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AGROTECHNOLOGIES BASED ON SYMBIOTIC SYSTEMS THAT FIX NITROGEN

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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 fixation (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.

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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

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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.

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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 ensure that inoculant strains: remain viable untile 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 (41,33). 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 use of 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 billion 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 feasible 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

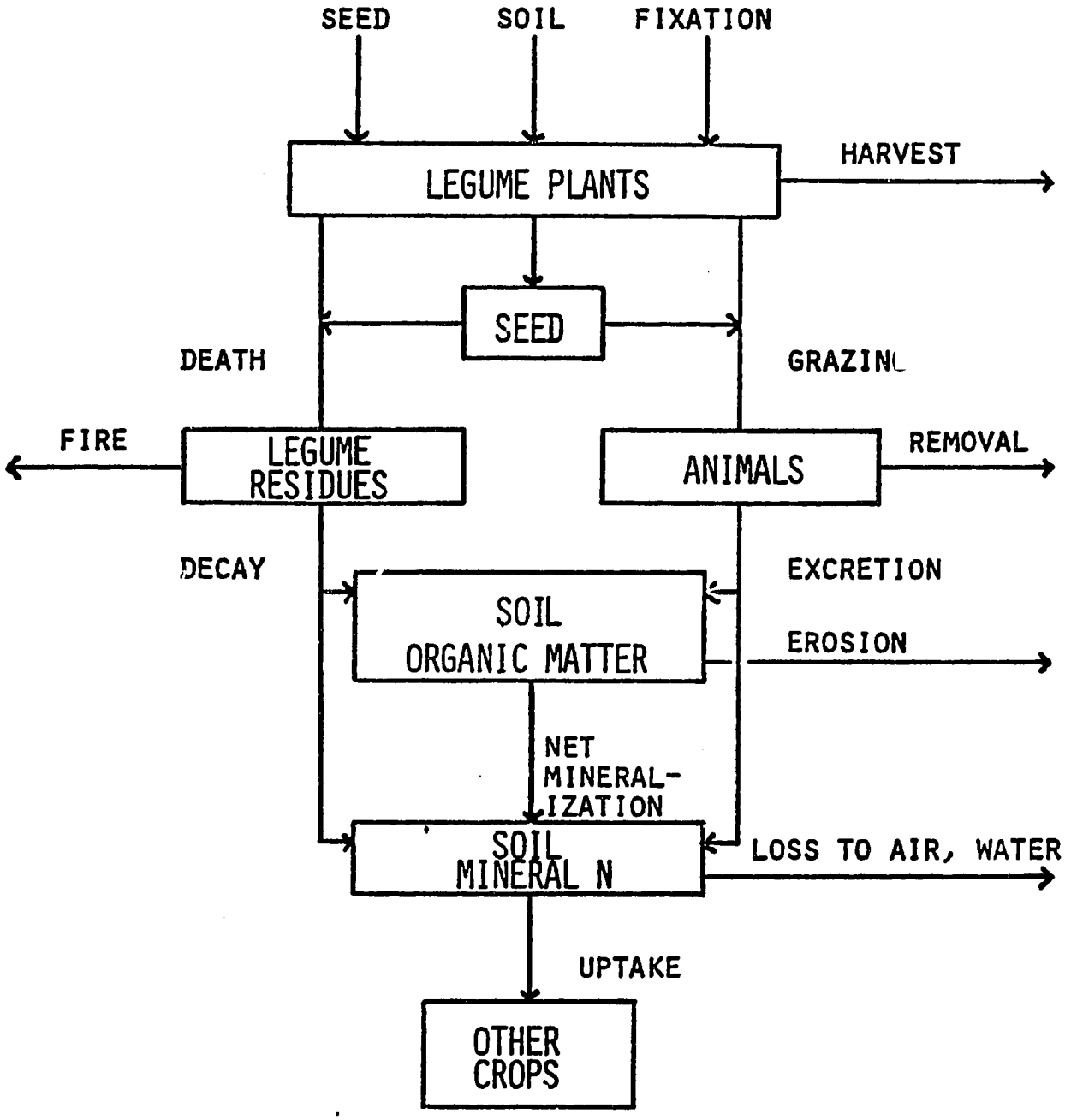
to legume growers. Demands for inoculation technology are increasing, associated mainly with the increased use of soybeans. There are dangers in trying to satisfy this demand by importation of inoculants developed in the U.S. or elsewhere. This is because inoculation technology as presently practiced 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 (consultancy 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 211-(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 us 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 (43) and in acid rainfall, 1.5 - 3.5 kg (44) are small compared to the nitrogen accumulated from the soil fixed biologically. About 50% of the nitrogen accumulated in legumes in fertile soils is attributed 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 50 - 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 leucaena and other forage legumes with a twelve-month growing season. Low levels are typically those of notoriously bad 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 'fog 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 comprehensive 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.

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 inoculant, 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.

Impacts of wide-scale implementation of BNF technology

The use of legumes to benefit other non-leguminous crops implies mixtures or rotations of crops. The production systems are therefore labor intensive and, in the case of mixed crops, not readily mechanized. Since this is already the circumstance of most production in developing countries no impact is likely. If BNF technology were to be employed in the U.S., for example, this would necessitate a swing away from the highly-mechanized monocrop systems currently employed and a major demand for farm labor.

Inoculant technology is scale-neutral but the use of legumes as green manures or in multiple crops and rotations is not. Such practices are more suited to small farms than large farms.

Inoculant technology does not increase nor displace appreciably the demand for labor. The intentional use of legume residues for the benefit of non-leguminous crops will create demand for laborers, since the technology involves extra cultivation steps that are not easily mechanized.

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