 kilograms of commercial ammonium sulfate fertilizer.

Azolla cultivation could significantly reduce the fertilizer input costs of raising high yielding rice crops, but would still require the purchase of certain inputs, especially phosphorus fertilizer. Farmers unable to obtain these inputs would probably find it difficult or impossible to raise azolla.

4. Political Constraints

At present the widespread cultivation of azolla is found only in communist countries. Azolla was cultivated in both China and Vietnam before the present governments came to power, but on only a small fraction of the area that azolla covers today. Analyzing the elements of this situation is difficult because at present the cultivation of azolla in

China and Vietnam cannot be compared to its cultivation in countries with a different political system. Because azolla cultivation is just being introduced to farmers elsewhere, there has been insufficient time for other countries to develop successful azolla programs that are in line with their different political systems.

Even without an adequate comparison, it is obvious that the successful azolla programs in China and Vietnam owe a considerable amount to the way their farming systems are organized. The commune and cooperative organizations of these countries that use azolla have highly trained azolla teams, whose sole function is to ensure the success of azolla cultivation. Training workshops to learn the newest techniques are held annually from the national level down to the local azolla team level. In addition, every level regularly publishes pamphlets about the practical applications of azolla.

The higher levels of the Chinese and Vietnamese systems can be transferred with minor modifications to other countries, but not the lower local levels. Most governments do not have the power to enforce their will on independent peasant farmers as effectively as China and Vietnam can influence their communes and cooperatives. Nor can a peasant farmer be expected to master all the intricacies of successful azolla cultivation that are known by a highly trained commune azolla team.

G. The Effect of the Implementation of Azolla Technology on the need for Inputs

1. Capital

Capital requirements for azolla cultivation are quite small. For most farmers, only a small amount of phosphorus fertilizer, often no

more than would be required for the rice crop, and pesticides to protect the azolla from pests and diseases are all that will be required.

2. Farm labor

In essence, the cultivation of azolla exchanges labor for nitrogen fertilizer. The present azolla technology is based on the Chinese and Vietnamese models and thus is extremely labor intensive. In fact, the cultivation of azolla can not be adopted by countries with mechanized rice farming systems until new capital intensive technology is developed.

Adoption of azolla cultivation by a developing country can only increase the demand for farm labor, especially when nursery stocks are being multiplied and during field cultivation. In addition, a few workers will have employment year-round because of the need to maintain azolla nurseries during the off season.

Rice requires about 20 kg of nitrogen per ton of the harvested crop. About half of this is recycled into the soil in the crop residue; therefore about 10 kg of nitrogen is removed per ton of harvested grain. A six ton rice harvest removes about 60 kg of nitrogen from the soil, equivalent to 300 kg of ammonium sulfate fertilizer. If azolla was substituted for ammonium sulfate, nearly all of the money required to purchase the 300 kg of ammonium sulfate fertilizer could theoretically be used to pay farm labor to grow azolla, or to gain a greater return on family labor.

Azolla appears to offer special opportunities for small farms, particularly family farms with abundant labor. Conversely, suitable azolla technology for large mechanized farms is not available.

Azolla is used successfully on large communes in China, but the organization of these communes is difficult to relate to family farms.

Azolla should improve the competitive situation of small peasant farms in developing countries.

3. Land

The land required for azolla cultivation is mainly related to nursery and field multiplication. For overwintering or oversummering, very small protected greenhouse or field areas are required, more in the area of small garden plots than large field areas. However, when azolla multiplication for field inoculation is to be achieved, much more land is required. Perhaps as much as 10 per cent of the rice crop area to be inoculated is a good estimate of the land area needed for azolla field multiplication. This land is not tied up permanently, however, but it will be devoted to azolla multiplication for a month or so prior to inoculation.

For farming systems that use azolla as a basal, soil incorporated green manure before the rice crop, all of the land to be planted into rice and fertilized with azolla will need to be devoted to azolla cultivation for probably a month prior to transplanting.

In situations where azolla is used as a soil-incorporated, topdressed green manure or as an unincorporated intercrop with rice, no land will be required to be devoted solely to azolla, except for the inoculation nurseries.

H. Conclusions

Azolla is being used as a primary source of nitrogen on an increasing land area in transplanted rice crops in China and Vietnam. The largest use of azolla in these countries is in the spring rice crop, mostly as a monocrop grown before rice as a basal, soil-incorporated green manure. Less is used as an intercropped topdressing green manure in transplanted rice that is planted in rows.

Use of azolla in the summer rice crop is hampered by high water temperatures and heavy pest attack. A search for suitable temperature-tolerant species or varieties could have high payoff.

Species used in agriculture today are A. pinnata, A. pinnata var. imbricata (sometimes referred to as A. imbricata), and A. filiculoides. A. pinnata and imbricata have been used for a long time in China and Vietnam, but their susceptibility to high temperatures and pest attack makes them suitable only for spring and some fall rice crops. A. filiculoides has just begun to be used widely in China, especially in areas where -- because of its cold tolerance -- it can be grown in late winter and early spring as a green manure for early spring rice. Although A. filiculoides has proved useful in China because of its cold tolerance, it is even less tolerant of high water temperatures (above 25-27°C) than A. pinnata. What is needed, then, is an azolla that can tolerate high summer temperatures, up to 40°C or so. A. microphylla, collected by T. Lumpkin in the Galapagos Islands, shows promise of becoming a suitable summer green manure for central China and a winter green manure in south China.

There is a great need to collect and characterize species and varieties of azolla extant in nature. This work is of the highest priority. The potential worth of A. microphylla in China has already been mentioned. However, it may be useful to point out that A. nilotica, collected by T. Lumpkin in the Sudan, has shown the highest nitrogen fixation of any azolla studied. Lumpkin was only able to collect 3 specimens of A. nilotica, yet many more strains and types are available in the Nile Basin, and these should be collected and characterized as soon as possible.

All species could prove useful. For example, varieties of filiculoides look promising now for use in certain agricultural situations. The same can be said about microphylla, imbricata, pinnata, and caroliniana.

Research programs should stress multidisciplinary approaches, with close linkages between institutions. Both tropical and temperate farming systems should be emphasized, but these programs should be centered in different places that are committed to the two systems. Both temperate and tropical research programs should be linked, and should cooperate in collection and characterization of species and varieties. The tropical program should focus on using azolla in tropical farming systems, notably small peasant farms, and the temperate program should focus on capital intensive mechanized rice production systems. An international meeting should be held that will have as its major agenda item the setting of international research priorities for azolla. The primary focus of research programs should be to find a useful role for azolla in farming systems. Basic research should not be neglected, but the potential usefulness of azolla is too great to delay its wider use in agriculture through emphasis on more esoteric topics at the expense of applied research.

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PAPER NO. 8. NATIVE PLANTS: AN INNOVATIVE BIOLOGICAL TECHNOLOGY

(By Dr. Cyrus M. McKell, Director of Research, Plant Resources Institute, Salt Lake City, Utah)

ABSTRACT

The concept of native plants concerns a new direction in botanical development. The term defines that idea that rather than adapting the environment to the plant, an indigenous plant expresses the best adaptation to an environment and by improving on this expression will yield various benefits. We are approaching the situation where bringing marginal lands into widespread agricultural utilization is employing technologies and plant species inappropriate to these situations. This is occurring with a total disregard for the climatic limitations of the environments within these areas. A new approach is required. It may even benefit traditional agriculture and forestry practices.

Development of native or indigenous plants, particularly with reference to those adapted to tropical and sub-tropical soils, will be beneficial at a variety of economies of scale. In some instances, their development will be small and amenable to utilization by individual farmers or farming groups. On the other hand, there will be instances where development will be large scale and have international implications.

Native plants can be particularly useful in sustaining fertility on depleted or marginal soils and improving general productivity. They connect the need for production with the new approach of an agroecosystem. Polycultural (mixed) cropping systems especially applicable in tropical locations rely heavily on the potential of adapted or indigenous plants to perform their beneficial functions. In this regard, native plants represent an under-utilized resource and constitute an opportunity for positive botanical development.

Numerous agricultural and forestry development programs have produced more problems than they have solved. The coordinated, integrated development of indigenous plants could allow for multiple and additional benefits greater than the initial goals of soil fertility, food production or raw materials.

There is an immediate need for inventories of existing native crops for their development potential. The world's tropical and sub-tropical germplasm is poorly known. Throughout the world existing knowledge of plants and their uses by indigenous peoples is disappearing due to conversion of farming systems to monocultural uses. Germplasm storage of potentially valuable varieties and strains requires immediate attention. Demonstration of practical working models with specific native plants must be performed.

One limiting factor to the development of native or other unconventional plants is an institutional bias against their development. The major emphasis of plant research during the last 100 years has been directed at the dozen or so primary food crops with the exclusion of most everything else.

To overcome this institutional bias will require innovation in policy, research and development, and program implementation. Development of native or adapted plants should allow for an integration of these concerns. The capabilities of various governmental and non-governmental institutions should be directed towards the goal of sustaining soil productivity in both the short and long term context.

I. INTRODUCTION

The purpose of this paper is to present a non-technical description and evaluation on the utility of "native" plants as an innovative technology to improve productivity on soils in tropical/subtropical areas. The paper addresses several major questions that appear as subsections.

The term native plant may not be fully understood and nec ; clarification for purposes of this paper. All plants may be considered native or indigenous to some location on the earth, but when a plant is taken to an area where it is not found, it becomes an introduced species. This distinction is too constraining and can easily overlook the important attribute of adaptation judged either from actual observation or from scientific evidence of ecological similarity. From the standpoint of the objectives of this report, native species may be consi ed as those plant species growing in an area that have not been exploited for commercial development and export. Some native species may have desirable attributes and a potential for intensive use while others may merely serve to fill in the spaces of the plant community in a general way and have but minor development potential. This paper, therefore, is limited to indigenous species that have not been extensively developed.

Native plants hold great promise for meeting the expanding needs of society for food, fiber, fuel, and enhanced land productivity. Often overlooked in favor of an imported species, in the search for a plant or plant product to serve a market or domestic need, plants native to a given region may already express the range of adaptation necessary for sustained utilization. A good example of indigenous plants being overlooked in favor of introduced species

is in rangeland improvement programs in the western U.S. where native shrubs were removed in order to plant introduced grasses (McKell 1976). Plant exploration and introduction have been carried on by the economically developed nations but the search for new plant materials has emphasized conventional crops and uses resulting in many native species being overlooked.

In the past, the common procedure has been to examine the files or materials found in plant introduction stations to find new plants and plant products rather than explore the locally available materials for possible new products. Because of the increase in energy costs and the energy component in existing products and production activities, a new look for alternatives is justified. A particularly attractive opportunity for development of native plants exists in areas of tropical and subtropical soils. These areas have not generally been of interest to the developed nations as a source of plant materials because the developed nations are, to a large extent, located in temperate climates. This approach has limited the extent of germplasm collection, research testing, and introduction to the primary crop species. Additionally, most American primary crop species are introductions from the Old World, and these have been genetically developed over long periods of time for intensive agricultural use. In contrast, many indigenous species have been ignored in favor of traditional crops.

II. THE ROLE OF NATIVE PLANTS IN SUSTAINING FOOD AND FORAGE PRODUCTION

Native plants serve a traditional role in many countries with tropical and subtropical soils. Various indigenous species have been used for food, fuel, livestock feed, construction, fiber, medicines, and other purposes on a sustained yield basis either gathered from natural plant communities (forests, rangelands, marshes, etc.) or harvested from small farmed plots under various degrees of cultivation. Cultures as diverse as Mexico, Sri Lanka, and Indonesia have well-documented histories of wide utilization of indigenous plants for medicines, foods, and other uses. Most of these native plants have not reached a level of development sufficient to make them commercially useful in the market place. Notable exceptions include rubber, corn, pineapple, potatoes, etc., which have been developed worldwide. Most species, however, are unspectacular in their attributes and find beneficial use in the day-to-day existence of the local people.

Over-use of native species brought about by population increase and energy shortages is creating adverse impacts on many species and their systems of production. Where previously a conservative level of plant utilization generally assured their natural replacement and did not reduce their genetic diversity, exploitation of land resources by overgrazing, intensive agricultural development, forest clearing, industrial development, and widespread soil degradation threatens to eliminate many useful species. For example, a recent National Academy of Science assessment of environmental degradation of the groundnut basin of Senegal (NAS 1980) indicates that overuse due to population increase and cyclic drought has resulted in the disappearance of

many native species used for fuit and livestock fodder. Theoretically, some of these species are still present in the non-cultivated bush areas. An example is Ziziphus mauritiana, a desirable fodder shrub, which had essentially been eliminated from areas adjacent to the intensively-cultivated farmlands by overuse. At a recent conference in Australia on Genetic Resources of the World, concern was expressed that valuable genotypes and gene combinations were being lost due to the impacts of human population expansion. Associated with the direct loss of genetic resources is a substantial reduction in soil fertility and an increase in less desirable plants.

Another equally important role of native plants is their linkage to improvements in crop performance and diversity. Indigenous or locally cultivated relatives of many common crop plants offer significant potentials for crop improvement programs within the temperate and tropical latitudes. Recent discoveries of wild perennial relatives of corn (Zea mays) could prove extremely important to the future development of this crop. Similarly, the expression of expanded environmental adaption often inherent in many native plants could allow for much wider cultivation of the species while reducing artificial inputs. Recent work with salt tolerance in major grain crops and tomatoes relies heavily on the adaptive qualities of various native and overlooked indigenous variation of these important crops (Epstein 1980).

III. WHERE NATIVE PLANTS ARE BEING USED TODAY

Native plants are presently being used all over the world. Many species find extensive use in developed agriculture and some native species already enjoy limited commercial use in areas of optimum adaptation (Table I). Opuntia cactus fruits in central Mexico are collected and sold locally. Fibers are removed from Agave lechuguilla for use in making Mexican mats, shoes, and baskets. Numerous species of native trees such as Mangosteen (Garcinia mangostana) in southeast Asia, Naranjilla (Solanum quitoense) in Columbia and Ecuador, pejibaye peach palm (Guiliema gasipaes) in Central America and soursop (Annona muricata) of the West Indies produce exotic fruits for local markets.

The important point is that the usefulness of some species is known only to local people or is generally not appreciated by a wide audience. A number of examples of fruit, vegetable, fiber, oil, and forage species are described by the National Academy of Sciences in their studies on underexploited plants (NAS 1975). Such underdeveloped species may possess unique features that could be useful in new applications or supplement existing crop plants if they were screened for optimum size, shape, product quality, and adaptability to various management practices.

The genus Atriplex is an example of a group of semi-arid sub-tropical plants currently used but possessing significant potential for increasing rangeland productivity. Various shrubby Atriplex species are valuable as livestock forage during seasonal dry periods when grasses are dry and below required levels of crude protein for animal nutrition. The protein content

is high and balanced with other nutritional requirements. The exploitive, subsistence-level grazing practices and extensive gathering of shrubs for fuel on the rangelands of Syria, Iraq, and other middle eastern nations has nearly caused the disappearance of these valuable fodder shrubs (Thalen 1979). An integrated development program of collection and revegetation with native shrub species and other adapted *Atriplex* species from similar climates could substantially restore rangeland productivity to this region.

Another example of a native plant that is receiving considerable attention on a pilot scale level is jojoba (*Simmondsia chinensis*), an evergreen shrub indigenous to the Sonoran deserts of the United States and Mexico (Hogan 1979). The plant is valued for the liquid wax contained in its seeds. The wax is similar to sperm whale oil and has a potential for use in many industrial processes. Field test plantings have been made in Arizona, California, Israel, Mexico, and Australia. As the plant is adapted to areas of extremely low rainfall (less than 10 inches) it could become an important cash crop for the appropriate arid areas (Hogan 1979).

Renewed interest in producing commercial rubber from guayule (*Parthenium argentatum*) has developed as a result of increased costs and uncertain availability of rubber from southeast Asia. The guayule shrub is native to northern Mexico and southwest Texas and could be grown on extensive areas of land now marginally used for grazing. Demonstration fields of guayule are being cultivated in the U.S. by two major rubber companies. Mexico has an active program of development involving assessment of native guayule populations and plans for a processing facility.

TABLE I Little Used but Potentially Useful Plants

Common Name	Scientific Name	Useful Portion	Potential Use	Present Growing Areas	State of Cultivation	Present Yield Per Hectare Per Year	Time to First Harvest
A. Humid Tropics							
Cocoyam	*Xanthosoma sagittifolium*	tuber	carbohydrate, protein	Tropical Americas, West Africa	domesticated	30–60 tons wet weight	3–10 months
Peach palm or pejibaye	*Guilielma gasipaes*	fruit and stem	carbohydrate, oil, protein, "heart of palm"	Central and Northern South America	domesticated	3 tons	6–8 years
Taro and dasheen	*Colocasia esculenta*	tuber	carbohydrate	Egypt, Philippines, Hawaii, Caribbean	domesticated	22–30 tons wet weight	6–18 months
Buriti palm	*Mauritia flexuosa*	fruit kernel, thoots, trunk and leaves	oil, starch, vitamins A and C, timber, cork, fiber, "heart of palm"	Amazon Basin, Venezuela, Guianas	mostly wild	?	?
Babassu palm	*Orbignya martiana*	fruit and kernel	oil, protein, fuel	Amazon Basin	mostly wild	1.5 tons	10–15 years
Pequi tree	*Caryocar brasiliensis*	fruit and kernel	oil, fuel	Amazon Basin, Central Brazil, Guianas	mostly wild	?	9 years
Seje palm	*Jessenia polycarpa*	fruit	oil resembling olive oil	Amazon Basin	wild	22 kg/tree per year	?
Winged bean	*Psophocarpus tetragonolobus*	pods, beans, tubers, foliage	protein, oil, carbohydrate, livestock feed	Papua New Guinea, Southeast Asia, Sri Lanka	domesticated	2.5 tons of dry beans	10 weeks
Durian tree	*Durio zibethinus*	fruit	carbohydrate, fat, vitamins, flavor	Southeast Asia	haphazardly cultivated	?	7 years
Mangosteen tree	*Garcinia mangostana*	fruit	highly prized flavor	Southeast Asia	domesticated	50 kg/tree per year	15 years
Pummelo tree	*Citrus grandis*	fruit	large citrus fruit	Southeast Asia	domesticated	?	several years
Soursop tree	*Annona muricata*	fruit	fruit and juice	Southern China, Australia, Africa, tropical Africa, West Indies	domesticated	6–10 tons	?
Uvilla tree	*Pourouma cecropiaefolia*	fruit	grapelike fruit	Western Amazon	wild	?	3 years
Chaya bush	*Cnidoscolus chayamansa*	leaves	vitamin-rich leafy vegetable	Mexico and Central America	domesticated	?	2–3 months
Ramie herb	*Boehmeria nivea*	stems and foliage	fiber and livestock feed	East and Southeast Asia, Brazil	domesticated	1.4 tons fiber, 20 tons feed	2 months
Chuasso herb	*Calathea lutea*	leaves	commercial wax	Amazon Basin, Central America	wild	0.8 tons of wax	9 months
Leucaena	*Leucaena leucocephala*	leaves, wood, pods, seeds, bark	livestock feed, timber, fuel, paper, soil fertilizer, dye stuffs, human food, erosion and watershed control, nurse tree, fire and wind breaks	Central America, Mexico, Southeast Asia, Northern South America, Australia, Hawaii, East and West Africa, Papua New Guinea, Caribbean, India	domesticated and wild	12–20 tons of forage, 20–50 tons of wood	less than 1 year to more than 3 years, depends on variety planted
B. Semarid and Arid Tropics and Subtropics							
Channel millet	*Echinochloa turnerana*	seed, leaves, and stems	carbohydrate, protein, livestock feed	Central Australia	wild	?	several months after heavy rain
Buffalo gourd	*Cucurbita foetidissima*	seed, root	oil, protein, starch	Mexico, Southwestern United States	mostly wild	2.5 tons of seed, 22 tons starch	2 years
Guar (cluster bean)	*Cyamopsis tetragonoloba*	seed, leaves, and stem	gum, protein, oil, livestock feed	United States, Pakistan, India, Australia, Brazil, South Africa	domesticated	18–24 tons green fodder, 0.9–2 tons seed	3–5 months

TABLE 1—Continued

Common Name	Scientific Name	Useful Portion	Potential Use	Present Growing Areas	State of Cultivation	Present Yield Per Hectare Per Year	Time to First Harvest
Apple-ring acacia tree	*Acacia albida*	leaves, shoots, pods, seeds	livestock feed, human protein	Tropical and Southern Africa	wild	200 kg protein	several years
Ramon tree	*Brosimum alicastrum*	leaves, twigs, nuts	livestock feed, carbohydrate, protein	Central America, Southern Mexico, Caribbean Islands	mostly wild	?	several years
Cassia shrub	*Cassia tiurita*	leaves	livestock feed	Australia, Israel	wild and cultivated	1/2 ton dry weight	1-1.5 years
Saltbush	*Atriplex* spp.	leaves and shoots	livestock feed	worldwide in warm and zones	wild and cultivated	1-1.5 tons	2 or 3 years
Candelilla shrub	*Euphorbia antisyphilitica*	stems and leaves	hard wax	United States and Mexican deserts	wild	?	2-5 years
Tamarugo tree	*Prosopis tamarugo*	pods and leaves	high protein, livestock feed	Atacama desert of Chile, Canary Islands	cultivated	10-20 sheep	5 years
Jojoba shrub	*Simmondsia chinensis*	seeds	liquid wax identical to sperm oil	United States and Mexican deserts, Israel	mostly wild	2 tons	3-5 years
Guayule shrub	*Parthenium argentatum*	whole plant	natural rubber	United States, Mexican deserts, Spain, Turkey	mostly wild	0.33 ton	1 year
C. Mountain Environments of Low Latitudes							
Grain amaranth	*Amaranthus caudatus*, etc.	seed, leaves	high lysine, high protein, starch, vitamins	Andean region of South America	domesticated	higher than maize	several months
Quinoa (grain)	*Chenopodium quinoa*	seed	protein, carbohydrate	Andean region of South America	domesticated	?	5-6 months
Peruvian parsnip	*Arracacia xanthorrhiza*	tubers, stems, leaves	carbohydrate, livestock feed	Andean region of South America	domesticated	?	10-14 months
Naranjilla shrub	*Solanum quitoense*	fruit	fruit and juice	Central and Northern South America	domesticated	1-2 tons of fruit	6-12 months
Winged bean	*Psophocarpus tetragonolobus*	pods, beans, tubers, foliage	protein, oil, carbohydrate, livestock feed	Papua New Guinea, Southeast Asia, Sri Lanka	domesticated	2.5 tons of dry beans	10 weeks
D. Saline Environments							
Eel grass	*Zostera marina*	seed	carbohydrates, protein	tidal flats and estuaries in all latitudes	wild	?	?
Pummelo tree	*Citrus grandis*	fruit	citrus fruit	brackish marshy areas in Thailand	domesticated	?	several years
Saltbush	*Atriplex* spp.	leaves and shoots	high protein, livestock feed	worldwide, including salty soils and saline irrigation waters	mostly wild	1-1.5 tons	2 or 3 years
Tamarugo tree	*Prosopis tamarugo*	pods and leaves	high protein, livestock feed	Atacama desert of Chile, Canary Islands	cultivated	5-20 sheep	5 years
Salt grass	*Distichlis spicata*	leaves and stems	livestock feed, sand stabilization	seacoasts from Australia to Spain, Argentina to Baja California	mostly wild	?	1 or 2 years
Spirulina, blue-green algae	*Spirulina platensis*, *Spirulina maxima*	entire alga	poultry feed, very high protein human food	Lake Chad, Valley of Mexico	cultivated	3 tons protein	several days

Taken from Revelle, R., 1978. Flying beans, botanical whales, Jack's beanstalk, and other marvels. The National Academy of Sciences, Washington, D.C.

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IV. RESEARCH EFFORTS ON NATIVE PLANTS

Research on native plants is being conducted by many different groups ranging from private individuals and companies to state, national, and international agencies. However, no coordinated research effort can be expected because of the diversity of potentially useful native species, the various countries in which they are growing and could be grown, and the risks involved in developing new crops for presently ill-defined markets.

As has probably been the case over the span of time that man has developed a civilized society, plant resources have been developed to meet existing and short-term anticipated needs. The difference today is the high cost of bringing new products into highly competitive markets. Opportunities for new products or uses from native plants can occur as a result of changes (or potential for changes) in consumer preferences or as existing products come into short supply and can be replaced by a native plant product.

It is difficult to clearly identify organizations performing research on native plants, but they fall into the following categories:

1. Broad spectrum agencies sponsoring exploration, collection and evaluation.

   Examples
   - USDA, plant introduction, plant materials centers (nationwide)
   - FAO (Food and Agriculture Organization of the U.N.), seed exchange, international development
   - SIDA (Swedish International Development Agency) sponsoring projects to preserve genetic resources.

2. Agricultural experiment stations doing work on individual plant species with local concern.

Examples - ● University of California Agricultural Experiment Station, Riverside, working on jojoba wax

● University of Hawaii Agricultural Experiment Station working with Lucaena trees

3. Private organizations, agricultural enterprises working to develop products from various species.

Examples ● Firestone Rubber Company working on quayule for rubber development

● Native Plants, Inc., developing new technology for tissue culture propagation of various plants

● Jojoba International, Inc., encouraging establishment of commercial plantings of jojoba.

Funding of native plant research is very dependent on the species in question. Obviously the potential for some species is greater than others depending on the scarcity and quality of the expected product, the abundance of the plants and the needs of society. Currently, there is a high interest in native plants with potential as sources for biomass energy. Unfortunately, there is little, if any, coordination in research funding for native plant development or in the establishment of priorities as to which species offer the best potential. As of 1979, the total U.S. funding for research and development of underexploited plants was limited to less than $10 million of which half was devoted to jojoba.

The uncertain path of development for a natural rubber product from the native shrub quayule (Parthenium argentatum) illustrates the problems of developing a native plant. The National Academy of Sciences (1979) pointed

out that in 1904 a company was formed to extract rubber from the guayule bush. By 1910 this company was the 6th largest in Mexico but the wild stands of plants quickly became depleted. Expelled from Mexico by Pancho Villa, the company continued limited operations in Salinas, California. Cut off from natural rubber supplies from Southwest Asia in 1942, the U.S. took over the company and planted over 12,000 hectares of production and experimental plots of guayule. These fields were just coming into production after the war in 1945, but because natural rubber was again plentiful and a fledgling synthetic rubber industry gained the needed federal price supports, the guayule fields were destroyed. Recognizing the need for a dependable supply of natural rubber, Congress passed the Native Latex Commercialization Act of 1978 which makes $30 million in federal funds available for research. Subsequently, Firestone Tire and Rubber Company and Goodyear Tire and Rubber Company have initiated field trials in the Southwest. In Mexico, plans are underway for a natural rubber extraction facility southwest of Saltillo, Coahuilla using guayule from native stands and later from established plantations.

Obviously, a more integrated and organized effort will be needed to bring the benefits of other native plants into reality. The research community and society simply cannot be subjected to political and economic vagaries over a long period during the development of a new crop of national value. Coordination is needed to stimulate innovation in policy planning, research and development funding, and commercial implementation.

To bring native plants into commercial production, substantial, integrated programs are necessary. We know that the genetic quality of conventional crops and appropriate cultural practices have been improved over a long period of time. With this history of development, we can expect that new crops/products from

native plants can be developed with much greater efficiency. Significant breakthroughs may take place (such as the application of various biotechnologies) but for the most part, research funds, time, and vision will be needed to unlock the resources represented by most native plants.

One of the first research steps consists in identifying promising native plants and describing some of their characteristics. A recent survey sponsored by the National Science Foundation (Soil and Land Use Technology 1978) described six new crops with a potential for development in the arid and semiarid United States. A thorough coverage was given to ten new agricultural crops (Ritchie 1979) that already have received some development attention. Goodin and Northington (1979) helped to stimulate interest in native plants with their conference on Arid Land Plant Resources. Probably the greatest stimulus to the development and use of native plants in recent years has been the series of bulletins published by the National Academy of Sciences. "Underexploited Tropical Plants with Promising Economic Value," (NAS 1975c) describes 36 tropical and subtropical plants that have a high potential for use as cereal, root, vegetable, fruit, oilweed, forage, and fuel. "The Winged Bean - A High Protein Crop for the Tropics" (NAS 1975b) provides information on a tropical legume native to Southeast Asia and New Guinea with a potential for improving human nutrition. "Guayule: An Alternative Source of Natural Rubber" (AS 1977) is a report on the development potential of a subtropical desert shrub of Mexico and Southwestern U.S. that produces a latex product similar to natural rubber from Southeast Asia. "Lucaena: Promising Forage and Tree Crop for the Tropics" (NAS 1977) provides information on a vigorously-growing tree and bushy plant that produces nutritious forage as well as restoring soil fertility. Other benefits include timber, fuel, and pulpwood as well as soil conservation and stabilization. "Tropical Legumes, Resources for the Future" (NAS 1979)

reports the findings of a group of legume specialists on 200 species that warrant research and development to achieve their optimum potential. "Products from Jojoba" (NAS 1975a) gives a review of the chemistry of the liquid wax obtained from this shrub native to Southwestern U.S. deserts.

These publications all highlight the immense potential existing within the botanical world to augment agricultural, forestry and horticultural production, particularly in the developing countries. These and other surveys consistently document the immediate need to develop thorough inventories of indigenous knowledge concerning native plants and their uses, germplasm collection and storage, and conservation of existing habitats. The rapid disappearance of extensive semi-arid, sub-tropical or tropical plant community compounds the problem of collecting, researching and developing these under-exploited plant resources.

V. HOW DO/COULD NATIVE PLANTS INCREASE OR DECREASE THE NEED FOR FERTILIZER, PESTICIDES, IRRIGATION, AND MACHINERY?

Any change in the present use pattern of fertilizer, pesticides, irrigation, and machinery would depend completely on the nature of the native plant being developed, whether the particular plant could be developed on an intensive or extensive basis, or the degree to which the plant is susceptible to insects and diseases. However, any move to increase productivity would generally require an increase in the level of inputs. The adaptation of some indigenous plants to multi-cropping systems or polycultures could significantly reduce the need for artificial inputs. The scope of such production systems is just in its infancy of development, however, and models appropriate to widespread application are virtually non-existent.

Some specific examples of inputs required by various native plants will illustrate their variable nature.

A. Fertilizer

Three possibilities relative to fertilizer use may be seen:

1. Legume species may have minimal fertilizer requirements consisting mainly of phosphorus, sulfur, and micronutrients. In turn the legumes and other species may fix nitrogen and release it in the root zone to companion and follow-on crops.
2. Some native species may not require high levels of fertilizer because of their adaptation to low nutrient environments.
3. Non-legume species may require substantial amounts of fertilizer to achieve optimal production levels.

A brief discussion of each possibility will illustrate the fertilizer requirements.

Leguminous native plants are particularly attractive for development because they can serve to increase soil nitrogen as well as provide useful products such as fuel, forage, and wood biomass. Fast growing Lucaena trees have been shown to provide foliage containing 1000 to 1300 lbs. of nitrogen a year and can restore the fertility of tropical soils depleted of nitrogen and organic matter (NAS, 1977). Felker (1979) suggested that mature tree-legume orchards receiving no irrigation or nitrogen after establishment may increase soil fertility up to four times greater than non-leguminous tree species. Numerous legume shrubs and trees such as Acacia, Prosopis, Demodium, Cassia, and Stylosanthes enhance soil fertility while at the same time serving as live fences, crop interplantings or range and pasture fodder. Many examples of soil fertility increase are given in "Tropical Legumes: Resources for the Future" (NAS 1979), "Tropical Pastures" (Sherman 1977), and in papers presented at the International Symposium on Browse in Africa (ILCA 1980).

Some native species may not require large amounts of fertilizer because they are adapted to soils of medium to low fertility. Under such conditions, plant growth and production could be expected to be correspondingly low. If high yields for commercial production are desired, the level of fertility must be increased accordingly. Intensive cropping has been shown to deplete soil fertility and any continuous production in a new agricultural location would eventually require a regular soil fertilization program.

Non-legume native plants may require large increments of fertilizer to produce at levels sufficient to be commercially attractive and to cover costs of production and development. These species are those requiring optimal soil and water conditions. Possible requirements for fertilizer and other inputs for such crops are summarized in a report prepared for the National Science Foundation (Soil and Land Use Technology 1978).

Another potential strategy is represented by the selection and development of native plants adapted to saline environments. The ability to tolerate the environmental constraints and still produce utilitarian by-products is one potential avenue for overcoming high fertilization inputs. This is an approach to native plant development which has virtually been ignored in plant research. The existence of salt tolerant wild selections of existing crops could improve the infertility tolerance of these species and therefore potentially reduce their existing needs for fertilization. Such possibilities will require concerted efforts to determine and enhance the range of adaptability for most crop species.

B. Pesticides

Very few if any of the native plants having a high potential for development have been studied from the aspect of insect, disease, or weed problems normally associated with intensive cultivation. Whereas many insect or disease organisms may be held in check in a diverse plant community, they may increase to epidemic proportions when their host plan is grown in a pure stand. An example of such an epidemic occurred when black grass bug populations nearly devastated pure stands of introduced wheatgrasses which had been seeded to replace sagebrush and other plants in western rangelands (Haws et al 1978). Plantings of native species will require research and plant protection measures similar to those already necessary for the production of conventional crops.

In tropical countries where multicropping systems represent the most sustainable method of farming systems, the pesticide requirements could be minimized by host/predator interaction within the farm plots (Gliessman 1980).

Testing and development of such models needs to be greatly expanded, however.

C. Irrigation

Requirements for irrigation will depend on the kind of native plant selected for development. As a concept, the use of plants indicates an adaptation to a specific environment and its constraints. Species adapted to tropical soils may not require irrigation if the pattern of rainfall is adequate and meets the critical stages of plant development. Areas of subtropical soils typically have periods of rainfall deficiency and various strategies must be employed to obtain production under such conditions. These strategies available consist of the following:

1. Choose native plants with low water requirements that can be grown in desert or semi-desert conditions. Some examples are: jojoba, atriplex, guayule, buffalo gourd, guar, cassia, acacia species (Revelle 1978).
2. Develop technologies to increase the effectiveness of natural precipitation or irrigation. Alternate fallow, spaced plantings, water harvesting, or drip irrigation can be effective in obtaining plant establishment and production. Where land is not a limiting factor, these extensive practices can be economically effective. Evanari et al (1971) demonstrated how an ancient desert civilization survived in the Negev desert by using precipitation optimizing practices such as water harvesting and spaced plantings. Recent work at the University of Arizona (Fraiser 1975) indicates high potential for using water harvesting to foster plant production under desert conditions. Biomass plantings, deep rooted tree crops, and drought adapted species would be most suitable for these technologies.

3. Utilize available irrigation water to support maximum production of new crops from high yielding native plants. Where soils with a high productive potential may be available for intensive use, possibly by replacing a lower value traditional crop with a high value new crop, irrigation may be justified. Close plantings, tillage, pest control, and fertilization may also be needed to optimize production. Grain amaranth, winged bean, and guar are possible species for intensive development, but many others may be considered with adaptations of irrigation techniques to meet plant needs and weather patterns.

D. Machinery

Because of the varied nature of native species available for development, no definite statement can be made regarding machinery requirements. Several items would certainly be needed for land preparation, tillage, and transportation of crops to storage and market. Harvesting may be done by machinery in the case of a uniform plant such as guar or guayule where leaves and seeds are easily available for cutting or removal by a glade or catcher. Where fruits, stems, or roots are not uniformly exposed and are retained on the plant, either hand labor or a specialized piece of machinery may be needed.

Regions of the world where hand labor is abundant and available for planting, cultivating, and harvesting, the development of new crops from native plants using hand labor rather than machinery is most appropriate. In other nations, labor intensifying machinery can be developed. This has been the pattern followed in the development of conventional crops starting with tillage and land preparation.

It is important to recognize that the development of native plants for their various uses can be directed at local levels in response to specific needs as well as to wider industrial and international markets. Machinery and labor requirements will be dependent upon which level of development is pursued.

VI. WHAT IS THE POTENTIAL ROLE OF NATIVE PLANTS TO RESTORE, IMPROVE OR SUSTAIN FOOD PRODUCTION OF TROPICAL AND SUBTROPICAL SOILS AND LIKELIHOOD OF GENERAL USE

There is a high potential for some native plants to positively affect food production of tropical and subtropical soils. One of the most promising strategies is the increased use of leguminous plants for multiple purposes of food, livestock fodder, and wood while concurrently improving soil fertility (Sherman 1977). As fertilizer costs continue to escalate in response to energy expenses, fertilizers will become economically prohibitive in many developing countries. Incorporation in the cropping system of a legume rotation, green manure, or animal manures derived from legume feeds may be the best remaining option to replace fertilizers (NAS 1980) and maintain agricultural productivity.

Non-legume native species have various potentials for positive benefits to food production. Many species are already known locally but have not received sufficient notice to be introduced or developed for use in other (similar) regions. To achieve such recognition may well require:

1. A shortage in food from existing crop plants.
2. Development of new lands that are better suited for new crops.
3. Adaptation of new crops to economically compete with conventional crops.

In any of the three cases above, some form of research and development intervention would be needed to raise the perspective and incentives of local people. The likelihood of general use depends on the individual species.

For example, the general qualities of seeds from the jojoba plant have been known for many years (Hogan 1980) but only until recently has any development effort appeared substantial enough to bring the plant into widespread use. The shortage and cost of sperm whale oil is a big factor motivating jojoba development in more than five countries. Some applications will be less spectacular but no less needed.

Plantings of the legume tree, Acacia albida in Mali (Webber and Dulansey 1978) hold considerable promise for improving subsistence agriculture production there, but the effort is but a "drop in the bucket" compared with the needs in that area of West Africa.

In view of the diversity of native plants available for development and the number of countries with suitable environments that presently produce below their potential, judicious support of native plant development programs seems justified. The likelihood of spontaneous development or widespread use of native plant resources seems unlikely without external encouragement. Otherwise, many useful native plant species and ecotypes stand in jeopardy of becoming lost as deforestation, land depletion, industrial development, or other activities eliminates the natural plant communities.

VII. WHAT ARE SOME RESEARCH DEVELOPMENT AND IMPLEMENTATION SCENARIOS IN WHICH NATIVE PLANTS COULD REALIZE THEIR POTENTIAL OF ENHANCING TOPICAL SOIL PRODUCTIVITY?

A. The program of planting seedlings of Acacia albida legume trees in Mali (Webber and Dulansey 1978) serves as a model for development of the potential of a native plant. In this program, CARE set up production nurseries to produce tree seedlings in soil-filled plastic tubes. Acacia albida is an indigenous legume tree native to sub-Saharan Africa. The tree has the unique feature of being leafless during the rainy season. This allows for cultivation of other crops directly under the tree. The leaves and pods provide fodder and green manure and the roots fix nitrogen. It is an ideal candidate for selection, improvement, and application to various semi-arid agroforestry systems.

In Mali teams of local farmers were employed to plant the seedlings in preselected agricultural/pasture areas of good soils. Planters were paid on a per tree basis for planting and protection. Subsequently, these local people were encouraged (in their work training orientation) to take a special interest in the seedlings to see that they received appropriate management/protection to ensure their survival from grazing animals. Benefits expected are increases in soil productivity and livestock feed.

B. A scenario for planting a live fence of a legume shrub to enhance soil fertility by N-fixation and livestock manure might be as follows. Seedlings could be propagated at a government research station after selection from depleted stands of palatable shrubs. These plants would then be distributed to village elders for allocation to heads of families for planting around the fields and houses in the immediate vicinity of the village to enhance

kitchen garden production and feed small livestock through the dry season. Excess fodder could be utilized on the farm plots as green manure.

C. A scenario for development of a high value native tree fruit crop would logically start with a program of selecting the most desirable biotypes for their fruit quality, tree size and form, and maturity pattern. Because of the long term requirements for genetic improvements that would combine the best qualities in various selections a dual development program would be undertaken. The first would be to vegetatively propagate (by rooted cuttings of a few plants or by tissue culture for thousands) the best selection(s). Propagules would normally be grown in containers until ready for field transplanting. Sufficient acreage would be planted to provide experience in intensive management and production for a local, regional (city) or international cash market. As experience is gained with product acceptance, the criteria for the genetic breeding program would be modified. By the time suitable genetic materials would be available, the market requirements would be sufficiently known to guide large scale development plantings and improved cultural practices, possibly involving machinery.

Levels of capital and manpower needed could be determined or extrapolated on the basis of experience with a pilot program. Pilot demonstration programs are therefore a most plausible way to approach development of promising native plants.

VIII. WHAT CHANGES IN ATTITUDE ARE NEEDED?

One of the most critical attitudinal problems in developing new crops from native plants is one of institutional identification with sustainable and diversified plant development. Traditional crops, mostly of temperate origin, have received the majority of institutional attention whether they be government, research, or commercial organizations. A new and more innovative approach to plant development is required when referring to native or adapted plant development. The various groups which directly affect these development efforts include the following:

Cultivators

All efforts should include the local farmers who would be closest to a given project. The objective would be to seek sufficient involvement in planning, planting, and management to bring local people to thinking that the project is theirs -- not something imposed from outside by government. The active efforts of an individual farmer in the Dakotas to bring sunflower into widespread cultivation reflects the importance of this element in the introduction of "new" crops.

Legislators

Politicians should be encouraged to provide a favorable and stable policy for innovative product development, to be optimistic but not raise unrealistic goals and expectations, and finally to be willing to support financial needs of the pilot project until full scale development perspectives can be determined. The efforts of the Guayule Commission is an example of this coordinated effort at policy and implementation.

Financiers

Banks/bankers need to be educated about the realities and potentials for development of a new crop. Available capital for second phase development would be needed if the private sector is to follow the pilot development. Orientation and involvement would be needed to assure support when it is needed. Tax incentives and loan guarantees may be useful methods for financial institutions to foster more rapid development and diversification of new crops.

International

Policy makers within the international donor community need to clearly understand the risks as well as the opportunities for a successful program. Stepwise project implementation is a desirable approach in which needed research as well as development experience is gained as the program develops. This approach could be directly implemented by requiring agricultural, forestry, and horticultural development projects to direct a certain percentage of the program to research and development on native species or varieties which could improve the overall program output. Involving host country politicians, research people, and local farmers should be a cardinal operating policy.

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IX. WHAT BIOPHYSICAL, CULTURAL AND SOCIOECONOMIC CONDITIONS WOULD BE CONDUCIVE TO PROJECT IMPLEMENTATION

Obviously, the best place for a native plant development project would seem to be where it is needed most. However, there are qualifications to this simplistic statement.

A. Biophysical Conditions

A high degree of adaptation of a native species to the climate, soils, topography, and animal uses, including resistance to parasites, is essential. From an ecological standpoint, the approach should be to seek areas that are ecologically equivalent to the original habitat of the native plant species. This is usually done by testing of plantings in various locations of similar climate. However, the time period during which the plantings are under observation may not be sufficient to experience the range of environmental extremes that is common to the area. Detailed experiments under laboratory greenhouse and controlled environment chambers may help to document the full range of adaptation possessed by the species being tested. A development philosophy should be to adapt the crop to the land not the land to the crop.

B. Cultural Conditions

For a new crop or agricultural product to be successfully produced, it must not be contrary to the cultural traditions of the people to grow, consume, or use. For example, an improved high protein maize (corn) variety was considered for development in India to meet food shortages. However, the yellow color of the seed coat was objectional because it resembled a grain product fed to animals (R. Cummings 1972). A social custom study would be advisable to determine if any taboos, customs, or adverse values exist regarding the potential crop and its required production practices.

C. Socioeconomic Conditions

Critical to the development of any new crop from a native plant is whether the product is socially acceptable and is within the ability of local people to handle the costs of development. There is less chance of gaining social acceptance of a project if the payoff period is too far into the future. An early return on the investment may be needed to maintain interest and commitment to a project. Further, the amount of capital required for development may exceed the capacity of individuals or banks to handle. Thus, smaller increments of development and interim returns to investment may be desirable and/or necessary. An example with animals should illustrate this point. A small farmer could finance the purchase of several animals of an improved breed of goat or a pen of rabbits but may not be able to finance a cow or bull, not to mention the greater risk in having a high amount of capital tied up in one animal.

The above conditions are most likely to exist in the less developed tropical countries, in the more rural and remote regions of such a country, and with people of tribal or nomadic social organization. The less educated people would likely be more difficult to reach and to gain their acceptance of a development program.

Communication tools such as radio, newspapers, and films should be developed to help both in the search for useful plants as well as to disseminate information on new uses and opportunities for economic diversification.

X. WHAT ARE THE MAJOR CONSTRAINTS ON DEVELOPMENT AND IMPLEMENTATION OF NATIVE PLANT USE?

Development of a native plant species to commercial or economically significant levels would not be easily accomplished based on current observations of jojoba and guayule. Many constraints must be overcome to satisfactorily bring a native plant into development.

A. Scientific Constraints

A major scientific problem in plant development is lack of tehnical information. A sufficient amount of general information is needed to identify plants of high potential. Additional species information can help determine feasibility for development and the suitability of products or uses to meet identified needs. Progress toward development may well depend on technical data regarding planting, management, harvest, processing, and conservation. Pilot demonstration programs designed to answer technical problems and work out procedures are essential to guide development.

Particularly needed are scientific studies on ways to establish plants and obtain optimum productivity under arid, semi-arid, and tropical conditions. Problems dealing with microorganisms and plant growth, drought resistance, physiology of stress, and application of engineering to improve adaptation present challenges for scientific research on indigenous plants.

B. Environmental Constraints

Existing land uses may pose one of the largest constraints to development. Such commitments of land must be seen in relation to the long term value and need for the land as it currently exists. Where decreasing soil fertility

and vegetation degradation are occurring, a shift to a leguminous native plant could bring multiple benefits. For native plants with industrial potential (i.e., guayule) processing may influence air and water quality. Whether utilization costs can be internalized in the value of the product or plant use must be determined. In most instances, it must be stated that the environmental benefits of developing native or adapted plants will most likely outweigh the negative impacts. The potential to reduce existing environmental degradation and more sustained land utilization must be considered a positive consequence.

C. Culture Constraints

Impacts of development may cause social change, community growth, and increased need for services. Such changes need to be addressed but at this time little information is available. In general, the cultural impacts from developing new crops or practices from native plants should be positive or neutral. In the context of tropical countries, the perceptions of regional, community, tribal, or family groups must be considered. Resistance to change may be manifested by refusal to cooperate or allow project development. Involvement of local leaders of status and decision makers is a necessity.

D. Economic Constraints

The major economic constraint to development is probably the lack of seed money, venture capital, or government support to conduct pilot scale programs. From the pilot program, cost data can be extrapolated for planting, production, transportation, and marketing. From these preliminary data, decisions can be made toward major financing and long or short-term commitment

of funds, either by the private sector or through government grants and loans. Because of the generally speculative nature of developing high potential native plants to meet needs that are not clear, private sector funding may have to be government subsidized.

E. Political Constraints

A major political constraint is the instability and short longevity of many political leaders in less developed countries. Although a new crop development program may be highly favored by the political leadership, the prospect of change must be worked into the project alternatives. Inasmuch as agricultural development is highly important and not as politically sensitive as other sectors of a country, it should be possible to work within political constraints as long as the project does not appear to run counter to current political/social philosophy. For example, pilot plantings of palatable fodder shrubs in Syrian rangelands by FAO and the Syrian Ministry of Agriculture were described as an extension of socialistic-oriented cooperative marketing and fattening units to increase meat production and increase the stability of the livestock industry (DRAZ 1978). In reality, the system had many free enterprise profit making opportunities to increase the incentive of individuals to participate in the scheme. Yet, political leaders touted the success of this cooperative project and declared it to be in harmony with the socialistic philosophy mandated by the government. New crops must not appear to compete with existing production systems but should complement them. Constituents must be convinced that the proposed developments will provide benefits equitably. Additionally, adapted crops which could represent a higher cash return than traditional crops, should receive special attention from the international donor community to sponsor their development and commercialization for the economic benefit of lesser developed countries.

XI. HOW WOULD IMPLEMENTATION OF A NATIVE PLANT TECHNOLOGY AFFECT THE NEED FOR INPUTS OF CAPITAL?

Because of the varied types of native plants, no specific capital requirements can be determined for all native plants. There is no doubt but that a native plant development program would require significant inputs of technology and capital. However, those plants that produce a crop would require greater inputs than those used for reforestation, improving soil fertility or increasing rangeland forage production (Table 1).

Careful analysis of the infrastructure of a region or county may give an indication of available processing capacity. For example, vegetable oil extraction facilities are available in the ground nut basin of Senegal and these might be available in the peanut processing off season to extract hydrocarbon latex from giant milkweed plants presently growing in waste places and margins of fields. A small pilot program with these native plants could provide some of the data necessary to determine the feasibility of proceeding to larger phases of development. In a like manner any proposed new crop should be analyzed for capital inputs and available facilities for production processing and transport.

XII. WHAT WOULD BE THE IMPACT OF WIDE SCALE IMPLEMENTATION OF NATIVE PLANT USE ON SOCIO ECONOMIC STRUCTURE?

It would be false to assume that only a large commercial-type farm or a family-sized farm would be suitable for native plant development. Much depends on the nature of the plant species and the magnitude of development necessary. From Table 1 it can be seen that some crops such as Cocoyam and Buffalo gourd could easily be grown on small plots and collected for commercial markets. In contrast, industrial feedstocks, biomass, and high volume crops such as guayule, ramie, lucaena and guar would better be grown in large fields and be harvested and treated mechanically.

Small field operations would cause little change on socioeconomics structure except to provide an additional income stream to communities. Large operations may disrupt communities by increasing their population or requiring the establishment of new communities. An excellent example here in the U.S. is the 110,000 acre Navajo Irrigation project near Farmington, New Mexico. The large commercial farm style of operation has left little opportunity for community development of a traditional native culture, nor has it provided an opportunity for family farm or cooperative group farm development. The project has addressed only the large scale production-economic aspects of development. Socioeconomic problems remain unsolved as illustrated by the attempts being made to resettle Navajo workers in a modern subdivision quite foreign to existing patterns of community settlement.

In summary, the various options available to develop native plants of high potential could enhance existing social and economic patterns or could disrupt them with large developments depending on the suitability of the land, the adaptability of native plants to given locations and the institutional insensitivity that might prevail in their development. Properly designed pilot projects could help to provide guidelines for larger scale development and experience in problem solving necessary for the commercial utilization of high-potential native species.

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PAPER NO. 9. MYCORRHIZA AGRICULTURE TECHNOLOGIES

(By Dr. John A. Menge, Associate Professor, Department of Plant Pathology, University of California—Riverside)

Introduction - What are mycorrhizal fungi?

Mycorrhizal fungi are beneficial fungi which are associated with plant roots via a symbiotic association whereby both the host plant and the fungus benefit. Mycorrhizae are the structures which are formed by the symbiotic association between plant roots and mycorrhizal fungi. Mycorrhizae contain both plant roots and fungal tissues. In nature, mycorrhizae are far more common than non-mycorrhizal roots (Frank, 1885; Schlicht, 1889; Stahl, 1900). Nearly all plant species are associated with mycorrhizal symbionts. Because of their importance to plants and their widespread distribution, mycorrhizae must be considered in all aspects of plant ecology, crop science, and agriculture.

Mycorrhizal fungi are frequently divided into four very different types (Mosse, 1978): ectomycorrhiza, vesicular-arbuscular mycorrhiza (abbreviated as VA mycorrhiza), ericaceous mycorrhiza, and orchidaceous mycorrhiza. As indicated by their names, ericaceous mycorrhiza and orchidaceous mycorrhiza are associated with ericaceous plants (blueberries, cranberries, azaleas, etc.) and orchidaceous plants (orchids), respectively. Because of the relatively low economic impact of these plants and the small amount of available data on these types of mycorrhiza, they will not be discussed further.

Ectomycorrhizae - Ectomycorrhizae are associated primarily with trees such as pine, hemlock, spruce, fir, oak, birch, beech, eucalyptus, willow and poplar. Ectomycorrhizae are formed by hundreds of different fungal species belonging to the Basidiomycetes (mushrooms and puffballs) and Ascomycetes (cup fungi and truffles). These fungal symbionts are stimulated by root exudates and grow over the surface of host feeder roots to form a thick fungal layer known as a fungal mantle (Fig. 1).

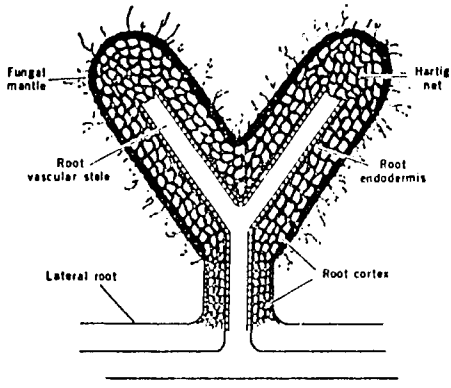

Fig. 1. Diagram of a typical ectomycorrhiza including the Hartig net, fungal mantle and external hyphae (courtesy D. H. Marx).

Hyphae of ectomycorrhizal fungi penetrate between the cells of the host root, develop around the root cortical cells, replace the host middle lamella, and form the Hartig net which is the distinguishing feature of ectomycorrhizae. In response to the fungal invasion, the host roots usually swell substantially and may branch dichtomously or in a coralloid manner (Fig. 1). The root cells are not injured, however, and function of the roots is enhanced, as we shall discuss later.

Vesicular-arbuscular (VA) mycorrhizae - VA mycorrhizal fungi have the widest host range and form by far the most common type of mycorrhizae. VA mycorrhizae occur on liverworts, mosses, ferns, some conifers, and most

broad-leaved plants. Gerdemann (1968) lists only fourteen families that are considered primarily non-mycorrhizal. The important crop families which are non-mycorrhizal are Cruciferae (cabbage, broccoli, mustard, etc.), Chenopodiaceae (spinach, beet, etc.), Cyperaceae (sedges) and Caryophyllaceae (carnation, pinks, etc.). Wetland rice is also usually non-mycorrhizal. Nearly all other important agronomic crops including wheat, potatoes, beans, corn, alfalfa, grapes, date palms, sugar cane, cassava and dryland rice are associated with VA mycorrhizal fungi. Although many trees have ectomycorrhizae, most have VA mycorrhizae. Sixty-three of sixty-six tropical trees in Nigeria (Redhead, 1968) are associated with VA mycorrhizae. So are most important tree crops such as cocoa, coffee, rubber, and citrus. Some trees such as juniper, apple, and poplar can have either ectomycorrhizae, or VA mycorrhizae.

The fungi which form VA mycorrhizae, about 80 species, are in a few genera in the Zygomycetes class of fungi. They are so common in soils that literally any field soil sample from arctic to tropical regions will contain these fungi (Mosse, 1978).

The hyphae of VA mycorrhizal fungi penetrate directly into the root cortical cells of host plants. Inside of the host plant cells VA mycorrhizal fungi form minute coralloid structures known as arbuscules (Fig. 2). Arbuscules are thought to be the site of nutrient transfer between the symbiotic partners. The host plants obtain fertilizer nutrients from the mycorrhizal fungus while the fungus obtains sugars or other food materials from the plant. Although the arbuscule of VA mycorrhizal fungi occurs inside root cells, they remain covered by the host cell membrane and so are not in direct contact with the host cytoplasm. Vesicles are balloon-like mycorrhizal fungus structures which usually form inside the host root (Fig. 2). These structures

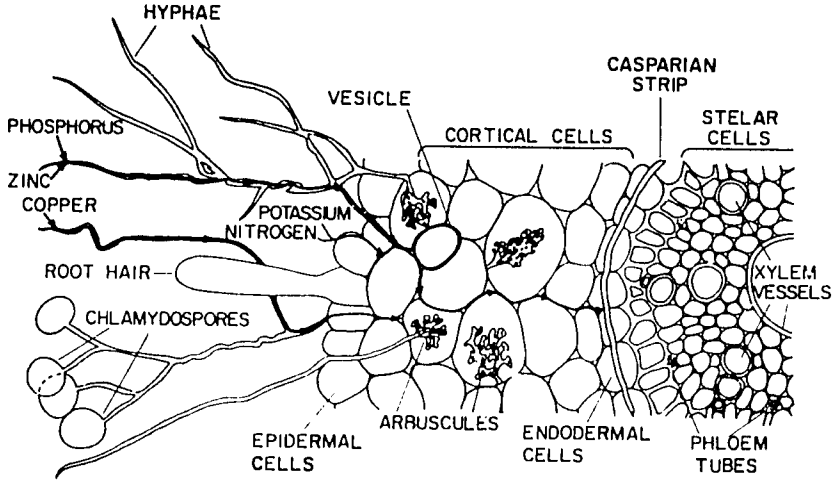

Fig. 2. Diagram of a typical vesicular-arbuscular mycorrhiza including vesicles, arbuscules, spores and external hyphae.

are thought to be storage organs which the fungus produces to store nutrient materials inside of the plant host. VA fungi also produce abundant spores either inside or outside of host roots. These spores are the survival structures of VA mycorrhizal fungi. They are long-lived and extremely resistant to most unfavorable soil conditions and these spores are responsible for the widespread occurrence of VA mycorrhizal fungi in nearly all soils throughout the world. Despite the intracellular penetration of roots by VA mycorrhizal fungi, they do not affect the outward appearance of roots except by inducing a yellow coloration in the roots of some hosts (Becker, 1976). Detection of VA

mycorrhizal roots is best done by staining roots (Phillips and Hayman, 1970) and examining them microscopically for the presence of hyphae, arbuscules, or vesicles.

Arbuscules of VA mycorrhizal fungi are short-lived and generally survive for less than two weeks before they are digested by the host plant (Mosse, 1973a, Scannerini et al., 1975). Roots of plants normally release large quantities of chemical "exudates" into the root zone (Bowen, 1969). Since the arbuscules are covered by the host membrane it is thought that the symbiotic association is regulated by the host plant via the cell membrane. The more nutrient materials released by the plant membrane to the arbuscule of the mycorrhizal fungus, the more abundant the mycorrhizal colonization (Ratnayake, et al., 1978). By restricting nutrients passing through the plant membrane the plant is capable of restricting mycorrhizal infection in roots. A similar mechanism can be postulated for the regulation of ectomycorrhizae by plant roots.

How do mycorrhizal fungi improve growth of agricultural plants?

The VA Mycorrhizal symbiosis results in marked increased in crop growth and development (Fig. 3). For example, inoculation of fumigated sand or soil with VA mycorrhizal fungi will increase the growth of citrus by as much as 1600% (Fig. 3); (Kleinschmidt and Gerdemann, 1972), grapes by 4900% (Possingham and Obblnk, 1971), soybeans by 122% (Ross, 1971), pine by 323% (Wilde, 1966) and peaches by 80% (LaRue et al., 1975). Growth responses due to VA mycorrhizal fungi have been observed in cotton (Rich and Bird, 1974) tomatoes (Daft and Nicolson, 1966) corn (Gerdemann, 1964), wheat (Khan, 1975), clover (Powell,

1977) barley (Benians and Barber, 1972), potatoes (Black and Tinker, 1977) and ornamental plants (Wallace et al., 1973) and in many other crops.

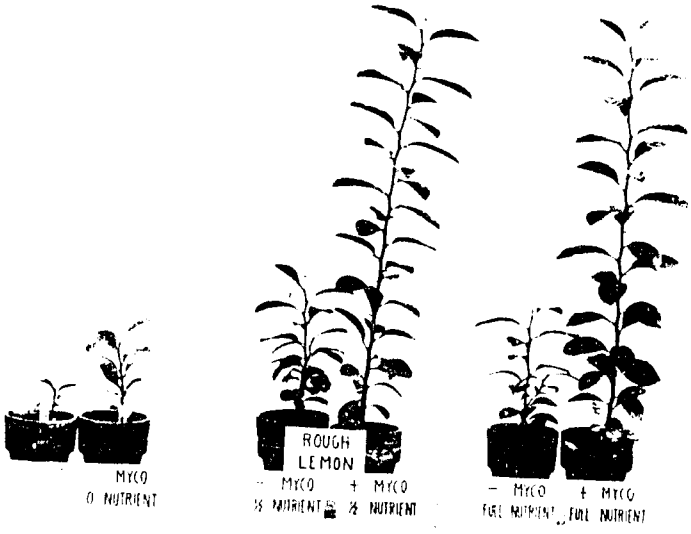

Fig. 3. The growth of citrus (Rough lemon) seedlings with (+Myco) and without (-Myco) VA mycorrhizal fungi and at different nutrient levels.

VA mycorrhizal fungi consistently stimulate plant absorption of phosphorus (Ross and Harper, 1970; Possingham and Obbink, 1961; Gerdemann, 1968; Mosse, 1973), and zinc (LaRue et al., 1975; Mosse, 1973a), calcium (Ross, 1970, 1971), copper (Ross, 1970; Ross and Harper, 1970; Mosse, 1957; Kleinschmidt and Gerdemann, 1972), iron (Mosse, 1957), magnesium (Holevas, 1966; Mosse, 1973a), and manganese (Ross, 1970; Mosse, 1973a). Increased uptake of phosphorus is perhaps the most important benefit provided by mycorrhizal fungi.

Most mycorrhizal researchers agree that the increase in effective nutrient absorbing surface provided by mycorrhizal fungi is primarily responsible for the increase in uptake of soil nutrients by mycorrhizal plants. Hyphae from mycorrhizal plant roots can extend up to 8 cm into the surrounding soil and transport nutrients this distance back to the roots (Rhodes and Gerdemann, 1975). Bieleski (1973) has calculated that VA mycorrhizal fungi may increase the effective absorbing surface of a host root by as much as ten times. Nutrient ions such as phosphorus, zinc, and copper do not diffuse readily through soil. Because of this poor diffusion, roots deplete these immobile soil nutrients from a zone immediately surrounding the root. Mycorrhizal hyphae extend into the soil past the zone of nutrient depletion and can increase the effectiveness of absorption of immobile elements by as much as sixty times (Bieleski, 1973). Sanders and Tinker (1973) have calculated that approximately 50 cm of mycorrhizal hyphae per cm root is necessary to account for the uptake of phosphorus by mycorrhizal plants. Experimental observations indicate that plant roots can have more than 80 cm of mycorrhizal hyphae, more than the amount necessary to account for the observed phosphorus uptake. Plant uptake of mobile soil nutrients such as nitrogen and potassium is rarely improved by mycorrhizal fungi. The reason is that normal soil diffusion is adequate to supply roots of plants with these nutrients whether the roots have a large absorbing surface or not. Generally plants which are most dependent upon mycorrhizal fungi for nutrient uptake are those which have roots with a low surface to volume ratio; that is plants with coarse, fleshy roots with few root hairs (Baylis, 1967).

Although there are numerous speculations that mycorrhizal fungi can solubilize and absorb nutrients which are unavailable to plant roots, there is little evidence to support this claim. Sanders and Tinker (1971) showed

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conclusively with ^{32}P-labelled phosphate that mycorrhizal fungi utilize the same phosphorus sources as do plant roots but they are able to absorb from a larger soil volume and so are responsible for the vast majority of phosphorus absorption by crop plants.

Mycorrhizal fungi can also enhance water transport in plants (Safir et al., 1971) and prevent water stress under some conditions (Menge et al., 1978a). These results are probably not due to a direct effect of mycorrhizal fungi, but instead to the improved nutrient status provided by the mycorrhizal fungi. Mycorrhizal fungi can endure much drier soil conditions than can most plants and it is thought that plants may benefit substantially from mycorrhizal infection under drought or water-stressed conditions (Mosse, 1973, Ruehle and Marx, 1979). Ectomycorrhizae, in particular, with their mantle which surrounds roots, may provide a physical barrier against root dessication.

Considerable evidence exists which suggests that mycorrhizal plants may be better equipped to withstand toxic effects of salt. Calcium, magnesium, and sodium concentrations in non-mycorrhizal citrus were 41, 36, and 150% greater respectively than in mycorrhizal citrus (Menge et al., 1978b). Hirrel and Gerdemann (1978) found that a mycorrhizal fungus increased tolerance of bell peppers to salinity. Trappe et al. (1973) indicated that VA mycorrhizal fungi provided resistance to the toxic effects of arsenic. Mycorrhizae may also provide tolerance to excessive soil manganese and aluminum (Hayman, 1980).

It has been conclusively shown that mycorrhizal fungi act to increase nodulation by symbiotic nitrogen-fixing bacteria such as Rhizobium (Mosse, 1976, Mosse et al., 1976). Mycorrhizal fungi may stimulate other beneficial rhizosphere organisms as well (Bagyaraj and Menge, 1978).

Ectomycorrhizal fungi have been reported to provide resistance to plant disease in many plants (Marx, 1973). Although mycorrhizae never confer complete immunity, they often appear to reduce the severity of disease or symptom expression. Marx (1973) believes that resistance of ectomycorrhizae to disease may result from: 1) mechanical protection by the mantle, 2) better plant nutrition, 3) production of antibiotics by the mycorrhizal fungus, 4) competition for infection sites, 5) formation of phytoalexins, and 6) alteration of root exudates. Evidence is accumulating that VA mycorrhizal fungi exert similar effects upon plant pathogens. Schenck et al., (1975) has reported mycorrhizal resistance to root-knot nemotodes. Schönbeck (1978) has examined a variety of foliar and root pathogens on mycorrhizal plants with the conclusion that root pathogens (Thielaviopsis, Fusarium, nematodes, etc.) are usually inhibited by mycorrhizal fungi while foliar pathogens (viruses, rusts, etc.) are often more severe on mycorrhizal plants. Davis et al. (1978, 1979) and Davis and Menge (1980) concluded that the VA mycorrhizal fungus Glomus fasciculatus produced little resistance to Phytophthora root rot of citrus and indeed increased Phytophthora root rot of avocado and Verticilllium wilt of cotton. It is believed that VA mycorrhizal effects on disease are a result of improved phosphorus nutrition resulting from the increased absorbing surface conferred by mycorrhizal hyphae. This effect is magnified when the normal absorbing capacity of roots is reduced because roots are partially decayed.

There have been reports of mycorrhizal fungi actually reducing growth of some plants (Cooper, 1975; Johnson, 1976; Crush, 1976). These parasitic effects are rare and the reason for them is not understood, but they apparently occur in grasses, cereals, and tomatoes at or above optimum soil nutrient levels when the plant is actively regulating mycorrhizal invasion.

Mycorrhizae as substitutes for fertilizers

In the past 40 years the use of agricultural fertilizers has more than doubled. Crop yields have risen dramatically as a result. However, because of shortages in some fertilizer supplies and the current cost of energy which is used to produce some fertilizers, the cost of fertilizers both in terms of dollars and energy has risen tremendously. Agricultural economists indicate that as energy costs rise the most responsive agricultural input is the fertilizer input. That is, as energy costs rise, fertilizer use will decrease. This response is a dangerous one since chemical fertilizers are said to account for 1/3 - 1/2 of the current US agricultural output (Lockeretz, 1977).

Estimates indicate that agriculture uses between 2.6 and 4.4% of all US energy use. Fertilizers and their application comprise 30-45% of the total agricultural energy use. Nitrogen is the main energy user with phosphorus and potassium accounting for only 16% of the fertilizer energy use (Lockeretz, 1977).

Because mycorrhizal fungi increase the efficiency of fertilizer use, they can be thought of as "biotic fertilizers" and can indeed be substituted for substantial amounts of some fertilizers (Menge et al., 1977, 1978b). Mosse (1973a) maintains that 75% of all phosphorus applied to crops is not used during the first year and reverts to forms unavailable to plants. In soils high in pH or high in aluminum or calcium carbonate, nearly 100% of the phosphorus fertilizer can be immobolized to non-useable forms via chemical soil reactions. Tropical oxisols and ultisols are notorious for their capacity to immobolize phosphorus. Because mycorrhizal plants are better suited to exploiting soil with low amounts of available phosphorus, zinc, and copper, the

addition of large amounts of these fertilizers each year may be unnecessary. Menge et al. (1978b) compared mycorrhizal citrus seedlings with non-mycorrhizal seedlings which received various amounts of phosphorus fertilizer (Fig. 4).

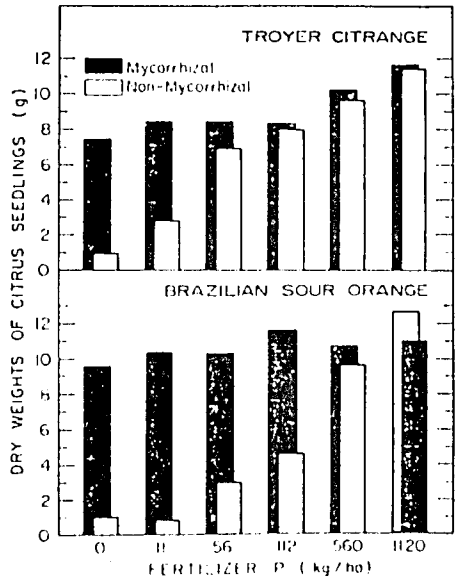

Fig. 4. Dry weights of mycorrhizal and non-mycorrhizal Brazilian sour orange and Troyer citrange seedlings fertilized with different amounts of phosphorus.

Mycorrhizal Troyer citrange which received no fertilizer phosphorus were equal in size to non-mycorrhizal Troyer citrange which received 112 kg phosphorus/ha (Fig. 4). Similarly, mycorrhizal Brazilian sour orange which received no fertilizer phosphorus were equal in size to non-mycorrhizal plants which received 560 kg phosphorus/ha. Concentrations of phosphorus in non-mycorrhizal Brazilian sour orange leaf tissue were never above 0.05% (less than 0.09%

phosphorus indicates phosphorus deficiency) even when seedlings were fertilized with 1120 kg phosphorus/ha. Concentrations of phosphorus in leaves of mycorrhizal Brazilian sour orange were above deficiency levels in all seedlings fertilized with more than 56 kg phosphorus/ha. Concentration of phosphorus in leaves of mycorrhizal Troyer citrange were never in the deficiency range even when plants were not fertilized with phosphorus. Non-mycorrhizal Troyer citrange, on the other hand, required over 56 kg phosphorus/ha before adequate phosphorus concentrations were restored to the leaves. At current retail costs for triple super-phosphate, it appears that use of mycorrhizal fungi could result in savings of $111-558/ha ($45-226/acre) in the cost of phosphorus fertilization of citrus in fumigated nursery soil. In one California citrus nursery, it was found that inoculation with mycorrhizal fungi could reduce phosphorus fertilization by 2/3 and thereby save $652/ha ($264/acre). Similar savings in phosphorus fertilizers have been shown by Kormanik et al. (1977) in fumigated forest nurseries in the production of sweetgum.

Timmer and Leyden (1980) have shown that mycorrhizal fungi can be substituted for 4.3 ppm copper fertilizer in the culture of citrus seedlings in Texas. Menge et al. (unpublished data) has shown that mycorrhizal fungi can be substituted for 64 ppm zinc fertilizer in the greenhouse culture of citrus and even nitrogen fertilization can be reduced by as much as 300% in the presence of mycorrhizae. This nitrogen savings effect is probably due to an increased efficiency of nitrogen utilization resulting from improved phosphorus nutrition of the plant.

Since mycorrhizal fungi are present in most soils, their unique fertilizer-absorbing abilities are normally already being utilized by most crop plants. If mycorrhizal fungi are removed or damaged in any way, then the amount of fertilizer required by a crop increases enormously. This is

demonstrated effectively by Menge et al. (1978b), who reported that citrus grown in fumigated soil or in hydroponic solutions often require massive phosphorus applications for adequate growth compared to field grown citrus. Chapman and Rayner (1951) reported that citrus in the field can absorb phosphorus from phosphorus deficient soils more efficiently than either corn or tomatoes, and citrus orchards do not normally require phosphorus fertilization. Differences in phosphorus absorption by citrus grown in fumigated soil and citrus grown in non-fumigated soils can be reconciled if mycorrhizal fungi, which are present in nearly all citrus orchards (Menge et al., 1975) are the equivavent of 100-500 lbs phosphorus/acre.

When and if the cost of fertilizer use becomes exorbitant, we must devise the most efficient fertilizer supply systems possible--to minimize costs while conserving energy and non-renewable resources. I submit that mycorrhizal fungi could be one alternative which might increase crop yields and yet reduce fertilizer costs and energy demands.

Current commercial utilization of mycorrhizal fungi

Disturbed sites - Although nearly all plants require mycorrhizal fungi for maximum growth, the widespread occurrence of these fungi in nearly all soils limits the immediate needs for inoculation with mycorrhizal fungi. In my opinion, mycorrhizal fungi are currently commercially utilizable in only three major agricultural areas: 1) disturbed sites, 2) fumigated soils, 3) greenhouses. Mycorrhizal fungi have been conclusively shown to improve revegetation of coal spoils, strip mines, waste areas, road sites and other disturbed areas (Daft and Nicolson, 1974; Daft et al., 1975; Daft and Hacskaylo, 1976; Marx and Bryan, 1975; Reeves et al., 1979). In these stressed

sites, mycorrhizal fungi are usually lacking and adding mycorrhizal fungi provides a nutritional advantage to associated plants in addition to providing possible resistance to low pH, heavy metal toxicants, and high temperature.

Fumigated or chemically treated sites - Fumigation with biocides or pesticides such as methyl bromide (Menge et al., 1978c), chloropicrin (O'Bannon and Nemec, 1978), dazomet (McEwen et al., 1973), 1,3-D (O'Bannon, and Nemec, 1978), vapam (Nesheim and Linn, 1969) and vorlex (Nesheim and Linn, 1969) may destroy or inhibit root infection by mycorrhizal fungi. Application of many soil fungicides such as arasan (Nesheim and Linn, 1969), banzot (Stewart and Pfleger, 1977), benomyl (Sutton and Sheppard, 1976), botran (Nesheim and Linn, 1969), carbofuran (Backman and Clark, 1977), chloramformethane (Jalali and Domsch, 1975), dichlofluanid (Jalali and Domsch, 1975), ethirimol (Jalali and Domsch, 1975), lanstan (Nesheim and Linn, 1969), mylone (Nesheim and Linn, 1969), PCNB (Sutton and Sheppard, 1976), sodium azide (Backman and Clark, 1977), thiabendazole (Jalali and Domsch, 1975), thiram (Surron and Sheppard, 1976), triademifon (Jalali and Domsch, 1975), tridemorph (Jalali and Domsch, 1975), and vitavax (Sutton and Sheppard, 1976) have also been reported to be harmful to mycorrhizal development. Flooding, planting non-mycorrhizal crops, or removing topsoil, may also reduce the population of mycorrhizal fungi to a level requiring reinoculation (Black and Tinker, 1977; Redhead, 1971).

Fumigation with the biocide methyl bromide to remove soil-borne pests is required by regulation for the production of many nursery crops. It is also regularly used in many field agricultural situations. This chemical is extremely toxic to mycorrhizal fungi and most field fumigations are sufficient to destroy the native mycorrhizal inoculum (Menge et al., 1978c). Stunting of crops following fumigation with methyl bromide is common and is due to the destruction of mycorrhizal fungi. Although a relatively small amount of land

is treated with this chemical, less than 100,000 acres annually in the U.S., stunting following fumigation with methyl bromide has been reported in the U.S., Africa, Spain, Peru, Venezuela, and many other countries (Menge et al., 1975). Crops which are routinely grown in methyl bromide fumigated soils include strawberries, tomatoes, tobacco, nursery crops, tree crop replants, and some vegetable crops. For many of these crops the addition of mycorrhizal fungi following fumigation with methyl bromide is not only recommended but is imperative.

It appears that inoculating methyl bromide fumigated crops is economically possible. The cost for inoculating nursery-grown citrus with mycorrhizal fungi is about $288/acre, while the cost for phosphorus fertilizer alone is $336/acre. Fumigated tomatoes receive $51 worth of phosphorus per acre while the cost for mycorrhizal inoculation is less than $28/acre. Mycorrhizal fungi can provide additional benefits to the crop other than just improved phosphorus nutrition.

For nursery plants grown in methyl bromide fumigated soil, inoculation with mycorrhizal fungi should be imperative for the following reasons: 1) the plants grow better (prevents stunting following fumigation), 2) there is a decreased need for fertilization, specifically phosphorus, zinc and copper, resulting in decreased fertilizer cost and energy conservation, 3) there is decreased chance for water stress and therefore reduced transplant injury, 4) mycorrhizal plants survive better especially if transplanted to fumigated, poorly fertilized, or disturbed soil, 5) plants will be inoculated with effective mycorrhizal fungi rather than leaving mycorrhizal infection to chance, 6) mycorrhizal plants may be more resistant or tolerant to some plant diseases.

Greenhouses - Greenhouse culture utilizes growth media such as pine bark, vermiculite, perlite, builders sand, and peat moss which are devoid of mycorrhizal fungi. In addition, most greenhouse operators steam, pasteurize, or chemically treat their mixes to eradicate harmful pathogens. Nurserymen have compensated for the absence of beneficial mycorrhizal fungi by applying luxury amounts of fertilizer and water in order to achieve desired growth. Inoculation of container grown plants to reduce irrigation, fertilizer, and pesticide applications and cost can be done as demonstrated by Chatfield et al. (1979), Linderman (1978) and Crews et al. (1978).

Commercial production and inoculation with mycorrhizal fungi

Many ectomycorrhizal fungi can be readily cultured on artificial media and inoculum can be grown under standard laboratory conditions (Marx and Bryan, 1975). Experimentally, sterilized vermiculate and peat moss is frequently saturated with a liquid nutrient medium (Marx and Bryan, 1975) and is infested with a desirable ectomycorrhizal fungus. Ectomycorrhizal fungi generally grow quite slowly and may take several months to completely colonize the vermiculite-peat moss mixture. This material can be used on a small scale to inoculate nurseries and greenhouses with mycorrhizal fungi. Recently Abbott Laboratories, North Chicago, Illinois has rapidly produced massive amounts of inoculum of the ectomycorrhizal fungus Pisolithus tinctorius (Ruehele and Marx, 1979). Abbott Laboratories produced the peat moss-vermiculite-nutrient solution inoculum under large-scale commercial conditions using commercial fermenters. The inoculum compared well to experimental inoculum prepared by D. H. Marx (personal communication). Under the direction of D. H. Marx the U. S. Forestry Service has undertaken a massive testing

program using the commercially produced inoculum. The inoculum will be tested in nearly one hundred-tree nursery test sites throughout the U. S. Results will be available within four years which will indicate the commercial feasibility of producing and utilizing mycorrhizal inoculum in fumigated tree nurseries.

Ectomycorrhizal inoculum can best be applied in the nursery. Once the trees become infected, the benefits can be transferred to wherever the trees are grown. In the nursery, mycorrhizal inoculum can be distributed by hand and rototilled into the soil before planting seed. Special machinery has already been built and is in currently being used to incorporate ectomycorrhizal inoculum (D. H. Marx, personal communication).

Commercial production of mycorrhizal inoculum for use in sterilized or fumigated soil is presently being attempted at several locations in the United States. Currently, the only way to produce suitable quantities of a mycorrhizal inoculum is on roots of susceptible host plants. The possibility of pathogenic organisms contaminating mycorrhizal inoculum is an extremely serious problem when growing VA mycorrhizal inoculum in semi-sterile cultures in the greenhouse. For this reason, many scientists will consider mass production of VA mycorrhizal fungi only if it is done axenically. Realistically, however, not only must these obligate parasites be grown *in vitro*, but they must produce large quantities of spores in culture which will survive under soil conditions and infect plants in nature. Information gained from the culture of other formerly obligate parasites suggests that the possibility of realizing this goal in the near future is unlikely. Even if mycorrhizal fungi are cultured axenically, mycorrhizal inoculum for field use will probably be produced on the roots of suitable host plants.

It is proposed that with proper safeguards, mycorrhizal inoculum, free of plant pathogens, can be produced on plants in the greenhouse. Fig. 5 illustrates a proposed scheme for producing mycorrhizal inoculum (Menge et al., 1977). VA mycorrhizal fungi can be isolated by using bits of roots or soil

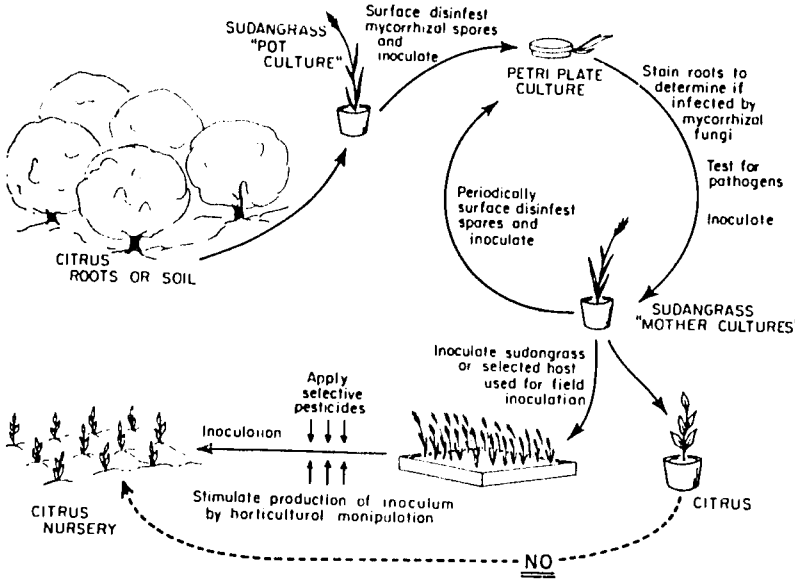

Fig. 5. Proposed scheme for the commercial production of vesicular-arbuscular mycorrhizal inoculum.

from the field to inoculate roots of "trap plants" growing in sterilized soil in the greenhouse. Sudangrass (Sorghum vulgare Pers.) is frequently used, but other plants such as tomato, soybean, corn, and safflower may be equally suitable. The soil used throughout is a low nutrient sand fertilized once per week with 1/2 the standard Hoagland's solution minus phosphorus. After production of VA mycorrhizal spores in the "pot cultures", the spores can be removed by wet sieving (Gerdemann and Nicolson, 1963), elutriation (Furlan and Fortin, 1975), or centrifugation (Ross and Harper, 1970). These spores must be surface disinfested with substances such as chloroamine T or sodium hypochlorite and streptomycin to assure that pathogens do not accompany the spores (Mosse and Phillips, 1971). These surface disinfested spores are used to inoculate the roots of plants which were germinated and grown under aseptic conditions in growth chambers. The containers illustrated are made from plastic petri plates (Fig. 5) and filled with the low nutrient sand. After 1-4 weeks when the mycorrhizal fungi have infected roots grown under aseptic conditions [root pieces can be removed and stained (Phillips and Hayman, 1970) to observe infection], root pieces are carefully removed and used to infect suitable host plants grown in sterilized soil in the greenhouse. Similar root pieces can be removed, examined, and plated on agar to observe pathogenic organisms. If no pathogens are observed, the greenhouse "pot culture" may be used as a "mother culture" to produce inoculum which will be used in the field. Inoculum should be produced on selected hosts which have no root diseases in common with the host plant for which the inoculum is intended. For instance, inoculum for citrus could be produced on sudangrass but never on citrus. In this way the wide host range of most VA mycorrhizal fungi can be utilized. As another precaution against propagating pathogens along with

mycorrhizal inoculum, the field inoculum should be drenched several times with pesticides chosen to eliminate pathogens known to infect the host for which the inoculum is intended. Mycorrhizal inoculum intended for citrus should be drenched with a nematicide to control the citrus nematode and fungicides to control Phytophthora and Rhizoctonia. Suggested pesticides are Ethazole and PCNB. PCNB reduces the population of mycorrhizal spores but the other pesticide can actually increase spore production (Menge et al., 1979). Several other pesticides can be used without harming mycorrhizal fungi (Sutton and Sheppard, 1976). Horticultural practices could also be used at this point to maximize spore production. Eliminating fertilization and slowly reducing the water may be effective in increasing spore production. When spores are ature, plant tops are removed and roots, soil, and spores can be ground up and partially dried (7-20% moisture content) and stored at 4°C until used. If concentrated spore suspensions are desired, spores can be concentrated by wet sieving (Jackson et al., 1972), elutriation (Furlan and Fortin, 1975), or centrifugation (Ross and Harper, 1970) before storage. VA mycorrhizal inoculum can be freeze-dried if desired (Jackson et al., 1972). Inoculum produced in this manner should be consistently infective and yet pathogen free.

Using the method described above, the estimated costs for producing mycorrhizal inoculum are shown in Table 1. These figures are derived from production costs of a foliage plant greenhouse and could be reduced considerably since mycorrhizal inoculum quality is of importance and not plant quality. A reasonably generous estimate of the cost of mycorrhizal production, including technical labor and quality control, together with a small margin of profit, indicates that consumers may pay about 0.18¢/500 spores of VA mycorrhizal fungi (Table 1). Such a cost could reasonably be borne by consumers

such as greenhouse operators or nurserymen (see section on Current commercial utilization of mycorrhizal fungi).

A similar method to that outlined above has recently been patented in England and is being perfected for large scale commercial use (Hayman, 1980). In this method plants are grown in peat blocks which are standing in a shallow nutrient-flow culture. After VA mycorrhizal spores are produced in the peat blocks they are ground up, roots and all, for inoculation. The finished product is not only excellent mycorrhizal inoculum but is light and easy to ship.

Table 1. Estimated cost of production of vesicular arbuscula mycorrhizal inoculum on sudangrass in 4" pots

Item		Cost/pot
1. Labor		
a. to prepare the soil mix		0.03
b. potting, inoculating, and seeding		0.05
c. moving pots to growing area		0.03
d. pruning		0.02
e. spraying (insecticides and fungicides)		0.03
f. watering		0.02
g. harvesting		0.01
h. grinding and packaging		0.03
i. quality control		0.02
j. maintenance of mother cultures		0.05
	Labor cost	0.29
2. Materials		
a. pots 4"		0.07
b. seed		0.002
c. fertilizer		0.02
d. shipping containers		0.025
e. insecticides and fungicides		0.03
	Materials	0.147
3. Overhead expenses		
a. heat		0.08
b. depreciation on greenhouse		0.008
c. depreciation on boilers		0.003
d. maintenance allowance		0.006
e. office supplies		0.002
f. management and office work		0.03
g. return on investment		0.01
h. loss due to undeveloped plants		0.001
i. taxes		0.06
j. laboratory, incubator, etc.		0.04
	Total for overhead	0.24

Total cost $0.677

Selling price $ .90
0.18¢/500 spores

Although many methods have been used to inoculate plants with VA mycorrhizal fungi in greenhouse trials, few inoculation methods are acceptable for large scale commercial inoculation. Jackson et al. (1972) studied several different methods to inoculate corn and found that layering inoculum under the seed was superior to seed inoculation or banding the inoculum. Hall (1979) developed a method for pelleting seed with a mycorrhizal infection and determined that mycorrhizal fungi could survive up to 28 days under these conditions. Menge et al. (1977) found that layering inoculum below the seed and banding inoculum were superior to seed inoculations. Crush and Pattison (1975) experimented with several means of inoculating seeds with VA mycorrhizal fungi, but again found that sowing seed above pelleted mycorrhizal inoculum was the most effective method for obtaining mycorrhizal infection. Hattingh and Gerdemann (1975) reported growth responses of citrus in a fumigated nursery after inoculating citrus seed with mycorrhizal inoculum. Gaunt (1977) inoculated onion and tomato seeds with a VA mycorrhizal fungus and reported that seed inoculated plants grew as well as plants that were inoculated by mixing VA mycorrhizal inoculum into the soil. Commercial applications of mycorrhizal inoculum using fertilizer banding machinery were successfully carried out in citrus nurseries in California (Ferguson, 1980).

Commercial VA mycorrhizal inoculum is currently being produced using the method described above in two citrus nurseries--Brokaw Nursery, Saticoy California and the Thermal Ranch, Thermal, California. Experimental VA mycorrhizal inoculum is being produced and distributed on a large scale by Abbott Laboratories, North Chicago, Illinois. Other major corporations which are currently supporting or carrying out research on VA mycorrhizal fungi include Dow Chemical Co., Rohm and Haas Co., Dupont, Monsanto Co., and Ceiba-Geigy Chemical Co.

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Plants growing in all soils do not respond favorably to VA mycorrhizal inoculum. If soil nutrition is optimum, mycorrhizal fungi will not enhance growth of plants. A method for detecting which soils require mycorrhizae for maximum production of citrus was devised by Menge et al. (1980). In soils with less than 34 ppm available P (Olson analysis), 12 ppm available Zn, 27 ppm available Mn, or 3% organic matter, citrus trees will probably require mycorrhizal fungi for maximum growth. Mycorrhizal inoculations are recommended only in soils with these characteristics. It is estimated that this includes approximately 85% of the southern California citrus soils. Similar studies could be done with other crops to determine which soils require mycorrhizal infestation.

Potential uses for mycorrhizal fungi

Because mycorrhizal fungi occur on most agronomic crop plants and improve the growth of these plants, the potential use of these fungi as commercial "biotic fertilizers" is enormous. Large-scale field inoculations with mycorrhizal fungi are rare because of limited inoculum, and natural field soils usually contain adequate populations of indigenous mycorrhizal fungi. Under these conditions, any growth benefit due to mycorrhizal inoculation would depend primarily upon the superiority and/or placement of the mycorrhizal inoculum. Beneficial responses under these conditions would be predicted to be far less than the responses obtained in fumigated or partially sterilized soil. However, greenhouse and field experiments in which plants were inoculated with mycorrhizal fungi in non-fumigated soils have demonstrated that growth responses due to mycorrhizal fungi can occur under these circumstances.

In greenhouse experiments, utilizing untreated soil, Mosse and her colleagues (Mosse, 1973b, 1975, 1977; Mosse and Hayman, 1971; Mosse et al., 1969) demonstrated that preinoculation with mycorrhizal fungi could provide the following growth increases:

Centrosema sp.	- 34%
corn	- 306%
Melinis sp.	- 41-60%
onions	- 48-3155%
strawberries	- 250%
Stylosanthes sp.	- 85-88%
sweetgum	- 45%
Viola sp.	- 527%

Other studies have noted similar growth increases in untreated soil:

corn	- 14% (Gerdemann, 1964)
corn	- 0-53% (Jackson, et al.,1972)
mahogany	- 151% (Redhead, 1975)
sudangrass	- 0-18% (Jackson et al., 1972)
white clover	- 80-100% (Powell, 1977)

In a large scale field experiment conducted in nonsterile, virgin, infertile fields, wheat preinoculated with a mycorrhizal fungus produced 220% more grain than non-mycorrhizal wheat (Khan, 1975). In a similar experiment (Khan, 1972), corn inoculated with a mycorrhizal fungus was 122% larger than non-mycorrhizal corn. Hayman (1977) reported white clover growth increases in the field due to inoculation with a mycorrhizal fungus. Black and Tinker, in an extremely well documented field experiment, found that fallow field inoculation with a mycorrhizal fungus increased potato yield 20%.

Not all mycorrhizal inoculations in nonsterile soil result in increased growth. Hayman (1977) indicated that mycorrhizal fungi did not stimulate growth of white clover at several field locations. Powell (1977) obtained significant growth increases of white clover after inoculation with mycorrhizal fungi in only 3 of 9 sites. Jackson et al. (1972) indicated that with certain mycorrhizal inoculation methods, growth of corn, sudangrass, and soybeans was not stimulated in nonsterile soil. Mosse (1977) obtained

significant growth responses of Stylosanthes sp. due to mycorrhizae in 6 of 11 nonsterile soils. Ross and Harper (1970) reported no growth stimulation of soybeans in nonsterile soil. Mosse (1977) indicated that the inoculum potential of indigenous mycorrhizal fungi is the major determinant governing growth responses of plants to mycorrhizal fungi in nontreated soil. Powell (1977) indicated that many indigenous mycorrhizal fungi are "inefficient" symbionts, and that inoculation by more efficient mycorrhizal fungi will result in growth increases even in nonsterile soil which contain high populations of "inefficient" mycorrhizal fungi. Jackson, et al. (1972) indicate that placement of mycorrhizal inoculum is equally important in affecting a plant growth response. Certainly, plants infected early in the growing season by mycorrhizal fungi are better than plants which do not become infected until later (Rich and Bird, 1974).

Huge expanses of tropical soils (such as the Brazilian Cerrado) are either deficient in phosphorus or immobolize phosphorus fertilizers. These marginal agricultural lands could be productive if mycorrhizal fungi, with the ability to efficiently utilize extremely small quantities of fertilizer, were developed and added to the soil. Cheap but readily available rock phosphate could be added as the phosphorus source. This phosphorus source is a poor fertilizer but releases small quantities of phosphorus for long periods of time. It has been shown that some mycorrhizal fungi utilize rock phosphate much better than others and can tremendously improve growth of plants growing in poor soils fertilized with this material (Mikola, 1980, Mosse, 1978).

Mycorrhizal fungi have been proposed as unstable soil or sand dune stabilizers as indicated by Sutton and Shepard (1976). Finally ectomycorrhizal fungi have been shown to improve rooting of a wide variety of non-host

plants and the possibility of utilizing them as a commercial root stimulant has been proposed by Linderman and Call (1977).

Current constraints on the commercial utilization of mycorrhizal fungi

The current major obstacles to the commerical utilization of mycorrhizal fungi are: 1) the lack of large scale field experiments under normal agricultural conditions, 2) the lack of cost-benefit analysis to determine the economics of mycorrhizal applications, 3) the trend toward excessive fertilization to substitute for the lack of mycorrhizal fungi.

Perhaps the most important deterrent of commercial utilization of mycorrhizal fungi is the lack of large scale field tests in a variety of agricultural soils and locations. The program initiated by D. H. Marx and the U. S. Forest Service will correct this deficiency for ectomycorrhizal fungi and within four years it will be known if these mycorrhizal fungi will indeed be economically feasible to utilize on a wide scale in the production of forest trees. This type of program remains to be established for VA mycorrhizal fungi. Without such data it is difficult to establish a potential market for mycorrhizal inoculum. Without a market there is little incentive for industry to initiate the production of commercial inoculum. Without commercial inoculum it is difficult to carry out large scale field tests. With the recent establishment of several commercial sources of mycorrhizal inoculum perhaps this cycle will be broken and more field tests will result. Once large scale field tests are seen to be successful, light weight commercial mycorrhizal formulations will develop and new application methods will be devised. Most importantly, from large scale field tests, cost benefit analysis can be accurately done to determine the economic benefit derived from the use of

mycorrhizal fungi. In the end, this will be the determining factor in the commercial application of mycorrhizal fungi. Biological scientists are rarely able to critically assess the economic factors involved in the application of a new technique and I recommend that agricultural economists should be asked to participate in the cost-benefit assessment of VA mycorrhizal inoculation.

It is well known that heavy phosphorus fertilization severely inhibits mycorrhizal infections (Daft and Nicolson, 1969; Mosse and Phillips, 1971). More recently, it is becoming evident that heavy nitrogen and zinc applications are also inhibitory to mycorrhizal fungi (Hayman, 1970; McIlveen and Cole, 1974). Daily applications of 100 ppm nitrogen under greenhouse conditions have been shown to completely eliminate mycorrhizal infections (J. A. Menge, unpublished data). Many commercial greenhouses add over 200 ppm nitrogen daily to their plants. In greenhouse and fumigated nursery conditions, growers are using excessive fertilization to substitute for the lack of mycorrhizal fungi. Under these conditions, not only do mycorrhizal fungi not benefit their host plants, but it is difficult to successfully establish mycorrhizal infections so that the plants will be mycorrhizal once they leave the supraoptimal fertility regime. As long as fertilizer is relatively available and not excessively expensive, it will take a major educational program to convince many growers to change their standard operating procedures and utilize mycorrhizal fungi which will not only be cheaper but will conserve fertilizer and energy.

In my opinion, granting agencies such as the National Science Foundation, Rockefeller Foundation, USDA competitive grants and the Israeli-U.S. granting agency BARD have effectively provided adequate funding for basic mycorrhizal research. The number of scientific papers on mycorrhizal fungi has quadrupled since 1960, which is evidence that there is great interest and

money available for basic mycorrhizal research. However, there are few agencies which will fund the final applied steps in a biological commercialization project. Research money for large scale "applied" or "demonstration" experiments is unavailable. Funding for small scale pilot projects is also not available. It remains for private industry to pick up the projects from this point, but they have been reluctant to do so. The transition is not going smoothly and seems to be proceeding slowly if at all.

Effects of mycorrhizal fungi on agriculture

It is very difficult for a scientist to speculate on the effects of a new procedure on the social and economic structure of an agricultural society. Frequently good ideas never receive the acclaim they deserve because of prejudices, ignorance, religious preferences, social mores and other reasons not fully understood by scientists. In my opinion, the effects of mycorrhizal technology would most alter the socio-economic structure in areas of intensive agriculture. These situations would be more prevalant in agriculture in developed nations. Mycorrhizal fungi are most useful in reclaiming sites disturbed by heavily mechanized industries or soil fumigation. Mycorrhizal fungi can reduce energy and fertilizer and increase the efficiency of crops grown intensively. Therefore, mycorrhizal fungi can be viewed as conservation measures or as substitutes for high energy uses in developed nations.

In underdeveloped nations, growers would have to be educated to the methods of producing, handling, and inoculating living microorganisms. This may be difficult. In countries with a less well-developed agricultural system, mycorrhizal fungi have not been altered and are probably functioning effectively and need not be applied under such conditions. Fertilizer in most

underdeveloped countries is probably applied sparingly as manure and therefore mycorrhizal fungi will not result in a great savings either of fertilizer or energy.

If superior strains of mycorrhizal fungi are developed, marginal agricultural land could be made productive. Huge amounts of marginal agricultural land exists in Africa and South America and the proper utilization of this land may well decide the future of some countries. Increased use of agricultural land will provide for a greater economic base, larger agricultural productivity, and a better way of life for large populations in underdeveloped countries. Education of agriculturists to the importance of mycorrhizal fungi may allow developing countries to avoid the excessive use of energy, fumigants, and fertilizers associated with intensive agriculture.

Conclusions and recommendations

It appears that mycorrhizal fungi may be one alternative which can immediately improve revegetation of disturbed sites, increase crop growth in fumigated soils and greenhouses, and yet reduce fertilizer costs and energy demands. If superior strains of mycorrhizal fungi were developed, they could potentially improve growth of nearly all agronomic crops in a wide variety of soils throughout the world. Both ectomycorrhizal fungi and vesicular-arbuscular mycorrhizal fungi are currently in commercial production on a small scale. The greatest obstacles to the commercialization of mycorrhizal fungi appears to be: 1) the lack of large scale field tests under typical agricultural conditions in a variety of locations, 2) adequate cost-benefit analysis to determine the economics of the utilization of mycorrhizal fungi, and 3) a reluctance on the part of growers to switch from an energy dependent,

heavy fertilizer system to a new, but cheaper, energy conservative system utilizing mycorrhizal fungi.

Recommendations which could substantially increase the commercial utilization of mycorrhizal fungi in order of relative importance are as follows:

1) Improved availability of grant funds for large scale field applications of mycorrhizal fungi in a wide variety of soils throughout the world. It would be useful to establis several pilot projects in various underdeveloped countries. These pilot projects could produce and distribute mycorrhizal inoculum on a variety of crops growing under different soil conditions. Cost-benefit analysis on such projects could adequately assess the economics of inoculation with mycorrhizal fungi.

2) Funds should be made available for the creation of a world wide culture bank of beneficial mycorrhizal fungi. The establishment of such a facility is currently being investigated by the mycorrhizal community. The National Science Foundation has already agreed to entertain a proposal for such a facility. The University of Florida has agreed to supply the facilities as well as substantial operating costs for such an establishment. A second idea would be to add the responsibility for maintaining mycorrhizal cultures to the already established government facility called the American Type Culture Collection which maintains many important fungal cultures.

3) It would be desirable to establish a USDA supported vesicular-arbuscular mycorrhizal research center which would be responsible for maintaining and coordinating U.S. research on mycorrhizal fungi. This facility would compliment the already established Mycorrhizal

Institute in Athens, Georgia which was created by the Forest Service to coordinate mycorrhizal research on forest trees.

4) A world survey should be conducted to collect and test as many different vesicular-arbuscular mycorrhizal species as possible. The discovery of a superior mycorrhizal strain with a wide host range could tremendously increase agricultural productivity throughout the world.

5) Research is necessary to elucidate the exact role of mycorrhizal fungi at improving plant growth under stress conditions such as drought, salt, toxic soil materials, or in marginal agricultural lands.

6) Research is necessary to elucidate the genetics of mycorrhizal fungi. Virtually nothing is known on this subject. The ability to breed these organisms could result in tremendously increased agricultural productivity.

7) Efforts should be intensified to grow vesicular-arbuscular mycorrhizal fungi in the laboratory using artificial media. A breakthrough in this area could improve the feasibility of attaining all of the above recommendations. However, since scientists have been trying to artificially culture VA mycorrhizal fungi since 1900, this objective may be difficult to achieve and incentives to work on such a problem are difficult to justify.

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PAPER NO. 10. UTILIZATION OF ZEOLITES IN AGRICULTURE

(By Dr. Frederick A. Mumpton, Department of the Earth Sciences, State University College, Brockport, N.Y.)

INTRODUCTION

As agriculturalists the world over increase their effort to expand crop and animal production, more and more attention is being paid to various mineral materials as soil amendments and as dietary supplements in animal husbandry. The close relationship between the agricultural and geological sciences is not new--the dependence of crop production on the existence and maintenance of fertile soil has often led the agronomist deep into the mineralogy and geochemistry of clays and other soil constituents. Likewise, the addition of crushed limestone to chicken feed to strengthen egg shells is well known, as is the use of bentonite as a binding agent in pelletized animal feedstuffs. Recently, one group of minerals has emerged as having considerable potential in a wide variety of agricultural processes. This group of minerals is the zeolite group, and the unique ion-exchange, dehydration-rehydration, and adsorption properties of zeolite materials promise to contribute significantly to many years of agricultural and aquacultural technology (Mumpton and Fishman, 1977).

Most of the initial research on the use of zeolites in agriculture took place in the 1960s in Japan where farmers for years have used zeolite rock to control the moisture content and malodor of animal wastes and to increase the pH of acidic volcanic soils. The addition of small amounts of the zeolites clinoptilolite and mordenite to the normal protein diet of pigs, chickens, and ruminants resulted in noticeable increases in the body weight and general "health" of the animals (Minato, 1968). The use of zeolites in rations also appeared to reduce odor and associated pollution problems and to provide a means of regulating the viscosity and nitrogen retentivity of animal manure. These same zeolites were also found to increase the ammonium content of paddy soils when added with normal fertilizers.

Although most of these results were of a preliminary nature and often published in rather obscure journals or reports of local experiment stations, they did suggest that zeolites could act as traps or reservoirs for nitrogen both in the body and in the soil. The growing awareness of such phenomena and of the availability of

inexpensive natural zeolites in the western United States and in other geologically similar parts of the world has aroused considerable commercial interest, and zeolites are fast becoming the subject of serious investigation in dozens of agricultural laboratories both here and abroad. Some of the ways in which zeolites can contribute to more efficient crop and livestock production are discussed below, along with their role in the rapidly expanding areas of fish breeding and aquaculture. At this stage, the number of published papers dealing with "zeoagriculture" is quite small, and hard data are few; however, the potential of these materials in such areas is readily apparent, and zeolites show promise of contriubting directly to increased agricultural productivity in all parts of the world in the years to come.

NATURAL ZEOLITES

Zeolites are by definition crystalline, hydrated aluminosilicates of alkali and earth metals that possess infinite, three-dimensional crystal structures. They are further characterized by an ability to lose and gain water reversibly and to exchange some of their constituent elements without major change of structure. Zeolites were discovered in 1756 by Freiherr Axel Fredrick Cronstedt, a Swedish mineralogist, who named them from the Greek words ζειν λιθος, meaning "boiling stones", in allusion to their peculiar frothing characteristics when heated before the mineralogist's blowpipe. Since that time, nearly 50 natural species of zeolites have been recognized, and more than 100 species having no natural counterparts have been synthesized in the laboratory. Synthetic zeolites are the mainstays of the multimillion dollar molecular sieve businesses that have been developed by Union Carbide Corporation, W. R. Grace & Company, Mobil Corporation, Norton Company, Exxon Corporation, and several other companies in the last 25 years in the United States and by chemical firms in Germany, France, Great Britain, Belgium, Italy, Japan, and the Soviet Union.

Although natural zeolites are well known to members of the geological community and their mineral-collecting colleagues as ubiquitous, but minor constituents in the vugs and cavities of basalt and other traprock formations, it was not until the late

1950s that the world became aware of zeolites as major constituents of numerous volcanic tuffs that had been deposited in ancient saline lakes of the western United States or in thick marine tuff deposits of Italy and Japan. Since that time, more than 2000 separate occurrences of zeolites have been reported from similar sedimentary rocks of volcanic origin in more than 40 countries. The high purities and near-surface location of the sedimentary deposits has prompted intense commercial interest both here and abroad, and applications based on the exciting bag of chemical and physical tricks of zeolites have been developed in many areas of industrial technology. The commercial use of natural zeolites is still in its infancy, but currently more than 300,000 tons of zeolite-rich tuff is mined each year in the United States, Japan, Bulgaria, Hungary, Italy, Yugoslavia, Korea, Mexico, Germany, and the Soviet Union. Natural zeolites have found applications as fillers in the paper industry, as lightweight aggregate in construction, in pozzolanic cements and concrete, as ion-exchangers in the purification of water and municipal sewage effluent, as traps for radioactive species in low-level wastewaters from nuclear facilities, in the production of high purity oxygen from air, as reforming petroleum catalysts, as acid-resistant adsorbents in the drying and purification of natural gas, and in the removal of nitrogen compounds from the blood of kidney patients (see Mumpton, 1978).

The applications and potential applications of both synthetic and natural zeolites depend, of course, on their fundamental physical and chemical properties. These properties are in turn related directly to the chemical composition and crystal structure of individual species.

Chemistry and crystal structure of zeolites

Along with quartz and feldspar, zeolites are "tektosilicates," that is, they consist of three-dimensional frameworks of silicon-oxygen $(SiO_4)^{-4}$ tetrahedra, wherein all four corner oxygen atoms of each tetrahedron are shared with adjacent tetrahedra, as shown in Figure 1. This arrangement of silicate tetrahedra reduces the overall oxygen:silicon ratio to 2:1, and if each tetrahedron in the framework contains silicon as its central atom, the structures are electrically neutral, as is quartz (SiO_2). In

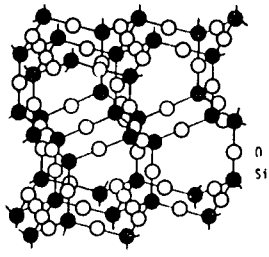


Figure 1. Three-dimensional arrangement of silicate tetrahedra in tektosilicates. Crystal structure of the beta-tridymite form of SiO_2.

zeolite structures, however, some of the quadrivalent silicon is replaced by trivalent aluminum, giving rise to a deficiency of positive charge. This charge is balanced by the presence of mono- and divalent elements such as sodium (Na^+), calcium (Ca^{2+}), and potassium (K^+) elsewhere in the structure. Thus, the empirical formula of a zeolite is of the type:

$$M_{2/n}O \cdot Al_2O_3 \cdot xSiO_2 \cdot yH_2O$$

where M is any alkali or alkaline earth element, n is the valence charge on that element, x is a number from 2 to 10, and y is a number from 2 to 7. The empirical and unit-cell formulae of clinoptilolite, the most common of the natural zeolites, follow:

$$(Na,K)_2O \cdot Al_2O_3 \cdot 10SiO_2 \cdot 6H_2O \qquad \text{or} \qquad (Na_4K_4)(Al_8Si_{40})O_{96} \cdot 24H_2O.$$

Elements or cations within the first set of parentheses in the unit-cell formula are known as exchangeable cations; those within the second set of parentheses are called structural cations, because with oxygen they make up the tetrahedral framework of the structure. Loosely bound molecular water is also present in the structures of all natural zeolites, surrounding the exchangeable cations in large pore spaces of the structure.

Whereas the framework structures of quartz and feldspar are dense and tightly packed ($\sim$2.6-2.7g/cm^3), those of zeolite minerals are remarkably open ($\sim$2.1-2.2g/cm^3) and void volumes of dehydrated species as great as 50% are known (Table 1). Each zeolite species has its own unique crystal structure and, hence, its own set of physical and chemical properties. Most structures, however, can be visualized as SiO_4 and AlO_4 tetrahedra linked together in a simple geometrical form, such as that shown in Figure 2a. This particular polyhedron is known as a truncated cubo-octahedron. It is more

TABLE 1. REPRESENTATIVE FORMULAE AND SELECTED PHYSICAL PROPERTIES OF IMPORTANT ZEOLITES

Zeolite	Representative unit-cell formula[a]	Void volume[a]	Channel dimensions[a]	Thermal stability	Ion-exchange capacity[b]
Analcime	$Na_{16}(Al_{16}Si_{32}O_{96})\cdot 16H_2O$	18%	2.6 Å	High	4.54 meq/g
Chabazite	$(Na_2,Ca)_6(Al_{12}Si_{24}O_{72})\cdot 40H_2O$	47	3.7 × 4.2	High	3.81
Clinoptilolite	$(Na_4K_4)(Al_8Si_{40}O_{96})\cdot 24H_2O$	39?	[illegible]9 × 5.4	High	2.54
Erionite	$(Na,Ca_{[illegible]},K)_9(Al_9Si_{27}O_{72})\cdot 27H_2O$	35	5 × 5.2	High	3.12
Faujasite	$Na_{58}(Al_{58}Si_{134}O_{384})\cdot 27H_2O$	47	7.4	[illegible]igh	3.39
Ferrierite	$(Na_2Mg_2)(Al_6Si_{30}O_{72})\cdot 18H_2O$		4.3 × 5.5 3.4 × 4.8	High	2.33
Heulandite	$Ca_4(Al_8Si_{28}O_{72})\cdot 24H_2O$	39	4.0 × 5.5 4.4 × 7.2 4.1 × 4.7	Low	2.91
Laumontite	$Ca_4(Al_8Si_{16}O_{48})\cdot 16H_2O$		4.6 × 6.3	Low	4.25
Mordenite	$Na_8(Al_8Si_{40}O_{96})\cdot 24H_2O$	28	2.9 × 5.7 6.7 × 7.0	High	2.29
Phillipsite	$(Na,K)_{10}(Al_{10}Si_{22}O_{64})\cdot 20H_2O$	31	4.2 × 4.4 2.8 × 4.8 3.3	Low	3.87
Linde A	$Na_{12}(Al_{12}Si_{12}O_{48})\cdot 27H_2O$	47	4.2	High	5.48
Linde X	$Na_{86}(Al_{86}Si_{106}O_{384})\cdot 264H_2O$	50	7.4	High	4.73

[a]Taken mainly from Breck, 1974, Meier and Olson, 1971. Void volume is determined from water content.
[b]Calculated from unit-cell formula.

easily seen by considering only lines joining the midpoints of each tetrahedron, as shown in Figure 2b. Individual polyhedra may be connected in several ways; for

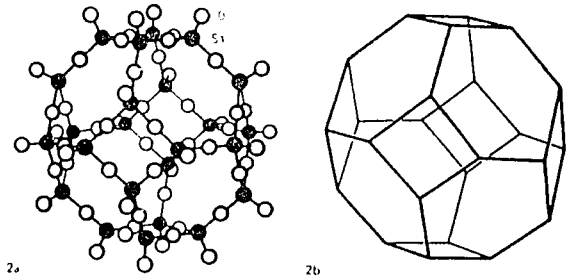


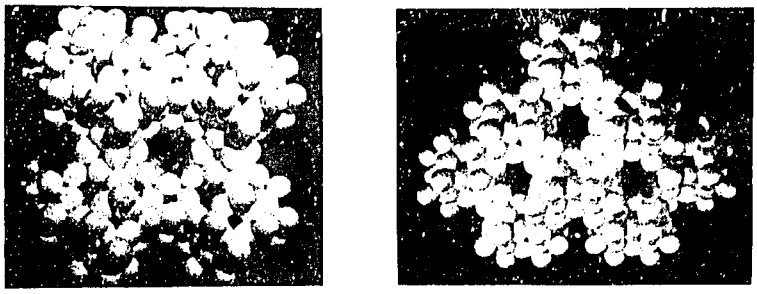
Figure 2. Simple polyhedron of silicate and aluminate tetrahedra. (a) Ball and peg model of truncated cubo-octahedron. (b) Line drawing of truncated cubo-octahedron; lines connect centers of tetrahedra.

example, by double four-rings of oxygen atoms as shown in Figure 3a, or by double six-rings of oxygen atoms, as shown in Figure 3b, the framework structures of synthetic zeolite A and the mineral faujasite, respectively. Solid-sphere models of synthetic

Figure 3. Arrangements of simple polyhedra to enclose large central cavities. (a) Truncated cubo-octahedra connected by double four-rings of oxygen in structure of synthetic zeolite A. (b) Truncated cubo-octahedra connected by double six-rings of oxygens in structure of faujasite.

zeolite A and of the mineral chabazite are illustrated in Figure 4.

It is evident (Figures 2 to 4) that once the water is removed from a zeolite, considerable void space is available within both the simple polyhedra building blocks and the larger frameworks formed by several polyhedra. Although water and other inorganic and



a b

Figure 4. (a) Solid-sphere model of the crystal structure of synthetic zeolite A. (b) Solid-sphere model of the crystal structure of chabazite.

organic molecules would appear to be able to move freely throughout a dehydrated zeolite framework, the passageways leading into the simple polyhedra are too small for all but the smallest molecules to pass; however, ports or channels up to 8 Å in diameter lead into the large, three-dimensional cavities (Figures 3, 4a, 4b).

Properties of Zeolites

Adsorption properties. Under normal conditions, the large cavities and entry channels

of zeolites are filled with water molecules forming hydration spheres around the exchangeable cations. Once the water is removed, usually by heating to 300° to 400°C for a few hours, molecules having effective cross-sectional diameters small enough to fit through the entry channels are readily adsorbed on the inner surfaces of the vacant central cavities. Molecules too large to pass through the entry channels are excluded, giving rise to the well-known "molecular sieving" property of most crystalline zeolites (Figure 5). The internal surface area available for adsorption ranges up to several hundred square meters per gram, and some zeolites are capable of adsorbing up to about 30 weight percent of a gas, based on the dry weight of the zeolite.

In addition to their ability to separate gas molecules on the basis of size and shape, the unusual charge distribution within a dehydrated void volume allows many species with permanent dipole moments to be adsorbed with a selectivity unlike that of almost all other sorbents. Thus, polar molecules such as water, sulfur dioxide, hydrogen sulfide, and carbon dioxide are preferentially adsorbed by certain zeolites over non-polar molecules, such as methane, and adsorption processes have been developed using natural zeolites by which carbon dioxide and other contaminents can be removed from impure natural gas or methane streams, allowing the gas to be upgraded to high-BTU products. In addition, the small, but finite, quadripole moment of nitrogen allows it to be adsorbed selectively from air by a dehydrated zeolite, producing oxygen-enriched streams at relatively low cost at room temperature. Both of the above processes may find application in agricultural technology (*vide infra*).

Dehydration-rehydration properties. Because of the uniform nature of the pores of structural cages, crystalline zeolites have fairly narrow pore-size distributions, in contrast to other commercial adsorbents, such as activated alumina, carbon, and silica gel. Adsorption on zeolites is therefore characterized by Langmuir-type isotherms, as shown in Figure 6. Here, percent of adsorption capacity is plotted against partial pressure of the adsorbate gas. Note that almost all of the zeolite's adsorption capacity for a particular gas (including water) is obtained at very low partial pressures,

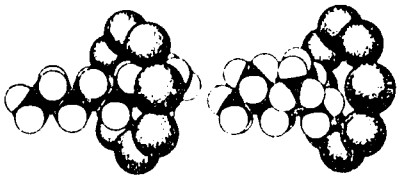


Figure 5. Stylized illustration of the entry of straight-chain hydrocarbons and blockage of branch-chain hydrocarbons at channel apertures.

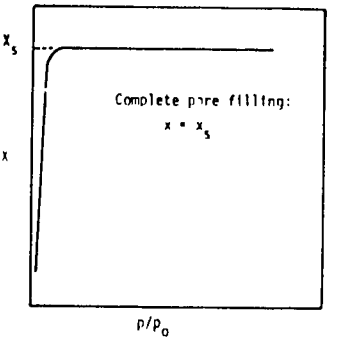


Figure 6. Langmuir-type isotherm for adsorption on crystalline zeolites illustrating almost complete saturation at low partial pressures of the adsorbate. x = amount adsorbed; p = pressure.

meaning that although their total adsorption capacity may be somewhat less than those of other adsorbents, (e.g., silica gel), zeolites are extremely efficient adsorbents even at low partial pressures. This property has been utilized in the zeolitic adsorption of traces of water from Freon gas lines of ordinary refrigerators which might otherwise freeze and clog pumps and valves. The extreme non-linearity of the water adsorption isotherms of zeolites has been exploited recently in the development of solar-energy refrigerators (Tschernev, 1978).

Ion-exchange properties. The exchangeable cations of a zeolite are also only loosely bonded to the tetrahedral framework and can be removed or exchanged from the framework structure easily by washing with a strong solution of another element. As such, crystalline zeolites are some of the most effective ion exchangers known to man, with capacities of 3 to 4 meq per gram being common. This compares with the 0.8-1.0 meq per gram cation-exchange capacity of bentonite, the only other significant ion-exchanger found in nature. Cation-exchange capacity is basically a function of the degree of substitution of aluminum for silicon in the zeolite framework: the greater the substitution, the greater the charge deficiency of the structure, and the greater the number of alkali or alkaline earth atoms required for electrical neutrality. In practice, however, the cation-exchange capacity is dependent on a number of other

factors as well. In certain species, cations can be trapped in structural positions that are relatively inaccessible, thereby reducing the effective exchange capacity of that species for that ion. Also, cation sieving may take place if the size of the exchanging cation is too large to pass through the entry channels into the central cavities of the structure. Analcime, for example, will exchange almost completely its sodium for rubidium (ionic radius = 1.49 Å), but not at all for cesium (ionic radius = 1.65 Å) (Breck, 1974).

Unlike most noncrystalline ion exchangers, such as organic resins or inorganic aluminosilicate gels (mislabeled in the trade as 'zeolites'), the framework of a crystalline zeolite dictates its selectivity towards competing ions. The hydration spheres of high-charge, small-size ions (e.g., sodium, calcium, magnesium) prevent their close approach in the cages to the seat of charge of the framework; therefore ions of low charge and large size (e.g., lead, barium, potassium), which normally do not have hydration spheres, are more tightly held and selectively taken up from solution than are other ions. The small amount of aluminum in the composition of clinoptilolite, for example, results in a relatively low cation-exchange capacity (about 2.3 meq/g); however, its cation selectivity is:

Cesium > Rubidium > Potassium > Ammonium > Barium > Strontium > Sodium > Calcium > Iron > Aluminum > Magnesium > Lithium (Ames, 1960).

Synthetic zeolite A, on the other hand, is more selective for calcium than for sodium, and thus, acts as a water softener in laundry detergents where it picks up calcium from the wash water and releases sodium (Savitsky, 1977).

Cation exchange between a zeolite (Z) and a solution (S) is usually shown by means of an exchange isotherm which plots the fraction of the exchanging ion (X) in the zeolite phase against that in the solution, as shown in Figure 7. If a given cation shows no preference for either the solution or the zeolite, the exchange isotherm would be the straight line "a" at 45° in Figure 7. If the zeolite is moderately or very selective for the cation in solution, curve b and c in Figure 7 would result,

respectively. If the zeolite is rejective of a particular cation, curve d would result. Such is the selectivity of clinoptilolite for cesium or ammonium, for example. Clinoptilolite will take up these ions readily from solutions even in the presence of high concentrations of competing ions, a facility that was exploited by Ames (1967) and Mercer et al. (1970) in their development of an ion-exchange process for the removal of ammoniacal nitrogen from sewage effluent.

APPLICATIONS IN AGRONOMY

Fertilizer and Soil Amendments

Based on their high ion-exchange capacity and water retentivity, natural zeolites have been used extensively in Japan as amendments for sandy soils, and small tonnages have been exported to Taiwan for this purpose (Minato, 1968; Hsu et al., 1967) The pronounced selectivity of clinoptilolite for large cations, such as ammonium and potassium, has also been exploited in that country in the preparation of chemical fertilizers that improve the nutrient-retention ability of the soils by promoting a slower release of these elements for uptake by plants. In rice fields, where nitrogen efficiencies of less than 50% are not uncommon, Minato (1968) reported a 63% improvement in the amount of available nitrogen in a highly permeable paddy soil four weeks after about 40 tons/acre zeolite had been added along with standard fertilizer (Figure 8). Turner (1975), on the other hand, noted little change in the nitrification of added ammonia when clinoptilolite was mixed with a Texas clay soil, although the overall ion-exchange capacity of the soil was increased. He attributed these conflicting results to the fact that the Japanese soils discussed by Minato (1968) contained much less clay, thereby accounting for their inherent low ion-exchange capacity and fast-draining properties. The addition of zeolite, therefore, resulted in a marked improvement in the soil's ammonium retentivity. These conclusions support those of Hsu et al. (1967) who found an increase in the effect of zeolite additions to soil when the clay content of the soil decreased. Although additions of both montmorillonite and mordenite increased the cation-exchange capacity of upland soils, the greater stability of the zeolite to

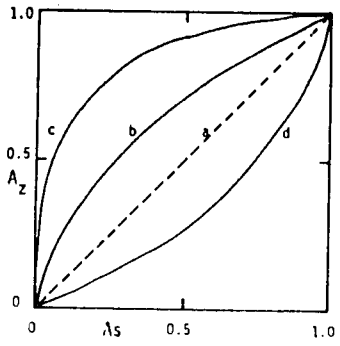


Figure 7. Types of ion-exchange isotherms for the reaction $A_s+B_z=A_z+B_s$. (a) no preference of the ion for either the zeolite or the solution; (b) small preference of the ion for the zeolite phase; (c) large preference of the ion for the zeolite; (d) small preference of the ion for the solution phase. (From Breck, 1974)

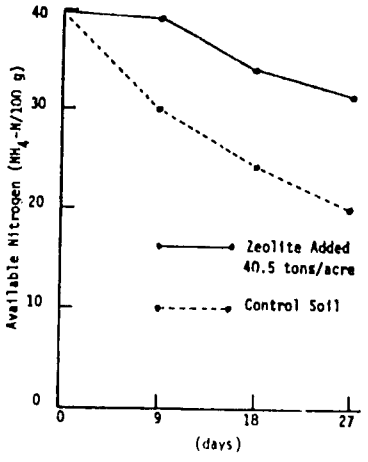


Figure 8. Change of soil nitrogen of paddy soil with time. Vertical water seepage in soil = 1.35 cm/day. (Yamagata Prefecture Board of Agriculture and Forestry, 1966; reported in Minato, 1968).

weathering allowed this increase to be retained for a much longer period of time than in the clay-enriched soils, according to Goto and Ninaki (1980).

Using clinoptilolite tuff as a soil conditioner, the Agricultural Improvement Section of the Yamagata Prefectural Government, Japan, reported significant increases in the yields of wheat (13-15%), eggplant (19-55%), apples (13-38%), and carrots (63%) when from 4 to 8 tons of zeolite was added per acre (see Torii, 1978). Small, but significant improvements in the dry-weight yields of sorghum in greenhouse experiments using a sandy loam (29% sand, 34% silt, 37% clay) were noted when 0.5-3.0 tons of clinoptilolite/acre was added along with normal fertilizer (McCarlin and Boyle, 1980); however, little improvement was found when raising corn under similar conditions. Hershey et al. (1980) showed that clinoptilolite amended to a potting medium for chrysanthemums did not behave like a soluble K source, but was very similar to a slow-release fertilizer. The same fresh-weight yield was achieved with a one-time addition

of clinoptilolite (equivalent to 3 g of potassium) as with a daily irrigation of Hoagland's solution, containing 238 ppm K, for three months (total of 7 g potassium added), with no apparent detrimental effect on the plants (see Figure 9).

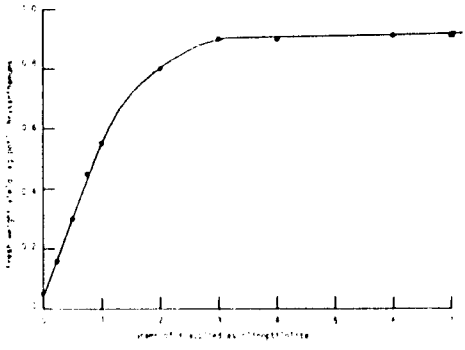


Figure 9. Yield of chrysanthemums as a function of potassium level supplied by one-time additions of clinoptilolite. Solid square represents total of 7 g of potassium supplied by daily irrigation with Hoaglan's solution containing 234 ppm K). Total time of experiment = 3 months. From Hershey et al., 1980.

Akson (1980) indicated that Great Western Sugar Company experiments in Longmont, Colorado, using clinoptilolite as a soil amendment resulted in a significant increase in total-matter production of sugar beets, although "high" levels of zeolite were required. The details of these experiments are considered proprietary and have not been released. Lewis et al. (1980) reported that the addition of ammonium-exchanged clinoptilolite in greenhouse experiments with radishes resulted in a 59% and 53% increase in root weight in medium (13%) and light (6%) clay soils, respectively. The nitrogen uptake by plant tops also increased with the zeolite treatment compared with an ammonium sulfate control (see Table 2). These authors also found that natural clinoptilolite added to soil in conjunction with

Table 2. Growth response of radishes to ammonium-exchanged clinoptilolite[1]

Parameter	13% Clay soil[2]		6% Clay soil[3]	
	NH_4-Clinoptilolite	$(NH_4)_2SO_4$	NH_4-Clinoptilolite	$(NH_4)_2SO_4$
Leaf area (cm^2/plant)	243	152	187	150
Plant weight (dry weight) (g)	1.84	1.12	1.40	1.1
Root weight (g)	14.5	9.5	11.6	7.6
N uptake (mg N/plant top)	.2	35.9	42.6	38.9

[1]Lewis et al., 1980. [2]Plants sampled 36 days after planting.
[3]Leached 5 times, plants sampled 34 days after planting.

urea reduced the growth suppression that normally occurs when urea is added alone (Table 3). The presence of zeolites also resulted in less NO_3-N being leached from the soil, as shown in Figure 10. Both zeolite treatments apparently made considerably more ammonium available to the plants, especially when clay-poor soils were employed.

Table 3. [illegible] natural clinoptilolite + urea.[1]

Parameter	[illegible] Clay Soil[2] Zeolite + Urea	Urea	[illegible] Clay Soil[3] Zeolite + Urea	Urea
Leaf area (cm^2/plant)	210	187	208	116
Plant weight (dry weight) (g)	1.59	1.21	1.35	0.71
Root weight (g)	13.8	4.2	12.4	6.3
N uptake (mg N/plant top)	45.5	38.6	44.4	18.9

[1]Lewis et al., 1980. [2]Plants sampled 36 days after planting
[3]Leached 5 times, plants sampled 24 days after planting.

The authors suggested that ammonium-exchanged clinoptilolite acted as a slow-release fertilizer, whereas, natural clinoptilolite acted as a trap for ammonium that was produced by the decomposing urea, and thereby prevented both ammonium and nitrate toxicity by disrupting the bacterial nitrification process. The ammonium selectivity of zeolites was exploited by Varro (1977) in the formulation of a fertilizer consisting of a 1:1 mixture of sewage sludge and zeolite, wherein the zeolite apparently controls the release of nitrogen from the organic components of the sludge into the soil.

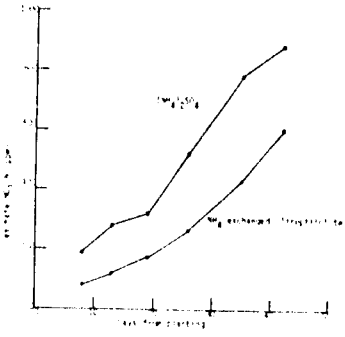


Figure 10. Cumulative leachate NO_3-N for banded NH_4-exchanged clinoptilolite and banded ammonium sulfate (Lewis et al., 1980)

Coupled with its valuable ion-exchange properties which allow a controlled release of micronutrients, such as iron, zinc, copper, manganese, and cobalt, the ability of clinoptilolite to sorb excess moisture makes it an attractive addition to chemical fertilizers to prevent caking and hardening during storage and to animal feedstuffs to inhibit the development of mold (Torii, 1974). Spiridonova et al. (1975) found that 0.5% clinoptilolite added to ammonium nitrate fertilizer decreased caking by 68%,

Pesticides, Fungicides, Herbicides

Similar to their synthetic counterparts, the high adsorption capacities in the dehydrated state and the high ion-exchange capacities of many natural zeolites make them effective carriers of herbicides, fungicides, and pesticides. Yoshinaga et al. (1973) found clinoptilolite to be an excellent substrate for benzyl phosphorothioate to control stem blasting in rice. Using natural zeolites as a base, Hayashizaki and Tsuneji (1974) found that clinoptilolite is more than twice as effective as a carrier of the herbicide benthiocarb in eliminating weeds in paddy fields as other commercial products. Torii (1974) reported that more than 100 tons of zeolite were used in Japan in 1973 as carriers in agriculture. A Russian patent was issued to Aleshin et al. for grouting compound containing 3-5% clinoptilolite to control herbicide percolation from irrigation canals to ground waters.

Heavy Metal Traps

Not only do the ion-exchange properties of certain zeolites allow them to be used as carriers of nutrient elements in fertilizers, they can be exploited to trap undesireable metals and prevent their uptake into the food chain. Fujii (1974) found that pulverized zeolites effectively reduced the transfer of fertilizer-added heavy metals, such as copper, cadmium, lead, and zinc, from soils to plants. The selectivitity of clinoptilolite for such heavy metals has been noted by several workers (e.g., Sato, 1975; Fujinori and Moriya, 1973; Chelishchev et al., 1974; Semmons and Seyfarth, 1978). In view of the attempts being made by sanitary and agricultural engineers to add municipal and industrial sewage sludge to farm and forest soils, natural zeolites may play a major role in this area also. The nutrient content of such sludges is desirable, but the heavy metals present may accumulate to the point where they become toxic to plant life and/or to the animals of human beings that may eventually eat these plants. Cohen (1977) reported median values of 31 ppm cadmium, 1230 ppm copper, 830 ppm lead, and 2780 ppm zinc for sludges produced in

typical U.S. Treatment plants. Zeolite additives to extract heavy metals may be a key to the safe use of sludge as fertilizer and help extend the life of sludge-disposal sites or of land subjected to the spray-irrigation processes now being developed for the disposal of chlorinated sewage. Similarly, Nishita and Haug (1972) showed that the addition of clinoptilolite to soils contaminated with radioactive strontium (Sr^{90}) resulted in a marked decrease in the uptake of strontium by plants, an observation having enormous import in potential treatment of radioactive fallout that contaminates soils in several Pacific atolls where nuclear testing has been carried out.

APPLICATIONS IN ANIMAL HUSBANDRY

Animal Nutrition

Based on the successful use of montmorillonite clay in slowing down the passage of nutrients in the digestive system of chickens and the resultant improvement in caloric efficiency, as reported by Quisenberry (1968), experiments have been carried out in Japan since 1965 on the application of natural zeolites as dietary supplements for several types of domestic animals. Because much of this work was of a superficial or non-statistically significant nature, it has been repeated and enlarged upon in recent years by researchers in the United States and several other countries seeking agricultural applications for zeolites.

Poultry

Using clinoptilolite from the Itaya mine, Yamagata Prefecture, and mondenite from Karawago, Miyagi Prefecture, Onagi (1966) found that Leghorn chickens required less food and water and still gained as much weight in a 2-week trial as birds receiving a control diet. Feed efficiency values (FEV)[1] were markedly higher at all levels of zeolite substitution; feedstuffs containing 10% zeolite giving rise to efficiencies more than 20% greater than those of normal rations (Table 4). Adverse effects on the health or vitality of the birds were not noted, and the droppings of groups receiving zeolite diets contained up to 25% less moisture than those of control groups, after a 12-day drying period, making them considerably easier to handle.

Table 4. Caloric efficiencies of zeolite supplements in poultry feeding

Group no.	Zeolite content of rations	Average starting wt. (g)	Average final wt. (g)	Average weight gain (g)	Average feed intake[2] (g)	Feed efficiency ratio[3]
1	10% Cp[4]	553.7	795.6	241.9	668	0.362
2	5% Cp	540.7	778	237.3	697	0.340
3	3% Cp	556.7	796	239.3	748	0.320
4	10% Mo	532.3	757.3	225.0	634	0.355
5	5% Mo	552.3	814.6	262.3	775	0.338
6	3% Mo	534.5	791.3	256.8	769	0.334
7	Control	556.5	789.3	232.8	782	0.298

[1]Onagi (1966). Tests carried out on 48-day-old Leghorns over a 14-day period, 30 birds/group. Normal rations consisted of 16.5% crude protein and 66% digestible nutrients. [2]Excluding zeolite.
[3]Feed efficiency = weight gain/feed intake (excluding zeolite).
[4]Cp = clinoptilolite; Mo = mordenite.

Arscott (1975) found that broiler chickens fed a diet of 5% clinoptilolite from the Hector, California, deposit gained slightly less weight over a 2-month period than birds receiving a normal diet, but average FEVs were noticeably higher (Table 5). Perhaps of greater significance is the fact that none of the 48 test birds on the zeolite diet died during the experiment, while 3 on the control diet and 2 on the control diet supplemented with antibiotics succumbed. In addition to an apparent feed-efficiency increase of 4-5%, the presence of zeolite in the diet appears to have had a favorable effect on the mortality of the birds.

[1]Weight gain/feed intake, excluding zeolite.

Table 5. Apparent caloric efficiency of zeolite in chicken rations[1]

Treatment data	Average weight (g)	Average consumptions (g)	Average F.E.V.[3]	Survivors of 1st birds
	4-week data[4]			
Control diet	730	1175	0.622	46
Control diet + antibiotics[6]	708	1116	0.634	47
Control diet with 5% clinoptilolite	703	1070	0.657	48
	8-week data[5]			
Control diet	1664	3478	0.470	45
Control diet + antibiotics	[illegible]	3563	0.486	46
Control diet with 5% clinoptilolite	1793	3647	0.499	48

[1]Adapted from data of [illegible]. [2]Feed consumed, excluding zeolite.
[3]Feed efficiency value = weight gain/feed (excluding zeolite).
[4]Starter rations (0 to 4 weeks). [5]Finisher rations (4 to 8 weeks).
[6]No zeolite in antibiotics.

Hayhurst and Willard (1980) confirmed many of Onagi's observations and reported small increases in FEV for Leghorn roosters over a 40-day period, especially during the first 10 days. The birds were fed a diet containing 7.5 clinoptilolite crushed to 10 x 20 mesh and mixed directly with the normal rations. Feces were noticeably dryer and less odoriferous. Unfortunately, only 17 birds were used in the study, and extensive statistical evaluation of the results could not be made.

Swine

Kondo and Wagai (1968) evaluated the use of zeolites in the diets of young and mature Yorkshire pigs in 60-day and 79-day experiments, respectively, and found that the weight gain of animals of both ages receiving diets containing 5% clinoptilolite was from 25 to 29% greater than that of animals receiving normal diets (Table 6). Feed

Table 6. Caloric efficiency of zeolite supplements in swine feeding[1]

Group	Age of pigs Start (days)	Age of pigs Finish (days)	Average weight Start (kg)	Average weight Finish (kg)	Average wt. gain (kg)	Average[2] feed intake (kg)	Average[3] F.E.V	Zeolite improvement
Experimental[4]	60	120	15.33	44.33	29.00	85.0	0.341	35%
Control[4]	60	120	14.65	35.75	22.93	90.6	0.253	
Experimental[5]	79	178	20.73	95.30	54.57	167.6	0.326	6%
Control[5]	79	178	31.20	73.50	42.30	139.2	0.308	

[1]Kondo and Wagai (1968). Tests carried out using 5% clinoptilolite in rations of experimental groups.
[2]Excluded zeolite. [3]Feed efficiency value = weight gain/feed intake.
[4]Eight Yorkshire pigs. [5]Twenty Yorkshire pigs.

supplemented with zeolites gave rise to feed efficiencies about 35% greater than those of normal rations when fed to young pigs, but only about 6% greater when given to older animals. In addition, the particle size of the feces of the control group was noticeably coarser than that of the experiment group, suggesting that the digestive process was more thorough when zeolites were added to the diet. The feces of animals in the control group were also richer in all forms of nitrogen than zeolite-fed animals, indicating that the zeolites contributed towards a more efficient conversion of feedstuff nitrogen to animal protein. Han et al. (1975, 1976) found that the digestibility of crude protein and nitrogen-free extracts tended to be improved as zeolite was substituted for wheat bran in swine diets at levels from 1 to 6% over a 12-week period. Anai et al. (1976) reported similar results using 5% zeolite for 8 pigs over a 12-week period and realized a 4% decrease in the cost of producing body weight of the animals. They also noted a decrease in malodor and moisture content of the excrement. Toxic or other adverse effects were not noted for any of the test animals described above. On the contrary, the presence of zeolites in swine rations appears to contribute measurably to the well-being of the animals. According to Torii (1978), tests carried out on 4,000 head of swine in Japan showed that the death rate and incidence of disease among animals fed a diet containing 6% clinoptilolite was markedly lower than for control animals over a 12-month period. As shown in Table 7, the decrease in the number of cases of gastric ulcers, pneumonia, heart dilation, and in the overall mortality rate is remarkable. The savings in medicine alone amounted to about 75¢ per animal, to say nothing of the increased value of a larger number of healthy pigs.

Table 7. Effect of zeolite diets on health of swine[1]

Period	Zeolite content of rations	Sickness causes				Medicine cost/head
		Gastric ulcer	Pneumonia	Heart dilation	Mortality rate (%)	
2/72 to 1/73	0	77	128	6	4.0	$2.50
2/73 to 1/74	6% clinoptilolite	2%	51	4	2.6	$1.75

[1]Test carried out on 4,000 swine at Xeai Farm, Morioka, Iwate Prefecture, Japan (Torii, 1974).

Although no control groups were monitored, Morita (1967) reported that the addition of zeolite to the diet of piglets severely afflicted with scours markedly reversed the progress of this disease within a few days. Four underdeveloped Laundry pigs were fed a diet containing 30% zeolite for the first 15 days and 10% zeolite for the remaining part of a month-long experiment. The severity of the disease decreased almost at once, and feces of all pigs were hard and normal after only 7 days. Although the pigs consumed an average of 1.75 kg of zeolite/head/day, no ill effects were noted, and once they had recovered from diarrhetic ailments, the pigs regained healthy appetites and became vital. In a recent Japanese patent disclosure, Makita (1978) claimed a method of preventing and treating gastric ulcer in swine by the addition of zeolite to their diets; supportive data, however, were not reported.

Apparently the vitalizing effect of a zeolite diet can be transferred from mother to offspring. Experiments at the Ichikawa Livestock Experiment Station, where 400 g of clinoptilolite was fed each day to pregnant sows and continued through the 35-day weaning period of their offspring, showed substantial increase in the growth rate of the young pigs. As shown in Table 8, test animals weighed from 65 to 85% more than control-group animals at the end of the weaning period (Buto and Takehashi, 1967). The authors reported that young pigs whose dams received the zeolite diet also suffered almost no attacks of diarrhea, while those in control groups were severely afflicted with scours, greatly inhibiting their normal growth. Ma *et al.* (1979) found that the

Table 8. Effect of prenatal zeolite diet on newborn pigs[1]

Species	No. of pigs	Group	Average weight (kg) New-born	21-days	35-days	Weight-gain improvement[2]
Yorkshire	6	Experimental	1.25	4.3	7.83	63%
Yorkshire	10	Control	1.10	4.2	4.81	
Laundry	6	Experimental	1.20	4.7	8.68	86%
Laundry	10	Control	1.10	4.0	4.67	

[1]Test carried out at Ichikawa Livestock Experiment Station, Japan. Four hundred grams of clinoptilolite given to sows in experimental group per day and continued to end of weaning period (Buto and Takenashi, 1967).

[2]Weight-gain of experimental animals ÷ weight-gain of control animals x 100.

addition of 5% zeolite to the rations of pregnant sows 20-90 days after mating gave rise to improved FEVs and increased litter weight at parturition. The earlier the zeolite was added, the greater was the apparent effect.

Studies were conducted at Oregon State University (England, 1975) with young swine using rations containing 5% clinoptilolite. Although lesser increases in growth rates were found than in the Japanese studies, the incidence of scours was significantly reduced for animals receiving the zeolite diet. Currently, heavy doses of prophylactic antibiotics are used to control such intestinal diseases, which, left unchecked, result in high mortality rates among young swine after they are weaned. Federal regulations are becoming increasingly stringent in this area, and if antibiotics are prohibited, other means must be found to control such diseases. Natural zeolites may be the answer.

In a preliminary study involving 16 early weaned pigs over a 19-day period, Pond and Mumpton (1978) found that animals on an antibiotic-free diet containing 10% clinoptilolite gained about 5% more weight per pound of feed than those on a control diet without antibiotics and about 4 more than those on an antibiotic-enriched diet (Table 9). The small number of pigs used, however, limits the significance of these findings. Castro and Elias (1978) found up to a 30% improvement in FEVs for 35 young pigs on a molasses-based diet when 7.5% clinoptilolite was substituted in the diet during the

Table 9. Effect of zeolite supplement in the diets of early weaned pigs[1]

	Basal Diet[2]	Zeolite Diet[3]	Antibiotic Diet[4]
Number of pigs	4	4	4
Average daily weight gain (g)	245	245	304
Feed efficiency value (FEV)[5] (weight gain/feed intake)	0.437	0.455	0.437

[1]Pond and Mumpton (1978).

[2]62% ground yellow corn, 19% cerelose, 21% soybean meal, 0.5% salt, 0.5% Hopro B vitamin supplement, 1.5% ground limestone, 2.5% dicalcium phosphate.

[3]Basal diet less 19% cerelose plus 10% clinoptilolite, -200 mesh, Castle Creek, Idaho.

[4]Basal diet plus 0.1% Aureofac 10 antibiotic. [5]Excluding zeolite.

35-65 kg growth period (Table 10). Feces of the zeolite-fed animals were also less liquid than those on a control diet. The addition of zeolites had little effect on the FEVs in the 65-100 kg growth range. These results support those of Heeney (1977) who

Table 10. Effect of zeolite supplement in molasses-based diets of young pigs[1]

	Zeolite level (%)				
	0	2.5	5	7.5	10
35-65 kg growth stage					
Daily gain (g)	621	684	700	704	659
Daily intake[2] (g)	2603	3113	3203	2970	3040
Daily feed intake[3] (g)	2603	3130	2940	2750	2740
Feed efficiency value (FEV)[4] (weight gain/feed intake)	0.241	0.224	0.238	0.256	0.241
65-100 kg growth stage					
Daily gain (g)[1]	541	562	526	562	535
Daily intake[2] (g)	[illegible]	[illegible]	4260	4330	4140
Daily feed intake[3] (g)	[illegible]	[illegible]	3750	4100	3730
Feed efficiency value (FEV)[4] (weight gain/feed intake)	0.152	[illegible]	0.140	0.137	0.143

[1]Castro and Elias (1973). [2]Including zeolite.
[3]Intake less zeolite. [4]Excluding zeolite.

supplemented normal corn-soy rations of 36 pigs with 2.5% and 5% clinoptilolite in a 120-day experiment (Table 11). He found little overall difference in the FEVs; however, for the first 30 days after weaning, FEVs of 0.455 and 0.424 were obtained for

Table 11. Effect of clinoptilolite supplement in the diet of swine[1]

	Control	2.5% Clinoptilolite	5% Clinoptilolite
Average initial weight (lb)	31.5	31.7	31.7
30-days			
Average weight (lb)	61.0	62.2	62.5
Average daily weight gain (lb)	1.09	1.12	1.17
Feed/pound of gain (lb)[2]	2.62	2.20	2.36
Feed efficiency value[3]	0.382	0.455	0.424
60-days			
Average weight (lb)	105.7	107.3	106.2
Average daily weight gain (lb)	1.59	1.61	1.52
Feed/pound of gain (lb)[2]	2.80	3.05	3.09
Feed efficiency value[3]	0.357	0.328	0.324
90-days			
Average weight (lb)	153.7	149.6	150.0
Average daily weight gain (lb)	1.72	1.51	1.57
Feed/pound of gain (lb)[2]	3.33	3.43	3.67
Feed efficiency value[3]	0.300	0.292	0.272
120-days			
Average weight (lb)	188.2	177.8	176.4
Average daily weight gain (lb)	1.56	1.28	1.27
Feed/pound of gain (lb)[2]	3.94	5.63	4.30
Feed efficiency value[3]	0.254	0.178	0.233
Overall			
Average daily weight gain (lb)	1.49	1.40	1.37
Feed/pound of gain (lb)[2]	3.42	3.45	3.34
Feed efficiency value[3]	0.292	0.290	0.299

[1]From Heeney (1977); 6 pigs in each treatment. Control diet = 76.9% ground corn, 20% soybean oil meal, 1.5% dicalcium phosphate, 0.5% $CaCO_3$, 0.5% salt, 0.1% trace mineral, 0.25% vitamin premix, 0.25% ASF250 antibiotic. Zeolite diets contained 2.5% and 5% replacement of corn.
[2]Excluding zeolite. [3]Weight gain/feed intake, excluding zeolite.

2.5 and 5.0% zeolite, respectively, compared with a value of 0.382 for the control animals, an increase of about 15% due to the presence of zeolites in the diet. Little improvement was noted between 30 and 120 days of the treatment. Pratley (1978) also found an 8% increase in FEV when 10% clinoptilolite was substituted into the diets of 165 young pigs during a 38-day trial immediately after weaning.

Ruminants

In an attempt to reduce the toxic effects of high NH_4^+ content of ruminal fluids when non-protein nitrogen (NPN) compounds, such as urea and diuret, are added to the diets of cattle, sheep, and goats, White and Ohlrogge (1974) introduced both natural and synthetic zeolites into the rumen of test animals. Ammonium ions formed by the enzyme decomposition of NPN were immediately ion exchanged into the zeolite structure and held there for several hours until released by the regenerative action of Na^+ entering the rumen in saliva during the after-feeding fermentation period. Both *in vivo* and *in vitro* data showed that up to 15% of the NH_4^+ in the rumen could be taken up by the zeolite. Thus, the gradual release of NH_4^+ allowed rumen microorganisms to synthesize cellular protein continuously for easy assimulation into the animals' digestive systems. The zeolite's ability to act as a reservoir for NH_4^+ "...permits the addition of supplemental nitrogen to the animal feed while protecting the animal against the production of toxic levels of ammonia" in the rumen (White and Ohlrogge, 1974).

Approximately 500 g of a synthetic zeolite was introduced into the 50-liter rumen of a cow; lesser amounts sufficed for sheep. The zeolite was added in the form of a foraminous bolus or as a finely divided powder with the normal rations, the latter method requiring periodic replenishment. Although natural chabazite and clinoptilolite were found to be effective in this application, synthetic F zeolite (Milton, 1961) appeared to work best of all. Synthetic F and W zeolites both have superior ion selectivities and total NH_4^+-exchange capacities. Considering the current non-availability of these products, however, and their probable high price when they became available, it is apparent that certain NH_4^+-selective natural zeolites, such as clinoptilolite

or phillipsite, may find definite application in ruminant feeding, especially if powdered zeolite can be mixed directly with the normal rations of the animals. The price would be only a few cents per kilogram.

In this same area, Kondo et al. (1969) found that clinoptilolite added to the feed of young calves improved their growth rate by stimulating appetite and decreased the incidence of diarrhea and soft feces. Five percent zeolite was added to the normal grass and hay diets of 10- and 184-day-old heifer calves over a 180-day period. The animals on the zeolite-supplemented diets gained approximately 20 more weight than those in control groups, and although the test calves consumed more feed, the feeding costs per kilogram of weight gained were significantly less than for control animals. No deleterous effects were noted, and the feces of the test animals contained slightly less water and fewer particles of undigested solids in the <5 mm size-range. The incidence of diarrhea and soft-feces was markedly less in zeolite-fed calves than in control animals (Table 12).

Table 12. Occurrence of diarrhea and soft-feces: young calves on diets supplemented with 5% clinoptilolite[1]

Time (days)	Incidence of diarrhea: Grass-fed + zeolite (2 calves)	Hay-fed + zeolite (2 calves)	Control group (6 calves)	Incidence of soft-feces: Grass-fed + zeolite (2 calves)	Hay-fed + zeolite (2 calves)	Control group (6 calves)
30	0	0	4	0	0	4
36-60	0	1	2	3	4	13
61-90	0	0	4	1	1	13
91-120	1	0	1	2	0	13
121-150	0	0	4	4	0	8
151-184	0	0	0	0	0	0
Total	1	1	13	16	5	51

[1]Data summarized from Kondo et al. (1969).

Watanabe et al. (1971) raised six young bullocks for 329 days on a diet containing 2% clinoptilolite, along with 72% digestible nutrients and 11% crude protein. Although little difference in the final weights of test and control animals was noted, test steers showed slightly larger body dimensions and reportedly dressed out to give slightly higher quality meat. These differences were reflected in the overall higher prices obtained for the test animals and a 20% greater profit. In addition, diarrhea

and other intestinal ailments were noticeably less prevalent in the animals on the zeolite diet, and the excrement from these animals was significantly less odoriferous, again testifying to the retentivity of clinoptilolite for ammonia. It is unfortunate that a much higher level of zeolite was not used in these experiments; earlier studies in the United States showed that as much as 40% clay could be added to animal rations without adverse effects (Ousterhout, 1970).

Sweeney et al. (1980) found increased protein digestion when 5% powdered clinoptilolite was added to a high-solubility protein diet of 18 Holstein steers and cows over an 118-day period; however, statistically significant increases in average daily weight gains were not noted. Dry matter intake was also increased when zeolite was added to the rations. According to Fukushima (1980), the addition of 2% zeolite to the rations of cows was effective in preventing diarrhea and in increasing milk production. These effects were apparently related to an increase in the albumin and a decrease in the urea-N content of the blood. Galyean et al. (1980) showed that the replacement of 1.25% of the normal rations of 48 steers by clinoptilolite (-50 mesh) resulted in a 12% increase in the feed efficiency values for the first 37 days and an overall 6% increase for the entire 148-day experiment. Test animals also gained an average of 5% more weight during this period. The greatest benefits, however, were achieved during the first 66 days of the study.

Excrement Treatment

In the United States, livestock production creates more than one billion metric tons of solid wastes and nearly 400,000,000 tons of liquid wastes each year (Laporte, 1975, p. 365). Accumulations of such magnitude pose serious problems to the health of man and beast alike and are the source of pollution of nearby streams and rivers. In addition, the large amount of undigested protein remaining in the excrement represents a valuable resource that for the most part is being wasted, due to our growing dependence on chemical fertilizers. The physical and chemical properties of many natural zeolites lend themselves to a wide variety of applications in the treatment of animal wastes, including (1) the reduction of malodor and associated pollution,

(2) the creation of healthier environments for confined livestock, (3) the control of the viscosity and nutrient retentivity of the manure, and (4) the purification of methane gas produced by anaerobic digestion of the excrement.

Malodor and Moisture Control

The semi-fluid droppings in large poultry houses commonly emit a stench that is discomforting to farm workers and to the chickens themselves. The noxious fumes of ammonia and hydrogen sulfide contribute to decreased resistance to respiratory diseases and result in smaller and less healthy birds (Ernst, 1968; Kling and Quarles, 1974). Torii (1974) reported that in many areas of Japan clinoptilolite is now mixed with the droppings directly or packed in boxes suspended from ceilings to remove ammonia and thereby improve the general atmosphere in chicken houses. The net result is reported to be an overall increase in egg production and healthier birds.

Koelliker et al. (1980) described a zeolite-packed air scrubber to improve poultry-house environments. By passing ammonia-laden air over a series of trays containing crushed clinoptilolite, 15-45% of the NH_3-N was removed even though the contact time was less than one second. There also appeared to be an associated reduction in odor intensity. The use of such a scrubber could improve the quality of the air in poultry houses without the loss of heat that accompanies normal ventilation. The ammonium-loaded zeolite could then be used as a valuable soil amendment on disposal.

Using clinoptilolite from Itava, Japan, Onagi (1965) noted that the water content, maggot population, and ammonia production were all minimized when chicken droppings were routinely mixed with 1/3 zeolite (Table 13). He found that similar results

Table 13. Effect of zeolite additions to chicken droppings[1]

Property	2:1	3:1	5:1	10:1	Control
Moisture content (%)	12.1	13.1	13.4	15.7	18.5
Maggot content (counts per unit area)	38	191	172	387	573
Ammonia generation (relative quantities)	115	170	245	590	450

[1]Onagi (1965). Clinoptilolite was spread on droppings of Leghorn chickens every third day for a 15-day period. The total amount of droppings is the same in all tests, including the control.

could be obtained if powdered zeolite was added directly to the rations of the birds, all without affecting the vitality or growth rate of the chickens (Onagi, 1966). Apparently, gaseous ammonia reacts with the hydrous zeolite to form ammonium ions which are selectively ion-exchanged and held in the zeolite structure. Onagi (1965) suggested from these experiments that the addition of zeolites to poultry wastes would substantially reduce labor costs associated with air-drying or the high energy costs of thermal treatment, while at the same time retain the valuable fertilizer components and meet ecological standards.

In swine raising, Kondo and Wagai (1968) found that the feces of pigs fed a diet containing 10% clinoptilolite were richer in all forms of nitrogen after drying than those from control groups (vide supra). As a result of this study and of other investigations, about 25 tons of clinoptilolite per month is spread on the floors of a Sapporo swine-raising facility to adsorb urine and other liquid wastes (Torii, 1974). The buildings are said to be dry, clean, and considerably less odoriferous. Nishimura (1973) reported that mordenite was used in treating liquid swine-wastes. Not only was 90% of the suspended solids removed, but significant reductions in the NH_4^+, B.O.D., and C.O.D. contents were also achieved, as shown in Table 14. In Akita Prefecture, Japan, a zeolitic mudstone is used to treat offensive odors and to reduce moisture content of swine excrement (Honda and Koizumi (1976). The dried manure is then sold as an inexpensive fertilizer for the cultivation of rice.

Table 14. Effect of zeolite treatment on liquid swine wastes[1]

	N (ppm)	COD (ppm)	BOD (ppm)	Transparency (%)
Original solution	554	1907	3600	0
Zeolite-treated effluent	19	24	21	24

[1]Nishimura (1973).

An innovative application of zeolites in excrement treatment was patented by Komakine (1974) and involves the addition of a natural zeolite and ferrous sulfate to chicken droppings. The ferrous sulfate inhibits zymosis and decomposition of the droppings, and the zeolite stabilizes the hygroscopic nature of this compound and captures NH_4^+ produced in the manure. The mixture is dried at 120°-150^oC and used as an odor-

less, organic fertilizer. It is also used as a protein-rich feedstuff for fish, fowl, and domestic animals. The zeolite-, ferrous sulfate-treated droppings contain 4.5% N, 4.5% P_2O_5, 2.4% K_2O, and 22% usable protein and have been successfully substituted for as much as 20% of the normal rations of swine, poultry, and edible carp.

Miner and Stroh (1976) found that the application of either clinoptilolite or erionite in granular form to a cattle feedlot in Idaho at rates of 0.5 lb/ft^2 (2.44 kg/m^2) resulted in a significant reduction in ammonia evolution and odor compared to untreated areas.

Methane Purification

Although it is well known that anaerobic digestion of animal excrement and other organic wastes produces an impure methane-gas product, this source of energy has generally been ignored for anything except local or in-house use (Jewell, 1974). One major drawback is the fact that in addition to methane, copious quantities of carbon dioxide and sulfur compounds are also produced during the digestion process, giving rise to low-BTU products that are extremely corrosive to pumps, valves, and other hardware needed in the operation. Nevertheless, the process is still an attractive one, and Goeppner and Hasselmann (1974) estimated that a billion cubic feet of 700 BTU/ft^3 methane gas could be produced by treating the 250,000 tons of manure produced each day in the United States. Jewell (1974) also suggested that the methane produced by the anaerobic digestion of the organic wastes of a typical New York State dairy farm of 60 head would be equivalent to the farm's entire fossil-fuel requirements.

A recent development by Reserve Synthetic Fuels, Inc., utilizing the adsorption properties of natural zeolites, suggests that such methane streams can be economically upgraded to high-BTU products. In 1975 this company opened a methane-recovery and purification plant to treat methane gas produced by decaying organic matter in the Palos Verde landfill near Los Angeles. As shown schematically in Figure 11, raw gas containing about 50% methane and 40% carbon dioxide is fed to 2 pretreatment vessels to remove moisture, hydrogen sulfide, and mercaptans. The dry gas is then routed through 3 parallel adsorption columns packed with pellets of dehydrated chabazite/

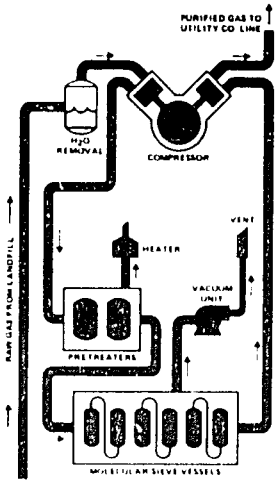


Figure 11. Methane-purification system. Palos Verde landfill.

erionite from a deposit near Bowie, Arizona, and carbon dioxide is removed by pressure-swing adsorption on the zeolite. Approximately one million cubic feet of methane meeting pipeline specifications is produced each day and delivered to local utility companies (NRG, 1975). Such a zeolite-adsorption process to upgrade impure methane streams produced by the digestion of animal manure appears to be technically feasible and awaits detailed economic and engineering evaluation.

AQUACULTURAL APPLICATIONS

In recent years, more and more fish products have found their way to the dinner tables and feeding troughs of every country, and the commercial breeding and raising of fish as a source of protein is becoming a major business in the United States and other countries. Many varieties of fish, however, are extremely sensitive to minor fluctuations in such factors as water temperature, pH, O_2, H_2S, and NH_4^+, and the chemical and biological environment of aquacultural systems must be maintained within close limits at all times. Processes based on the selective adsorption and ion-exchange properties of several natural zeolites for oxygen aeration of hatchery and transport water and for the removal of toxic nitrogen from tanks and breeding ponds may contribute significantly to increased production for human and animal consumption, as may the substitution of small percentages of relatively expensive fish food by ammonia-selective clinoptilolite.

Nitrogen Removal from Closed or Recirculating Systems

In closed or recirculating aquacultural systems, NH_4^+ produced by the decomposition of excrement and unused food is one of the leading causes of disease and mortality in fish. In oxygen-poor environments, even a few parts-per-million NH_4^+ can lead to gill damage, hyperplasia, and substantial reduction in growth rates

(Larmoyeux and Piper, 1973). Biological nitrification is a common means of removing NH_4^+ from culture waters; however, processes similar to those used in municipal sewage-treatment plants based on zeolite ion exchange have been found to be effective in controlling the nitrogen content of hatchery waters (Konikoff, 1973). Johnson and Sieburth (1974) proposed that zeolite ion exchange might be a useful backup or alternative to bio-filtration for NH_4^+-removal and have the advantages of low cost and high tolerance to changing temperatures and chemical conditions.

Unpublished tests conducted in 1973 at a working hatchery near Newport, Oregon, indicated that 97-99% of the NH_4^+ produced in a recirculating system was removed by clinoptilolite ion-exchange columns from waters containing 0.34-1.43 mg NH_3-N/liter (Kapranos, 1973). Peters and Bose (1975) substantiated these results and found that trout remained healthy during a 4-week trial when zeolite ion exchange was used to regulate the nitrogen content of tank waters. Becker Industries of Newport, Oregon, in conjunction with the U.S. Army Corps of Engineers, has developed a single-unit purification facility for hatchery-water reuse. The system incorporates a zeolite ion-exchange circuit for nitrogen removal and is designed to handle concentrations of 20-30 parts-per-million NH_3-N at flow rates of 10-15 Mgd, typical of the conditions encountered at most of the 200 fish hatcheries now operating in the Pacific Northwest (Kapranos, 1973). Piper (1975) also reported progress in the development of a nitrogen purification unit for trout and salmon hatcheries using clinoptilolite from a New Mexico deposit. Here, NH_4^+ is reduced from about 5 ppm to less than 0.1 ppm, at flow rates of 2.2-4.5 Mgd. The system is said to be economically superior to biofiltration and much more reliable in colder climates.

Jungle Laboratories of Comfort, Texas, has developed a similar ammonium-ion removal system using zeolite ion exchange for fish haulage applications, where brain damage due to excess NH_4^+ commonly results in sterility, stunted growth, and high mortality rates (Nichols, 1975). Throw-away cartridges and filters containing granular clinoptilolite will also be available for NH_4^+ removal from home aquaria. The U.S. Fish and Wildlife Service investigated zeolite ion-exchange processes for the treatment

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of recirculating waters in tank trucks used to transport channel catfish from Texas hatcheries to the Colorado River in Arizona (McCraren, 1975). Currently, about 2000 kg of 20-25-cm fish can be carried in 45,000 liters of water (about 0.04 kg/liter or 35 kg fish/m^3). If NH_4^+ can be removed, the number of fish hauled in such trucks can be nearly tripled. Slone et al. (1975) were able to achieve biomass concentrations of more than 0.112 kg/liter (35 kg/m^3) for catfish after 7 months in a vertical raceway using recycled water and a zeolite ion-exchange process to remove NH_4^+ after biofiltration. Ammoniacal nitrogen concentrations of less than 5 mf/liter were easily maintained.

Aeration Oxygen Production

As mentioned above, oxygen-enriched air can be produced by the selective adsorption of nitrogen by activated zeolites. A pressure-swing adsorption process (p.s.a.) capable of producing up to 500 m^3 of 90% oxygen per hour was developed in Japan (Tamura, 1970) for secondary steel smelting. Smaller generators with outputs of as little as 15 liters of 50% O_2 per hour are also manufactured by Koyo Development Company, Ltd. and used to aerate fish breeding tanks and in the transportation of live fish. Carp and goldfish raised in such environments are said to be livelier and to have greater appetites (Koyo Kaihatsu, 1974). It is obvious that in closed tanks and stagnant ponds, oxygen aeration could markedly increase the number of fish that could be raised per unit volume.

Oxygen, produced by small, portable p.s.a. units containing natural zeolite adsorbents, could be used to replenish free oxygen in small lakes where eutrophication endangers fish life. Fast et al. (1975) showed that the oxygen of hypolimnion zones could be increased markedly by aeration using liquid O_2 as a source. Haines (1976) demonstrated side-stream pumping as a means of improving the dissolved oxygen in the hypolimnion of a small lake in New York State and utilized about 32 kg liquid oxygen per day at a water flow-rate of 340 liters/min.

Fish Nutrition

The high-protein rations currently used in commercial fish raising are quite ex-

pensive, and their cost has been a limiting factor in the development of large-scale aquacultural operations. The physiology of fish and poultry is remarkably similar, and if the results achieved with chickens (*vide supra*) can be duplicated with fish, the substitution of small amounts of inexpensive zeolites (cost = a few pennies per pound) in normal fish food, with no adverse change in the growth rates and perhaps a small increase in feed efficiency, could result in considerable savings to the industry. The quality of the water in recirculating systems should also be improved by the use of zeolite-supplemented food, as should that of the effluents of once-through systems. In this area, Leonard (1979) reported the preliminary results of Anaconda Company's experiments wherein 2% clinoptilolite was added to the normal 48% protein food of 100 rainbow trout. After 64 days, a 10% improvement in the biomass increase was noted, compared with control experiments, with no apparent ill effects on the fish (Table 15).

Table 15. Effect of clinoptilolite additions to the diet of trout[1]

	Control 100% Normal feed[2]	Test 98% Normal feed 2% Clinoptilolite
Average starting weight (g)	10.2	10.1
Average 64-day weight	48.6	52.3
Average weight gain	38.4	42.2
Mortality	4	3

[1]100 rainbow trout. [2]Standard 48% protein fish food.

OCCURRENCE AND AVAILABILITY OF NATURAL ZEOLITES

Geological Occurrence

Since their discovery more than 200 years ago, natural zeolite minerals have been widely recognized by geologists as cavity and fracture fillings in almost every basaltic igneous rock (see Figure 12). Attractive crystals up to several centimeters in size adorn the mineral museums of every country; however, such traprock occurrences are generally too low-grade and heterogeneous for commercial extraction. The flat-lying and nearly monomineralic sedimentary deposits, on the other hand, are ideally suited for simple, inexpensive, open-pit mining. Most sedimentary zeolite deposits of economic significance were formed from fine-grained volcanic ash or other pyroclastic material which was carried by the wind from an erupting volcano and deposited onto the

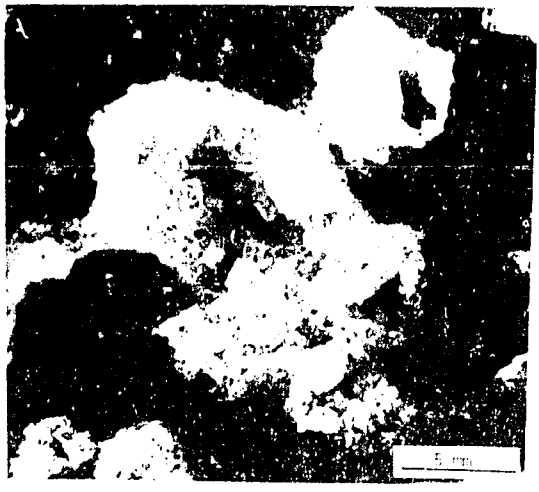

Figure 12. Typical specimen of an "igneous" zeolite occurrence. Zeolite crystals filling vugs and cavities in a basalt.

land surface, into shallow freshwater or saline lakes, or into the sea fairly close to the volcanic source. Much of the land-deposited material was quickly washed into lakes of the sea where it added to the air-borne material to form discrete layers or beds of nearly pure ash. Successive eruptions resulted in sequences of ash layers interstratified with normal lake or marine sediments, such as mudstones, siltstone, sandstones, and limestones, as well as beds of diatomite, bentonite, and chert (see Figures 13 and 14). In closed hydrologic basins, soluble salts are also present. The layers of volcanic ash (called volcanic tuff) vary in thickness from less than a centimeter to several hundred meters (Figure 15) and persist laterally for as much as 10 kilometers. Many of these bedded tuffs have been transformed almost completely into well-formed, micrometer-size zeolite minerals. Zeolitically altered tuffs occur in relatively young sedimentary rocks in diverse geological environments. Sedimentary zeolite deposits of this kind have been classified by Sheppard (1973), Mumpton (1973a), and Munson and Sheppard into the following types, although gradations between the types are the rule, rather than the exception:

1. Deposits formed from volcanic materials in hydrologically "closed" saline-alkaline lake systems;

2. Deposits formed in hydrologically "open" freshwater lake or ground water systems;

3. Deposits formed in marine environments;

4. Deposits formed by low-grade, burial metamorphism;

5. Deposits formed by hydrothermal or hot-spring activity in bedded sediments;

6. Deposits formed from volcanic materials in alkaline soils;

7. Deposits formed without direct evidence of volcanic precursors.

Figure 13. Clinoptilolite deposit, 1 m thick, near Buckhorn, New Mexico. Note several individual layers of altered tuff.

The most common zeolites in sedimentary deposits are analcime, chabazite, clinoptilolite, erionite, heulandite, laumontite, mordenite, phillipsite, and wairakite, with clinoptilolite ranking "number one" in abundance. Except for haulandite, laumontite, and wairakite, "sedimentary" zeolites are alkalic and are commonly more silicic than their igneous counterparts. Commercial interest is mainly in deposits of the first four type. Zeolitic tuffs in saline-lake deposits are generally a few centimeters to a few meters thick (see Figures 13 and 14) and commonly contain nearly monomineralic zones of the larger pore zeolites, erionite and chabazite (see Table 1), which are relatively uncommon in other types of deposits. "Open-system" deposits and

Figure 14. Clinoptilolite bed, 4 m thick, near Wellton, Arizona.

marine tuffs deposited close to their source are generally characterized by clinoptilolite and/or mordenite and may be several hundred meters thick. Zeolitic tuffs are commonly soft and lightweight, although some hard, siliceous deposits of clinoptilolite and mordenite are known. Many sedimentary zeolite beds contain as much as 95% of a single zeolite species, while others consist of two or more zeolites with minor amounts of calcite, quartz, feldspar, montmorillonite clay, and unreacted volcanic glass.

Most zeolites in sedimentary rocks crystallized from volcanic ash by reaction of the amorphous, aluminosilicate glass with pervading pore waters derived either from saline lakes or descending ground waters. Others originated from the alteration of pre-existing feldspars, feldspathoids, biogenic silica, or poorly crystalline clay minerals. Although the exact mechanism of formation is still under investigation, zeolites in sedimentary rocks probably crystallized as well-formed, micrometer-size crystals by means of a dissolution-reprecipitation mechanism, with or without an intermediate gel stage (see Mumpton, 1973b; Figures 16 and 17). The factors controlling whether a zeolite or a clay mineral formed or which of several zeolites formed from a given starting material are also only poorly understood, although temperature, pressure, reaction time, and the concentrations of the dissolved species, such as H^+, silica, alumina, and alkali and alkaline earth elements, seem to be paramount in importance. Early formed species

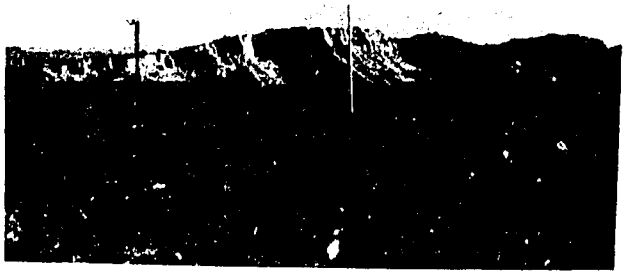

Figure 15. Mordenite/clinoptilolite deposit, 50 m thick, near Oaxaca, Mexico. Similar material used by Mayans about 2000 B.C.

also tend to react further with pore fluids of different composition, thereby yielding even more complex assemblages.

Figure 16. Scanning electron micrograph of chabazite rhombs from a saline-lake deposit tuff along Beaver Divide, central Wyoming (from Mumpton and Ormsby, 1976). The rhombs vary from about 1 micrometer to 10 micrometers in size.

Figure 17. Scanning electron micrograph of clinoptilolite laths with minor mordenite from a saline-lake deposit tuff near Hector, California (from Mumpton and Ormsby, 1976).

Geographic Distribution

The distribution of zeolite deposits in various geographic regions of the world is governed solely by the geology of those regions. Regions that have undergond past volcanic activity are likely to contain significant deposits of zeolite minerals. Although the zeolite phillipsite is known to have formed within the last 10,000 years in a small saline-lake deposit at Teels Marsh, Nevada (Friedom and Mariner, 1971) by the alteration of volcanic ash from the explosion of Mt. Mazuma (Crater Lake), and chabazite has been identified in deposits on the walls of ancient Roman baths in France, most potentially commercial deposits of zeolites are of Tertiary or lower Pleistocene age (70,000 to 3,000,000 years b.p.). Thus, any part of the earth that was subjected to volcanic activity during this period undoubtedly contains extensive deposits of volcanic ash, and if these ash deposits had an opportunity to react with percolating ground waters or alkaline pore waters from former saline lakes, beds of high-grade zeolites are apt to exist.

Table 7A. Reported Occurrences of Sedimentary Zeolites

Country	Zeolite Species	Mineable Deposit	Minor Occurrence	Chances for Finding Deposit
		EUROPE		
Belgium	Laumontite		I	Poor
Bulgaria	Clinoptilolite	III		Excellent
	Mordenite	I		Excellent
	Analcime		I	Poor
Czechoslovakia	Clinoptilolite	I		Good
Denmark	Clinoptilolite		I	Poor
Finland	Laumontite		I	Poor
France	Clinoptilolite		III	Good
Germany	Chabazite	II		Good
	Phillipsite	II		Good
	Analcime		II	Poor
Great Britain	Analcime		I	Poor
	Clinoptilolite		I	Poor
	Laumontite		I	Poor
Hungary	Clinoptilolite	II		Excellent
	Mordenite	I		Excellent
Italy	Chabazite	III		Excellent
	Phillipsite	III		Excellent
	Analcime		I	Good
Poland	Clinoptilolite	II		Excellent
Romania	Clinoptilolite	II		Excellent
Soviet Union	Clinoptilolite	III		Excellent
	Mordenite	II		Excellent
	Chabazite		I	Good
	Analcime		I	Good
	Laumontite		I	Good
Spain	Clinoptilolite		I	Good
	Mordenite		I	Good
Switzerland	Clinoptilolite		I	Poor
	Laumontite		II	Poor
Turkey	Clinoptilolite	II		Excellent
	Erionite		II	Excellent
	Chabazite		II	Excellent
	Analcime	I		Excellent
Yugoslavia	Clinoptilolite	III		Excellent
	Analcime	I		Good
	Mordenite	I		Excellent
	Erionite		I	Good
		AFRICA		
Angola	Clinoptilolite		I	Good
Botswana	Clinoptilolite		I	Good
Congo	Analcime	I		Good
Egypt	Heulandite		I	Good
Kenya	Phillipsite	I		Excellent
	Erionite	I		Excellent
Northwest Africa	Analcime	I		Good
	Mordenite		I	Good
	Clinoptilolite	I		Excellent
Republic of South Africa	Analcime		I	Poor
	Clinoptilolite	II		Excellent
Tanzania	Erionite	I		Excellent
	Chabazite	I		Excellent
	Phillipsite	I		Excellent
	Analcime	I		Excellent
	Clinoptilolite	I		Excellent
		ASIA		
Iran	Clinoptilolite	I		Excellent
Israel	Clinoptilolite		II	Excellent
Pakistan	Analcime		I	Good
Australia	Clinoptilolite	I		Good
	Analcime		I	Good
China	Clinoptilolite	II		Excellent
Formosa	Laumontite		I	Poor
	Analcime		I	Good
Japan	Clinoptilolite	III		Excellent
	Mordenite	III		Excellent
	Analcime		I	Poor
	Laumontite		I	Poor
	Natrolite		I	Poor
Korea	Clinoptilolite	II		Excellent
New Zealand	Analcime		I	Good
	Clinoptilolite	II		Good
	Mordenite	I		Excellent
	Laumontite	I		Good
	Erionite	I		Good
Oceania	Laumontite		I	Poor
		SOUTH AMERICA		
Argentina	Clinoptilolite	II		Excellent
	Analcime	I		Excellent
	Laumontite		I	Poor
Chile	Clinoptilolite		I	Excellent
		NORTH AMERICA		
Canada	Laumontite		I	Poor
	Clinoptilolite		I	Good
Cuba	Clinoptilolite	II		Excellent
	Mordenite	I		Excellent
Guatemala	Clinoptilolite	I		Excellent
Mexico	Clinoptilolite	II		Excellent
	Mordenite	II		Excellent
	Analcime		I	Good
	Erionite	I		Excellent
	Phillipsite		I	Excellent
Panama	Clinoptilolite	I		Excellent
West Indies	Natrolite		I	Poor
	Clinoptilolite		I	Excellent
		ANTARCTICA		
Antarctica	Laumontite		I	Poor
	Phillipsite		I	Poor

Although zeolites are now considered to be some of the most abundant and widespread authigenic silicate minerals in sedimentary rocks, their existence as major constituents of altered volcanic tuffs is still not common knowledge among the geologists of many countries. Because of their inherently fine crystal size, zeolites are not easily identified by ordinary microscopic techniques and have often been missed by geologists and mineralogists studying these formations. In general, zeolite identification requires sophisticated X-ray diffraction and electron microscopic equipment not available in many geological laboratories; however, once a particular soft, lightweight, clay-like rock from a particular area is identified in the laboratory as a zeolite rock, similar materials are rapidly located in the field by astute geologists.

Table 16 lists the countries where zeolites have been reported from sedimentary rocks of volcanic origin and estimates the chances of discovering additional deposits of these minerals in these countries. Sedimentary zeolites have been found on every continent, although few occurrences have been reported from the Middle East, Latin America, or the East Indies, mainly because geologists in these regions have been generally unaware of the widespread occurrence of zeolites in altered volcanic tuffs. Wherever zeolites have been found, however, man has used the soft, lightweight tuffs for hundreds of years as easily carved dimension stone in a variety of structures ranging from walls and foundations of buildings to barns and corrals to house livestock. Zeolitic blocks have been found in buildings associated with the Mayan pyramids at Monte Alban and Mitla in southern Mexico (Mumpton, 1973c) and are used today in the construction of modern dwellings in the Tokaj region of eastern Hungary. Although zeolites are currently mined in only a dozen countries (see Table 17), there is little doubt but what sedimentary zeolites will be found in every country where volcanic activity has played a major role during the Tertiary and Pleistocene epochs.

The high probability of finding mineable deposits of zeolites in countries where they have not yet been reported, but where there has been considerable

Table 17. Countries Currently Engaged in Zeolite Mining.

Country	Mineral	Mines	Remarks
United States	Clinoptilolite	12	Many more available
	Chabazite	4	Single deposit, four companies
	Erionite	2	
	Mordenite	1	
Mexico	Mordenite/Clinoptilolite	1	
Cuba	Clinoptilolite	1	
Japan	Clinoptilolite	8	Estimated
	Mordenite	5	Estimated
Korea	Clinoptilolite	2	
Bulgaria	Clinoptilolite	1	
Hungary	Clinoptilolite	1	
	Mordenite	1	Estimated
Soviet Union	Clinoptilolite	3	Estimated
	Mordenite	1	Estimated
Yugoslavia	Clinoptilolite	2	Several more available
South Africa	Clinoptilolite	1	
Italy	Chabazite/Phillipsite		Numerous, used for construction
Germany	Chabazite/Phillipsite		Several, used for construction

volcanic activity in the past, is illustrated by the discovery of major bodies of sedimentary zeolites in Mexico and in central Turkey in the early and late 1970s respectively. Both countries show promise of becoming major suppliers of mineral raw materials in the years to come, but, as with most developing nations, they have only limited in-house geological expertise to service their blossoming mineral industry. During the late 1950s and 1960s the geological similarity of the western United States and northern Mexico led geologists in this country to speculate about the existence of zeolite deposits south of the border. It was not until 1972, however, that this author (1973c) discovered the first such deposit in southern Oaxaca after visiting a large dimension stone quarry during a completely unrelated project. The rock was being used as a local dimension stone and closely resembled zeolitic tuffs in Japan that were being quarried for similar purposes. Subsequently the Oaxacan rock was shown to consist of about 90% clinoptilolite and mordenite, although the

mineralogical composition was unknown to local workers or to Mexican geologists. Shortly thereafter, several similar deposits were discovered in this part of Mexico by the author and Mexican colleagues who quickly learned to recognize zeolitic tuffs in the field. One such deposit was spotted in a road cut while driving past it at 50 miles per hour, suggesting that many more await discovery with only minimal exploration efforts. As a result of these discoveries, at least three other deposits of sedimentary zeolites have been found in the northern part of the country by Mexican geologists who are now atune to the existence of zeolites in volcanogenic environments and to their potential applications in industrial and agricultural technology (e.g., Rios Garcia and Badilla Cruz, 1978).

Similar to Mexico, major parts of the central Anatolian region of Turkey are covered by thick sequences of Tertiary volcanic rocks, but, with the exception of a few minor occurrences of analcime in saline-lake environments, reports of zeolites in the volcanogenic sedimentary rocks of this country have been rare. The principal reason for this is simply a lack of searching for zeolites in these environments combined with a lack of knowledge about the potential applications of such materials in industry. Turkey's few geologists have been more occupied with the chrome and borate resources to that country which are exported in large quantities to acquire badly needed currency. In 1977, however, several low-grade occurrences of erionite and chabazite were uncovered in Turkey's Cappadocia region, along with a major deposit of clinoptilolite in the vicinity (Ataman, 1978). In 1979 a second major deposit of this mineral was discovered by the author (Mumpton, 1979) and R.A. Sheppard of the U.S. Geological Survey, accompanied by a Turkish geologist, with a minimum of field effort, indicative to what must be a widespread distribution of such materials in volcanogenic sedimentary rocks of this country.

Mining and Milling

The mining of zeolites in bedded sedimentary deposits is a relatively straight forward process requiring only a minimum of equipment and trained personnel. Almost

all of the known zeolite deposits currently being mined are surface deposits overlain by a few to no more than 25 meters of overburden. The zeolite beds are usually flat-lying and vary only slightly in thickness along the length of the deposit. Shallow drilling is usually required to outline the areas of highest grade, but many deposits are mined by simple projection of the bed behind the outcrop. Commonly, the exposed bed can be broken in the mine by bulldozers or rippers; in places small amounts of blasting are required. In thinner deposits, care must be taken to eliminate overlying and underlying clays and volcanic ash from the ore to preserve purity, but in some of the thicker deposits this poses no problem.

Processing to the raw ore is dependent upon the envisioned end use; water-purification applications require a fine-sand fraction which must be prepared from the ore by crushing and screening whereas fertilizer and animal nutrition uses will likely make use of finely powdered material. In general, preparation steps involve only crushing, screening, and bagging. Where particle size is critical, the screened product must be washed to remove undersize material and then dried. More sophisticated applications may require that the zeolite be ion-exchanged to an ammonium or potassium form before being shipped to the consumer. In such cases, the pulverized and screened product must be subjected to a series of washes with chloride or sulfate salts of these elements, washed with water to eliminate excess salts, filtered, dried, and bagged. Crushed ore can be produced currently in the United States for about $30–40/ton, f.o.b. minesite.

DISCUSSION

Agronomic Applications

Although zeolites have been used for many years in Japan as soil amendments, they are only now becoming the subject of serious investigation in the United States as slow-release fertilizers, moisture-control additives to low-clay soils, traps for heavy metals, carriers of pesticides, fungicides, and herbicides, and deodorizing agents in fertilizer storage. As soil amendments they appear to retain moisture and to improve the overall ion-exchange capacity of sandy and volcanic soils. Studies are being carried out on both the zeolite as received and on zeolite that has been pretreated with nutritive elements, such as potassium or ammonium. In either case, the zeolite appears to act as a slow-release fertilizer, selectively holding such elements in its structure for longer periods of time, thereby increasing the efficiency of such additives and reducing the total cost of fertilization. Although the data available are not completely unequivocal, the greatest success appears to have been achieved with root crops, such as sugar beets, carrots, and radishes, where nitrogen is a vital nutrient. The optimum level of application, however, must still be determined for various types of soils and for the particular crop in question, as must the frequency and exact mode of application, the optimum particle size of the zeolite, and the nature of chemical pretreatment of the zeolite.

The ion-exchange specificity of certain zeolites for copper, lead, cadmium, and zinc suggests that the "life" of farm and forest soils amended with municipal and industrial sewage sludge can be extended by inhibiting the plant uptake of these deleterious metals for longer periods. Radioactive cesium and strontium from nuclear fallout or spills may also be controlled by selective ion exchange into zeolites added to soils. Zeolites apparently are useful carriers of herbicides,

pesticides, and fungicides and can prevent caking in stored fertilizers by absorbing excess moisture.

Table 18 lists organizations who have or are currently conducting experiments on the use of natural zeolites in agronomic applications

Table 18. Organizations Engaged in Zeolite/Agronomic Investigations.

Organization	Crop	Organization	Crop
Department of Horticulture Colorado State University Fort Collins, Colorado	Radishes	Agricultural Experiment Station New Mexico State University Las Crucas, New Mexico	Corn Sorghum
Department of Agronomy Colorado State University Fort Collins, Colorado	Sorghum Corn Wheat	Department of Plant Science University of New Hampshire Durham, New Hampshire	Radishes Corn
Department of Environmental Horticulture University of California Davis, California	Chrysanthe-mums	Texas Agricultural Experiment Station Texas A&M University Beaumont, Texas	Rice
U.S. Sugarcane Field Laboratory U.S. Department of Agriculture Houma, Louisiana	Sugarcane	Departmentof Soils, Water, and Engineering University of Arizona Tucson, Arizona	Nitrogen retention in soils

Animal Nutrition Applications

Despite the lack of statistical significance for many of the data, numerous studies strongly suggest that the addition of certain zeolite minerals to the die of swine, poultry, and ruminants results in decided improvement in the growth rate of the animals and in the feed efficiency (weight gain/pounds of nutritional feed consumed). In addition, the incidence of intestinal disease among young animals appears to be less when zeolites are part of the daily diet. The most dramatic results have been reported by overseas workers where experiments may have been conducted under conditions that were somewhat less sanitary than those generally

employed in the United States. Zeolite-supplemented diets appear to be most beneficial in swine during the first 30-60 days after weaning, although there is some evidence to suggest that zeolites in the rations of pregnant sows contribute to increased litter weights and healthier offspring. In Japan, 2-5% clinoptilolite in the diets of cattle appeared to result in larger animals and fewer incidences of diarrhea. One study in the United States found a 12% increase in feed efficiency for cattle during the first 37 days using only 1.25% zeolite.

The exact function of the zeolites in both dietary and antibiotic phenomena are not well understood and await serious physiological and biochemical investigation. The ammonium selectivity of clinoptilolite suggests that in ruminants it acts as a reservoir for ammonium ions produced by the breakdown of vegetable protein and non-protein nitrogen in rations, releasing it for a more efficient synthesis into amino acids, proteins, and other nitrogeneous compounds by microorganisms in the gastrointestinal lumen. From the concentration of ammonia in the portal blood of weanling rats fed a 5% clinoptilolite diet or dosed orally with this zeolite, Pond et al. (1980) postulated that the zeolite bound free ammonia in the GI tract, thereby preventing its buildup to toxic levels in the system. Such an antibiotic effect could indeed be responsible for the larger growths recorded for zeolite-fed animals.

Table 19 lists organizations who have or are currently conducting experiments on the use of natural zeolites in animal nutrition applications.

Excrement-Treatment Applications

Although the results are difficult to quantify, almost all studies of the use of zeolites as dietary supplements in animal rations have reported a noticeable decrease in excrement malodor and have attributed this observation to the high selectivity of the zeolite in the feces for the ammonium ion. Similar results were noted when zeolites were added directly to cattle feedlots, suggesting that not

Table 19. Organizations Engaged in Animal Nutrition Studies Using Zeolites

Organization	Animal	Organization	Animal
Department of Poultry Science Colorado State University Fort Collins, Colorado	Chickens	Department of Animal Science Cornell University Ithaca, New York	Swine
Department of Animal Science Colorado State University Fort Collins, Colorado	Swine	Department of Animal Science Oregon State University Corvallis, Oregon	Swine Rabbits
Clayton Livestock Research Center New Mexico State University Clayton, New Mexico	Beef Cattle	Western Washington Research & Extension Center Washington State University Puyallup, Washington	Dairy Cattle
Department of Poultry Science Oregon State University Corvallis, Oregon	Chickens	Department of Animal Science University of Kentucky Lexington, Kentucky	Calves
Livestock Nutrition Service Westminster, California	Cattle	Food & Animal Research, Inc. Juneau, Wisconsin	Calves
Department of Animal Science University of Vermont Burlington, Vermont	Ruminants	Department of Biology Cleveland State University Cleveland, Ohio	Chickens Swine
U.S. Meat Animal Research Center U.S. Department of Agriculture Clay Center, Nebraska	Pats (swine)	Department of Agricultural Engineering Oregon State University Corvallis, Oregon	Odor control
Department of Animal Science Pennsylvania State University University Park, Pennsylvania	Cattle		

only can healthier and less odoriferous environments be achieved by the addition of zeolites to animal manure, but that the nitrogen-retention ability of the manure can be improved as well.

Zeolite purification of low-BTU methane produced by the anaerobic fermentation of excrement and other agricultural waste products may be a means of producing cheap energy on individual farms or in small communities, and zeolite ion-exchange processes may be employed in the removal of ammonium ions from recirculating or

closed aquacultural systems, thereby allowing more fish to be raised or transported in the same volume of water. Aquacultural research of this type has been or is currently being conducted by Becker Industries, Newport, Oregon; the U.S Fish & Wildlife Service, Fich Cultural Development Center, Bozeman, Montana; Jungle Laboratories, Comfort, Texas; the Department of Fisheries and Wildlife, New Mexico State University, Las Crucas, New Mexico; the Narragansett Marine Laboratory, University of Rhode Island, Kingston, Rhode Island; and the Department of Zoology, Southern Illinois University, Carbondale, Illinois.

CONCLUSIONS AND RECOMMENDATIONS

Although they have been used locally for several years in Japan and in other parts of the Far East in small amounts, the utilization of zeolites as soil amendments, fertilizer supplements, additives to animal rations, and in the treatment of agricultural wastes is still in the experimental stage in the United States. Agricultural organizations who have or are currently investigating such uses for natural zeolites in this country are listed in Tables 18 and 19. The projects have generally been sponsored by grants or contracts from companies who themselves are developing applications for zeolites in one or more areas of technology, or they have been funded by the institutions themselves and make use of zeolite products provided free or at low cost by the companies. Table 20 summarizes the agricultural research efforts of companies who hold properties of natural zeolites. In addition, other, non-property holding organizations, such as International Minerals & Chemical Corporation, Cargill, Inc., and Lowe's, Inc., have also been involved in the development of uses of natural zeolites in agriculture.

Overseas, 6-8 agricultural stations in Japan continue to investigate natural zeolites as soil amendments and dietary supplements; Pratley Perlite Mining Company, who owns a large clinoptilolite deposit in South Africa, has made several studies of the use of zeolites in the rations of swine and poultry; and a recent Bulgarian-Soviet

Table 20. Zeolite Property Holders and Zeoagricultural Research Efforts

Organization	Zeolite Species[1]	Research Effort
Anaconda Company	Clinoptilolite, Erionite, Chabazite/Erionite, *Clinoptilolite*, *Chabazite*, *Mordenite*, *Phillipsite*	In-house; Sponsored
Colorado Lien Company	Clinoptilolite	Sponsored
Double Eagle Petroleum & Mining Company	Clinoptilolite, *Clinoptilolite*	Sponsored
Forminco	*Clinoptilolite*	None
Harris & Western Corp.	*Clinoptilolite/Mordenite*	None
Ladd Mountain Mining Co.	*Erionite/Clinoptilolite*	None
Leonard Resources	*Clinoptilolite*	Sponsored
Letcher Associates	*Clinoptilolite*	None
Minerals Research	*Phillipsite*	None
Minobras, Inc.	*Erionite*	None
Mobil Oil Corporation	Erionite	None
Monolith Portland Cement Company	Clinoptilolite	None
NL Industries	Clinoptilolite	None
Norton Company	Chabazite/Erionite, *Ferrierite*	None
NRG Corporation	Chabazite/Erionite	None
Occidental Minerals Corp.	Clinoptilolite, *Clinoptilolite*, *Erionite*	In-house; Sponsored
Rocky Mountain Energy Company	Clinoptilolite	Sponsored
Union Carbide Corporation	Chabazite/Erionite, Mordenite, Erionite	In-house; Sponsored
U.S. Energy Corporation	*Clinoptilolite*	None
W. R. Grace & Company	Chabazite/Erionite, *Ferrierite*	None

[1] Roman type = working mines; italics = prospects.

symposium[2] on natural zeolites contained seven papers on animal-nutrition applications and two on soil-amendment uses. Similar projects are in progress in Cuba and Hungary, where deposits of clinoptilolite and mordenite are abundant. The intense interest in

[2] Second Bulgarian-Soviet Symposium on Natural Zeolites, Kardzhali, Bulgaria, October 11-14, 1979.

the several socialistic countries mentioned above undoubtedly stems from their efforts to utilize their own natural resources and thereby reduce their dependency on foreign sources of expensive fertilizers and animal rations. These same objectives, of course, are desired by each developing nation - maximum use of local raw materials and minimal use of imported products that must be purchased with hard currency. Where they can be found within a particular nation or where they can be obtained from neighboring countries at a minimum of cost, natural zeolites have the potential to increase the agricultural productivity of that nation by reducing the need for or increasing the efficiency of chemical fertilizers and animal feedstuffs.

To convert the agricultural *promise* of natural zeolites into commercial reality, a concerted effort must be made in the United States and elsewhere by both the private sector and by state and federal funding organizations. The studies to date have been mainly of a preliminary nature - radishes have been grown instead of potatoes, and rats have been raised instead of beef cattle - or of limited duration or extent, with little information being developed to illuminate the long-term benefits or adverse impacts on food production. Many of the companies sponsoring this research have considered the results proprietary, and rightfully so; but workers in the field are therefore unable to obtain the latest information, a situation that often results in massive duplication of effort. Large scale testing of zeolites under sustained field conditions is greatly needed at this juncture as are projects involving statistically significant numbers of animals. Such projects will require continuous funding by state and federal agencies, or perhaps, international agencies if the results are to be applied directly to developing nations. It would be extremely instructive to carry out such testing in several developing nations themselves, where agricultural practices are not as finely tuned as in the United States, thereby allowing the zeolites to display their full bag of tricks.

The actual introduction of natural zeolites into specific agricultural processes should pose no major problems. Crushed and sized material could be added to the fields directly or banded into the soil either alone or with normal fertilizers using stan-

dard equipment. Likewise, the zeolite could be mixed as a powder or fine granules with normal feedstuffs provided for livestock, or be inserted as a bolus into the stomachs of ruminants. It could also be sprinkled on or mixed with manure accumulations on a daily basis for nutrient retentivity. None of these processes would require special machinery; in fact, all could be carried out by hand, if such were the common practice in that country. Users would, of course,need to be instructed as to the correct amount to apply to fields or to mix with normal rations, and the optimum time to apply it for specific crops, and considerable educational efforts may be necessary to convince the small farmer of the benefits of zeolite additives. In this regard, zeolites are no different than any innovative procedure that many farmers are wont to accept.

Because the use of zeolites in agricultural processes has not yet reached the proven or commercial stage, any scenario developed to introduce this promising technology into developing nations would involve contributions from both the United States and the developing nations. The contribution of the United States would be both geological and agricultural expertise in zeolite technology, whereas the contribution of the developing nations would be a willingness to search for deposits of zeolites if none have been reported thus far and a willingness to carry out some necessary long-term or large scale testing under field conditions. It is therefore recommended that any implementation plan begin with a series of visits by a team of zeolite experts from the United States to selected developing nations in different parts of the world where zeolites are known or have a high probability of occurring. In addition to a leader who would have a broad background in zeolite technology, the team would consist of 4-8 geologists, agronomists, animal nutritionists, and agricultural engineers who are not only experienced in the use of zeolites in agriculture or in the occurrence of zeolites in volcanogenic sedimentary formations, but who can incite an enthusiasm in others for the wonderful things that zeolites can do.

The team would include (1) a geologist who is not only knowledgeable about the occurrence of zeolites in such environments, but who is capable of working with local

resource people to find and evaluate potential deposits of zeolites in these countries; (2) an agronomist or plant scientist with considerable experience in the use of zeolites to improve crop productivity; (3) an animal nutritionist with the necessary expertise in the use of zeolites as dietary supplements in animal nutrition; and (4) an agricultural engineer who has worked with zeolites in excrement treatment to improve the health of confined livestock or the ammonium retentivity of animal wastes. The agricultural engineer would also provide practical experience to the team which otherwise might be missing in a group of esoteric scientists alone. Prior to the first visit to a developing nation, the team would arm itself with the latest information in the field by visiting the leading experiment stations and research laboratories in this country and abroad where zeoagricultural investigations are being carried out. Special emphasis would be placed on the recent work in Japan and in countries of eastern Europe.

Each visit would be for a ten-day period, wherein the first two days would be spent in the company of local geologists and/or agronomists examining the general terraine of the country and gaining a brief impression of the geology and the agricultural conditions. A third day would be devoted to a series of talks by each of the team members on his speciality before an audience of local geologists, agriculturalists, government officials, labor union leaders, and bureaucrats and anyone else who would be interested in finding out about this new technology. During the next several days the team would split into small groups for individual consultations *in the field* with local technical people responsible for the implementation of the technology. The geologists would, perhaps, visit suspected areas of zeolite formations, whereas the agronomist could inspect potential sites for study, providing samples of zeolite for initial investigation. The last day of each visit would be devoted to round table discussions by local agricultural experts, geologists, and team members to determine what had been accomplished and the next steps to take.

It is vital that the introduction of zeo-agriculture into a developing nation not end with the visit of a team of U.S. experts. On the contrary, the initial visit

should be followed up as soon as possible with specific plans for implementing the technology into the nation's agricultural processes. Although the implementation scenaria of all innovative technologies would appear to be similar from this point on, the zeolite scenario would involve a search for these materials in the developing nation if such materials had not already been reported from that country. Such exploration would probably be carried out by the local geological survey or mining agency, but should be assisted in the field by a geologist familiar with the occurrence of zeolites in such environments. If zeolites are known from the country or if they can be obtained from neighboring regions without difficulty, plans should be made with the country's agricultural people to field test the technology under optimum conditions. Such plans and tests should also be made with the assistance of agronomists or animal scientists already familiar with the use of zeolites in these processes.

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PAPER NO. 11. UNDEREXPLOITED PLANT AND ANIMAL RESOURCES FOR DEVELOPING COUNTRY AGRICULTURE

(By Dr. Noel Vietmeyer, Board on Science and Technology for International Development, National Academy of Sciences)

The 1940s was the decade of wonder chemicals. The miraculous properties of DDT, sulfa drugs, herbicides, nylon and plastics blinded us to the potentials of nature. Laboratories were limitless, nature seemed limited. Man-made was modern, nature seemed passé. Subsequent decades seemed to confirm the euphoric view; we gave up seeking our new product needs in the kingdom of nature, the previous wellspring for civilization's advances.

As a result, as we move toward the 21st century, we rely on fewer and fewer plants and animals. We ignore, or have forgotten, thousands of useful species that could broaden and balance our fount of resources. All this, in face of the recognition that within a few short decades the petrochemical explosion that began in the 1940s will be snuffed out.

However, there is now a big change occuring in the scientific community. Researchers are returning to nature's storehouse to take stock of its genetic possibilities; to scrutinize species that could make useful new crops and domestic animals--some of them are species that are wild and

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untested, some even poorly identified. Though they work largely out of the public eye, these dedicated researchers are quietly germinating ideas and laying roots that will grow with and shape our future. Some natural products now virtually unknown are likely to become mainstays of world agriculture.

Decision makers, entrepreneurs and the general public should pay more attention to these researchers' results. A groundswell of support for the development of new species could lead to a cornucopia of new foods fuels and industrial feedstocks. It may help extend productive agriculture to vast regions that today are not arable. It may help raise from despair the ever increasing numbers of humans in developing countries who waste their lives away in malnourished poverty. It may show how to cultivate crops that produce raw materials that now come from petroleum. It's a challenge. But some of the future's best resources are out there waiting in the land of nature.

Plants

Botanists and ethnobotanists can reel off long lists of obscure plants that seem to warrant recognition. Respondents to recent questionnaires sent out by the National Academy of Sciences named over 2,000 plant species that deserve much greater recognition. Almost none have been given agronomic attention. A few striking examples are given below.

Poor People's Plants

A friend recently told me that he had discussed the winged bean with an influential Filipino family. "They were incredulous that such a miraculous plant could exist," he said. "So, on a hunch, I took them out back to the

servents' quarters. There, climbing along a fence, was a winged bean plant laden with pods."

"'But that's just seguidillas,' they said, disappointment echoing in their voices. 'It's only a poor man's crop!'"

It is a universal phenomenon that certain plants are stigmatized by their humble associations. Scores of highly promising crop plants around the world receive no research funding, no recognition from the agricultural community; they are ostracized as "poor man's crops."

For information on a poor people's crop one has to turn, more often than not, to botanists and anthropologists; only they will have taken an interest in the plant. Often there has been no agricultural research on it at all--no varieties collected or compared, no germination or spacing trials, no yield determinations or even nutritional analyses. And yet the crop actually may be crucial to the lifestyle--even the survival--of millions of people.

Just 50 years ago, the soybean itself was a poor people's crop. In the United States, it was spurned by researchers for more than a century after Benjamin Franklin first introduced seeds from the Jardin des Plantes in Paris. To be a soybean advocate then was to risk being considered a crackpot. Early in this century, Americans still considered the soybean a second-rate crop fit only for export to "poor people" in the Far East. But then, in the 1920s, University of Illinois researchers established a comprehensive soybean research program that helped sweep aside this discrimination. The soybean acquired new status as a "legitimate" research target, and its development gained so much momentum that it is now the

world's premier protein crop.

Nowhere is the neglect of poor people's crops greater than in the tropics--the very area where food is most desperately needed. The wealth and variety of tropical plant species is staggering. Some of the Third World's best crops are waiting in the poor people's gardens, virtually ignored by science. Merely to have survived as useful crops, suggests that the plants are inherently superior. Moreover, they are already suited to the poor person's small plots and mixed farming, as well as to poor soils, and the diet and way of life of the family or village. Examples are the winged bean and amaranths.

Winged Bean

Perhaps no other crop offers such a variety of foods as the winged bean.* Yet it, remains a little-known, poor person's crop, used extensively only in New Guinea and Southeast Asia.

A bushy pillar of greenery with viny shoots, blue or purple flowers, and heart-shaped leaves, the winged bean resembles a runner-bean plant. It forms succulent green pods, as long as a man's forearm in some varieties. The pods, oblong in cross-section, are green, purple, or red and have four flanges or "wings" along the edges. When picked young, the green pods are a chewy and slightly sweet vegetable. Raw or boiled briefly, they make a crisp and snappy delicacy. Pods are produced over several months and a crop can be collected every two days, providing a continuous supply of fresh green vegetables.

If left on the vine the pods harden, but the pea-like seeds inside swell and ripen. When mature, the seeds are brown, black, or mottled. In composition they are essentially identical to soybeans, containing 34 to 42 percent protein and 17 to 20 percent of a polyunsaturated oil. The protein is high in the nutritionally critical amino acid lysine.

In addition to the pods and seeds, the winged bean's leaves and shoots make good spinach-like potherbs. Its flowers, when cooked, are a delicacy with a texture and taste reminiscent of mushrooms.

But perhaps the most startling feature of the plant is that, below ground, it produces fleshy, edible tuberous roots. These are firm, fiberless, ivory-white inside and have a delicious and delicate nutty flavor. The winged bean is therefore something like a combination of soybean and potato plants. And winged bean tubers are uniquely rich in protein--some contain more than 4 times the protein of potato.

Amaranths

Amaranths--major grain crops in the tropical highlands of the Americas at the time of the Spanish Conquest. They were staples of both Aztec and Inca. But the Conquistadores banned the cultivation of amaranths because the grain was a vital part of native religion and culture. With this political move the Spanish struck a blow for their church but they also crushed the crop. For 500 years little has been done to study or promote it.

Amaranths belong to a small group of plants, termed C_4, whose photosynthesis is exceptionally efficient. The sunlight they capture is utilized more effectively than in most plants and amaranthes grow fast. Vigorous and

tough, amaranths have been termed self-reliant plants that require very little of a gardener. They germinate and grow well under adverse conditions. They are easily cultivated and adapt well to the rural farmer's small plots and mixed cropping. Furthermore, they are relatively easy to harvest by hand and to cook.

Amaranths are annuals which reach 6 ft. in height and have large leaves tinged with magenta. They are cereal-like plants producing full, fat, seed heads, reminiscent of sorghum. The seeds are small but occur in prodigious quantities. Their carbohydrate content is comparable to that of the true cereals, but in protein and fat amaranths are superior to the cereals.

When heated, amaranth grains burst and taste like popcorn. In many regions, however, the grains are more often parched and milled. Amaranths flour is high in gluten and has excellent baking qualities, bread made from it rises and has a delicate nutty flavor.

Recently W.J.S. Downton, an Australian researcher, has found that the grain of at least one amaranth (Amaranthus caudatus var. edulis) is rich in protein and exceptionally rich in lysine, one of the critical amino acids usually dificient in plant protein. Indeed, the amount of lysine exceeds that found in milk or in the high-lysine corn now under development.

Conclusion

It is very hard to get grants for research on poor person's plants. Funding agencies resist; the plants are unknown to most of them, and the literature to support any claims may be sparse.

Nonetheless, it is now time for agricultural research facilities throughout the world to incorporate poor person's crops into their research efforts. Third World agricultural development needs this balance, for only when his own crops are improved will the poor man be able to feed his family adequately. In future decades it may be--as in the case of the soybeen--that today's poor person's plants will be feeding the world.

TREE LEGUMES: Shock Troops for the War on Deforestation

Man has deforested one-third of South America's native forests, one half of Africa's and two-thirds of Southeast Asia's. It is critically urgent that the remaining forest cover be protected from indiscriminate harvest and that many now-deforested regions be reforested. A "thin green line" of fast-growing leguminous trees may be either our last line of defense or our first line of attack.

To most people legumes are limited to the dining table, but to plant scientists legumes include not only vegetables but shrubs, vines and thousands of tree species, most of them indigenous to the tropics. Actually, the family Leguminosae is the third largest in the plant kingdom. But out of the 18,000 different species of legumes, farmers extensively cultivate only about 20 species including peas, beans, soybeans, peanuts, clover, alfalfa, and even licorice. Foresters cultivate almost none.

The potential of tree legumes as useful plantation species remains largely unrecognized, yet they offer a particularly promising area for exploration in these days of devastating deforestation. Indeed, they seem to have special attributes that could put them in the front lines of the battle to reclothe the scarred hillsides throughout the tropics.

Legumes, for example, are nature's pioneers in plant succession. They are among the first plants to colonize bare land. It therefore seems ecologically wise for man to deliberately exploit them for the same purpose: to quickly revegetate eroding or weed-smothered terrain, to halt erosion, and to provide protective ground cover under which slow-growing, climax-forest species can regenerate. Furthermore, many wood requirements might be met by these quick-growing small trees; and this could help spare the last remnants of the natural forests.

Many woody legumes have a hardy, irrepressible character, suited to a wide range of soils, climates, altitudes and environments. Like other pioneer species, they have a precocious nature and grow quickly in an attempt to overtop and preempt the space of their plant competitors.

Because of this innate compttitiveness, many tree legumes are easy to establish and cultivate. Some can be direct-seeded (avoiding the expense of nurseries and of transplanting fragile seedlings), and in some tests even spraying their seed out of aircraft has proven a suitable way to establish plantations. Many occur naturally in dense, pure stands, suggesting that they probably can be grown in monoculture without being decimated by pests.

A most important feature of many legume species is that nodules on their roots contain bacteria, which chemically convert nitrogen gas from the air into soluble compounds that the plant can absorb and utilize. Thus, for average growth these species require little or no additional nitrogenous fertilizer. Some produce such a surfeit of nitrogen--largely in the form of protein in their foliage--that they make excellent forage crops and the soil around them becomes nitrogen rich through the decay of fallen foliage.

In order to give an idea of the potential of this class of trees, three species of fast-growing legumes are mentioned below. Not one of these trees is widely exploited so far.

Leucaena

In the 1960's, University of Hawaii professor James Brewbaker found in the hinterland of Mexico certain varieties of Leucaena leucocephala that grow into tall trees. This was unexpected because the plant was previously known only as a weedy bush.

But in tropical climates Brewbaker's varieties have grown so tall and fast that they can be twice the height of a man in just six months; as high as a three-story building in two years; and as tall as a six-story building with a trunk cross-section as large as a frying pan in only six or eight years.

In the Philippines one hectare of these tall leucaenas has annually produced over 10 times the amount of wood per acre that a well managed pine plantation produces in the United States. Even among the world's champion fast-growing trees, this is exceptional.

Leucaena wood is thin barked and light colored. For such a fast growing species, it is remarkably dense (comparable to oak, ash, or birch), strong, and attractive. Its fiber is acceptable for paper-making and the wood can be pulped satisfactorily and in high yield.

But leucaena, a multipurpose plant par excellence, also has other uses. It can supply forage, for example, and researchers in Hawaii and

tropical Australia have found that cattle feeding on leucaena foliage may show weight gains comparable to those of cattle feeding on the best pastures anywhere. Also leucaena wood makes excellent firewood and charcoal. The plant is also a living fertilizer its factory for if its nitrogen-rich foliage is harvested and placed around nearby crops plants they can respond with yield increased approaching those effected by commercial fertilizer.

Although arborial leucaena varieties have been cultivated for only a decade or so, they are already being planted over tens of thousands of hectares in the Philippines. The World Bank has funded one large program. Batangas Province has a nursery producing 10,000 leucaena seedlings daily. The province's dynamic governor, Antonio E. Leviste, has decreed that other nurseries be set up throughout his province: in churchyards, cemeteries, schoolgrounds, roadsides--any idle ground. No government employee gets a paycheck until he has set up a leucaena plantation with at least 20 trees to produce seed. The consequent greening of Batangas has made citizens keenly appreciative of deforestation's ugliness and problems, as well as reforestation's rewards. Tree planting now interests the Batangas public intensely--not entirely for the sake of revegetating eroding watersheds, but for the income and benefits from exploiting leucaena forage, fuelwood, and "green manure." That the program has been adopted with gusto by the citizenry demonstrates the relevance of tree legumes to tropical problems as a sort of "appropriate forestry."

In more remote southern islands of the Philippines, leucaena (Filipinos call it ipil-ipil) is being planted over huge areas of former green-deserts, wastelands lost to coarse, sharp-edged "cutting-graces." With its vigor

and persistence, leucaena--if given a little care can overtop the grasses, shading them out of existence, and converting waste ground to highly productive forest. It is essentially a permanent forest because after felling, the stump of a leucaena tree regrows with such vigor that the plant is said to literally "defy the woodcutter."

Calliandra calothyrsus

In 1936 horticulturists transported seed of this small Central American tree to Indonesia. They were interested in it as an ornamental, for like other Calliandra species, it has flowers that are gorgeous crimson powder-puffs, glowing in the sunlight like red fireballs. But Indonesians instead took up Calliandra calothyrus as a firewood crop. Indeed, for 25 years steadily expanding fuelwood plantations of it have been established until they now cover over 75,000 acres in Java.

This small tree--barely taller than a bush--grows with almost incredible speed. After just one year it can be harvested. The cut stump resprouts readily giving new stems that can be 10 feet tall within six months. Some trees in Indonesia that are 15 years old have been harvested 15 times!

Calliandra wood is too small for lumber, but it is dense, burns well, and is ideally sized for domestic cooking. It is also useful for kilns making bricks, tiles, or lime and for fueling copra and tobacco dryers.

Indonesian villagers now cultivate Calliandra calothyrus widely on their own land, often intercropping it with food crops. The plant's value is dramatically exemplified by the village of Toyomarto in East Java. There,

land that was once grossly denuded and erosion-pocked is now covered with callindra forest and is fertile once more. Today the villagers actually earn more from selling calliandra firewood than from their food crops.

Conclusion

These are brief descriptions of only two species of small leguminous trees that have recently proven useful in combating deforestation in Southeast Asia. There are many other exciting species. In South Korea, foresters intercrop bushy Lespedeza species to provide firewood during the early years of the establishment of pine and other forests. In Central America, there are Enterolobium cyclocarpum and Schizolobium parahyba, in South America, Mimosa scabrella (M. bracatinga), Schizolobium amazonicum, Tipuana tipu, and Clitoria racemosa; and in the Pacific Islands, Albizia minahassae and Archidendron oblongum. In Africa, several fast-growing Albizia (A. adianthifolia, and A. zygia, for example) are indigenous, and two legume trees introduced from India, Acrocarpus fraxinifolius and Dalbergia sissoo, have shown exceptional growth rates on appropriate sites. In Asia there are also Acacia auriculiformis and Sesbonia grandiflora.

In foresters' terms many of these species have "poor form". Their trunks may be too narrow or too crocked for construction timber or veneer. But, these are species for "peoples' forestry". Their role is for:

- Farms, backyards, pasture lands, roadsides, canal banks and fencelines;

- Village woodlots and energy plantations to fuel kilns, electricity generators, cooking stoves, and crop dryers;
- Agrisilviculture (agroforestry), because they provide a wealth of products including forage, green manure, and food;
- Use in shifting cultivation, because the natural drop of protein-rich leaves pods and twigs contributes nitrogen organic matter and minerals to upper soil layers and can markedly speed up the rebuilding of warn out soils;
- Quick-rotation cash crops, both for the private landowner and the government forest department; and
- Utility purposes such as beautification, shade, and shelter belts.

ANIMALS

When early farmers discovered that animals could be tamed and managed, they eagerly experimented with many of the species surrounding them. In Asia and the Americas, the silkworm, yak, camel, water buffalo, llama, alpaca and guinea pig were selected. Egyptian tomb paintings at Saqqara painted in 2500 BC show addax, ibex, oryx and gazelle wearing collars and obviously domesticated. Ancient Egyptians apparently domesticated hyenas and baboons, as well.

But then the process essentially stopped. Today's farmers raise the same animals their Neolithic forebears were familiar with more than 10,000 years ago. (One exception is the rabbit, which French monks tamed between

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the 6th and 10th centuries because the Church considered newborn rabbits to be fish and they could be eaten when the Church calendar demanded abstinence from meat.) Although the world's menagerie contains some 4,000 species of mammals alone, only a mere six domestic animals produce virtually all of the world's meat and milk.

As agricultural man spread himself about the globe, he dragged with him this handful of species. He carried them beyond their natural boundaries, forced them upon strange and often fragile environments--usually driving out the native species that previously predominated there, and often drastically changed the environments to accommodate them.

Very little meat is eaten in developing countries and because most of them are in the tropics, it is not possible to change that much with cattle, sheep and pigs that have an evolutionary adaptation to the temperate environments from which they originated and are limited in their ability to adapt to new ones. But the world's fauna is a rich genetic bank that may be tapped to increase world food production. Some of the potential species are unexpected ones, as highlighted below.

Toads, Snails and Guinea Pigs

In rural areas of developing countries, it is important to produce small animals. They fit better into village life and if they can be eaten at one meal, then the lack of refrigeration is no hindrance. In Chile, there's a shiny, olive green toad (Calyptocephalella caudiverbera). It is a giant toad that can weigh three pounds or more. Its meat tastes like a cross

between lobster and chicken. It grows to be a foot long or more and lacks the toxic skin glands and warty appearance of other toads. Because of its superb and enigmatic taste, the wild toad has long been a delicacy of Chilean gourmets. But now, researchers at the La Serena campus of the University of Chile are learning how to farm them.

In 1975, the University's Institute of Food Technology started farms large enough to porduce 100,000 of the choice toads every two years. The intensive methods they developed have made it feasible to supply 10 to 15 tons of scallop-sized toad legs each year to grocery stores, restaurants and canneries.

The institute also has dug production ponds out of otherwise useless swampland. The eggs, larvae, tadpoles and adults are all kept apart because the voracious toads have no hesitations about cannibalism. Normally, however, they feed on small fish, crabs, crawfish and aquatic plants. The ponds are surrounded with flowers and shrubs to attract insects and boxes of rotten fruit are placed nearby to draw fruit flies to the area. With their long sticky tongues, the toads eagerly capture the insects. Other than this, the toads reportedly are given little attention and in 2 years they reach market size: about 7 inches long and weighing ½ lb.

Researchers are ecstatic over the ease and cheapness of toad farming, and they are looking toward the lucrative international frog meat market to export the tender, white drumsticks of these unique Chilean toads.

The Chilean toad is an example of a potentially valuable new resource for developing countries. In Nigeria, the Institute of Oil Palm Research is developing another one: the giant African Land snail (Achatina species).

This snail grows rapidly and may weigh up to half a pound. It is eaten widely in West Africa and is immensely popular in parts of Nigeria and Ghana. The meat has as much protein as beef, but it has considerably more of the important amino acids, lysine and arginine, than even eggs contain. The Institute has found the snails suitable for "farming" in shaded enclosures under the trees in rubber, cocoa or oil-palm plantations. With proper proportions of males and females, it has produced as much as 150 lbs of snail meat in the small enclosures each year.

In Peru scientists are looking to their indigenous fauna, too. One of Peru's serious and permanent problems is a lack of beef. Two-thirds of the steaks of which Peruvians are so fond, are imported despite the nation's chronic dollar shortage. The situation became so serious that five years ago the military junta put a ban on beef consumption 15 days in every month. Chicken production was once believed to be the answer to the problem, but although it has grown fast, so has the population. Big hopes were placed on fish too, but the country lacks the financial resources to install the facilities needed for national marketing. The guinea pig is now believed to be the best answer so far to the problem posed by the short supply of proteins of animal origin.

Guinea pig is a traditional staple. Although domesticated in the time of the Inca, it has not previously attracted much research attention. Yet guinea pig is widely consumed in Peru. The nutritional value of it's meat compares favorably with that of other meats. The animals can be raised in urban areas and in villages, where larger animals are scarce or impossible to keep. The fast growth, and rapid reproduction, makes the guinea pig

a sensible resource in the Peruvian environment. Added to this is the fact that guinea pigs can live off vegetation that is of inadequate nutritive value for feeding other livestock.

These resources are strange--even repugnant--to the majority of specialists working to increase food production and improve human nutrition in developing countries. But to the local inhabitants they are traditional foods that are much sought and enjoyed.

Crocodiles

In Africa, South and Southeast Asia, Australia and South America, the populations of crocodiles, alligators and caimans are fast headed for extinction. In Papua New Guinea in the 1960s, the two native crocodile species were headed the same way. But not today. In the last five years, a remarkably innovative project in this, one of the newest and most underdeveloped nations, has caused a dramatic turnaround in the crocodile's drastic decline there. Though the P.N.G. story has not been told widely, it is one with immense implications for the survival of crocodilians elsewhere. It is also a demonstration of how resources can be managed to conserve a species, to minimize impact on a fragile environment, and to provide wealth in remote villages in a developing country.

The P.N.G. program is based on an appreciation for crocodile biology. Each year, a female may lay between 30 and 70 eggs, but though most of them hatch, predators so relish the tender and remarkably vulnerable young hatchlings that almost none survived the 15 years needed to reach breeding size. In nature, then, there can at any time be found a plethora of tiny crocodiles, but a paucity of breeders. Commercial hunting worsens the imbalance because

hunters always seek the biggest specimens, irregardless of the resulting damage to the breeding populations.

Recognizing that a ban on hunting would be largely unenforceable in remote areas (and grossly unpopular where man-eaters sometimes occur), the P.N.G. Government decided in 1970 to restructure the trade so that shooting breeders would lose its attraction and the profit would come from exploiting the hordes of tiny hatchlings that would result. This was done through a law banning the sale of large skins, supplemented by a stiff tariff on small skins.

Today, villagers in the steamy swamps of P.N.G. have tens of thousands of tiny crocodiles in their care. They raise them for a year or two and can sell them for up to $100, each. Crocodile farming has already become the main cash earner for the people there. I personally met a village leader in Wewak who had come to oversee shipment of $14,000 worth of skins headed to New York by airfreight.

The P.N.G. crocodile project is characterized by:

Good Science. Despite popular "man-eater" impression, crocodiles live mainly on fish, though the researchers in P.N.G. have found that young ones also grow well on frogs, snails and beetles. The feeding efficiency is astounding: 1½ lbs of food gives 1 lb of weight gain, and foot-long animals can grow to be 5 and six feet long in less than 2 years. (Conventional domestic livestock require 5 to 8 lbs of food to produce 1 lb of weight gain.) Crocodile farming is also space efficient: dozens of animals are raised in an area the size of a household living room ; in a swamp or jungle, that's important.

Good Conservation. Because the program is based on harvesting young hatchlings from the wild, the economic value of the wild populations and their habitats becomes forcefully apparent. The program's future depends on them. It gives economic value to wildlife protection. Out of pure self-interest, the people become guardians and conservers of habitats and wildlife. In a sense, the farming project is just a tool for conserving the species in its own wild habitat.

Good Sociology. The villagers have a sophisticated knowledge of the crocodile; the animal is part of their culture and heritage. They don't have to be taught how or where to catch crocodiles, and they take quickly to the program. Introducing cattle or Western-style crop-raising would require massive and tedious education and training.

Good Environmental Management. The program is based on living with the existing landscape and resources. It requires none of the bush-clearing fencing, forage-grass planting or pesticide spraying that rearing other domestic animals would demand. That's important in a fragile tropical rainforest ecosystem.

Good Economic Development. What other agricultural product could give a $14,000 income in a remote jungle village?

Butterflies

In remote jungle towns in the north of Papua New Guinea are operating butterfly farms; some of the most unusual farms in the world.

Around the edge of a field are planted flowering shrubs to attract the adult butterflies whose mouthparts are adapted for drinking nectar from

flowers. These butterfly "forages" include hibiscus, flame-of-the-forest and the strange, pipe-like aristolochia. Within half-acre circlets of these flowers are planted leafy plants that the caterpillars feed on. The combination provides a complete habitat where butterflies find everything they need for their life cycle. Thus few leave, and the farmer retains his livestock without fencing or walls.

Butterflies may seem exotic livestock to us, but even in the remotest P.N.G. jungle, a villager knows and understands their habits, location and lifestyle. And butterflies don't require bank loans, veterinary services, artificial insemination or the other impedimenta of the conventional livestock. Also, when farming insects, the villager can work when and if he wants to: there are no deadlines. No hard labor and no danger, either. To a Papua New Guinean, the strange thing is that people are willing to pay for a butterfly.

And pay well they do. Ounce for ounce, exotic butterflies are far more valuable than cattle. And worldwide demand for butterflies is rising. Millions are caught each year and sold to museums, entomologists, private collectors, and perhaps most of all, to ordinary citizens. The fragile, iridescent creatures, mounted in plastic, decorate purses, trays, tabletops, screens and other ornamental objects.

With their butterfly farms many rural Papua New Guineans are for the first time participating in a cash economy and butterflies are beginning to improve the welfare of many villages. At Bulolo, the government has established an insect-buying agency to help the butterfly farmers of Papua New Guinea. It purchases insects from farmers and fills specific orders requested by overseas buyers. Profits go to the villager.

Perhaps the most striking feature of the program is that it is actually conserving, and even increasing, the numbers of butterflies. Basically, it is an exciting, pioneering conservation project because it develops a tremendous economic incentive to preserve populations and habitats--the program relies on healthy wild populations to keep the farms stocked.

Because of this, conservation organizations are becoming excited by the program, seeing in it a model that could be duplicated to help save endangered exotic butterflies everywhere.

FUEL

The fuels paradise of recent decades has blinded us to the possibilities of alternative energies, especially those for powering vehicles. The internal combustion engine, however, remains the most immediately practical prime mover for motor transport. Finding alternative energy sources for it poses one of the most severe problems facing the world. The world is not so much running out of energy as it is running out of liquid and gaseous fuels. Living plants that produce liquid fuels would indeed be boons for the future. Farmers would become energy producers. Today this is already a distantly glimpsed possibility. Two examples are given below.

The Gasoline Plant

Near Irvine in southern California can be found a field of what is perhaps the most revolutionary and little-explored development in modern

agriculture. The crop is Euphorbia lathyris and this field is the first attempt at cultivating this wild cactus-like shrub. It is the brainchild of Melvin Calvin, professor of chemistry at the University of California at Berkeley. Euphorbia lathyris and related species produce a milky latex, one-third of which is composed of hydrocarbons--compounds similar to those found in crude petroleum oil. Although there are as yet few hard facts on which to base firm projections, Calvin estimates that the plants might be capable of each year producing 10-50 barrels of oil per acre.

The hydrocarbon in Euphorbia lathyris and similar species is principally polyisoprene, the same molecule that makes up rubber in the rubber tree. But in Euphorbia, it is liquid rather than solid. This is because it is a smaller molecule, but Calvin points out that its hydrocarbon molecules are similar in size to those found in crude oil. He thinks that Euphorbia type hydrocarbons might even be processed into fuels and petrochemicals in existing oil refineries.

One of the world's most distinguished scientists, Calvin received the 1961 Nobel Prize for Chemistry in recognition of his achievements in unravelling the chemical processes of photosynthesis. Growing petroleum plants is a new venture for him, but already, he projects that the United States' vast petroleum demands could be met by plantations covering an area the size of the state of Arizona. He calculates the costs of harvesting petroleum from trees to be competitive with current oil prices: a total of between $5 and $15 per barrel for growing and processing the plants.

A plantation of such plants should be economic in dry lands unsuitable for growing food. Though little is known of their requirements or yields, Euphorbia species are hardy and need little or no irrigation and care.

Calvin foresees that the plants will be mowed near the ground and the harvested plants crushed to release latex in much the same fashion as is done with sugar cane. The stumps quickly resprout new stems so that replanting would be unneccessary.

This is truly a pioneering concept, and the field near Irvine is the first small step in evaluating its practicality. Already, larger plantations are planned. The University of Arizona has a million-dollar grant from the Diamond Shamrock Corporation to develop Euphorbia lathyris into a crop; the Government of Kenya is investing (perhaps unwisely) $10 million in plantations of it. If such projects are successful, this obscure wild plant will enable the world's desert countries to have oil fields on top of the ground.

Diesel Fuel You Grow on the Farm

Ohio State University in Columbus, Ohio transports students around its spread-out campus using a fleet of buses. Nothing unusual in that. But, this year OSU is using soybean oil as fuel.

Over the past decade various student projects at the OSU engineering school have shown that vegetable oils can be used as fuel for diesel engines. For a full year the university has run a large, 60-passenger bus partly on soybean oil. The experiment proved so successful that in September the whole university fleet was switched to the new fuel.

The soybean oil is collected from deep-fat fryers in cafeterias and kitchens across the University, filtered through muslin cloth by the engineering students to remove gunk and solids, and blended into diesel fuel. A ratio of 1 part soybean oil to 4 parts diesel was settled on as

it gave a stable mixture, lowest fuel consumption, and actually smoked less than diesel fuel alone.

The first bus maintained its normal 40 hour a week schedule. After 4,500 miles on the soy -diesel blend the engine was taken apart and inspected. Little or no abnormal wear had occurred. The engine was actually in such fine shape that it was merely reassembled and returned to service without further attention.

Although it is little-known to the general populace that diesel engines can be run on vegetable oils, this knowledge is not new. In the 1890s, Rudolf Diesel concluded that any material that was injectable and would ignite at the temperatures generated by compressing air could serve as fuel for his engine.

During World War II this knowledge was put to use. When Japan was cut off from petroleum supplies, the 65,000 ton Yamoto, the largest and most powerful battleship of its time, used edible, refined soybean oil as bunker fuel. Japanese forces occupying the Philippines and Allied troops trapped in northern Burma used coconut oil for fueling diesel trucks and generators.

Since then, that experience has been largely forgotten. But in the U.S., South Africa, Australia, Brazil, Canada, Thailand, Japan and perhaps elsewhere, individual researchers are rediscovering that diesel tractors, buses and stationary engines can operate when fueled with sunflower, soybean , peanut, rapeseed and other vegetable oils.

The experiences are usually solitary and most involve only very short running times. The practical potential of vegetable oils as commercial

diesel fuel substitutes is therefore uncertain. But, at least in short runs, they work.

Of all the research laboratories testing diesel engines fueled by vegetable oils, the South African government's Division of Agricultural Engineering has the most experience. At its laboratory near Johannesburg it is running 10 tractors on sunflower oil. Fiat, International Harvester, John Deere, Landini, Massey Ferguson and Ford tractors are being used. With two exceptions the tractors started satisfactorily on undiluted sunflower oil. All operated normally, delivered almost full power, and had virtually the same fuel consumption as on diesel fuel. A Ford 7000 tractor has run trouble-free for almost 1,400 hours of operation on a farm using a blend of 20 percent sunflower oil and 80 percent diesel fuel. At the end of this time it was found that deposits in the combustion chamber, cylinders and piston ring grooves were no worse than those formed burning normal operation on diesel fuel. On the other hand carbon deposits on the injector nozzles were worse and contributed to an eventual 4 percent power loss and serious gumming of the crankcase oil.

The rapid compression of fuel and air in the cylinder of diesel engines generates enough heat to ignite the mixture and power the engine. Unlike a gasoline engine, no spark is needed. Injecting the fuel into the combustion chamber is the most crucial step in a diesel engine. The fuel must be forced in against the pressure of the compressed air and to make this doubly difficult, the fuel has to be in the form of mist. If not atomized, the fuel burns slowly and unevenly, reducing engine efficiency, raising unburned pollutants in the exhaust and the lubricating system, and even

forming deposits of solid carbon in the engine itself.

Vegetable oils are more viscous and less easily atomized than diesel fuel and are therefore more difficult to inject successfully. This is probably why the injector tips suffered build-ups of carbon. Coking and the resulting incomplete combustion diluted the lubricating oil and gummed it up because vegetable oils will pdymerize when they are hot and next to metal.

The South African engineers, however, have found a way that now seems to avoid all difficulties. They slightly modify the sunflower oil in chemical reactions using small amounts of ethanol or methanol. The resulting ethyl or methyl esters derived from sunflower oil caused much less coking than diesel fuel itself. Furthermore, they produced much less exhaust smoke, and the engine ran much quieter so that the characterstic diesel knock was much less audible. And, against all expectations, the engine gave more power with the new fuel than with diesel fuel. Thus tractors were running on a renewable fuel grown by farmers, and achieving better results than on diesel fuel. Much yet remains to be done to test the widespread applicability of these results, but it is a line of research that is bright with promise.

CONCLUSION

Development specialists usually promote resources and technologies that are familiar to them in their own lives. Most agronomists, foresters, animal scientists and nutritionists know little about the wealth of plants and animal s to be found in the developing world. They all but ignore the

significance poor people's crops, leguminous trees, and animal resources such as snails, guinea pigs and butterflies. Instead they recommend and sponsor the introduction of species that are foreign and unconnected to the lives of those they want to help.

This paper identifies just a few exciting underexploited resources for developing country agriculture. Detailed information on them and many others can be found in the following National Academy of Sciences reports (all of which are available without charge from the Commission on International Relations, JH 215, National Academy of Sciences, 2101 Constitution Avenue, N.W., Washington, D.C. 20418):

The Winged Bean: A High Protein Crop for the Tropics

Leucaena: Promising Forage and Tree Crop for the Tropics

Underexploited Tropical Plants with Promising Economic Value

Tropical Legumes: Resources for the Future

Guayule: An Alternative Source of Natural Rubber

Making Aquatic Weeds Useful: Some Prespectives for Developing Countries

Firewood Crops: Bush and Tree Species for Energy Production