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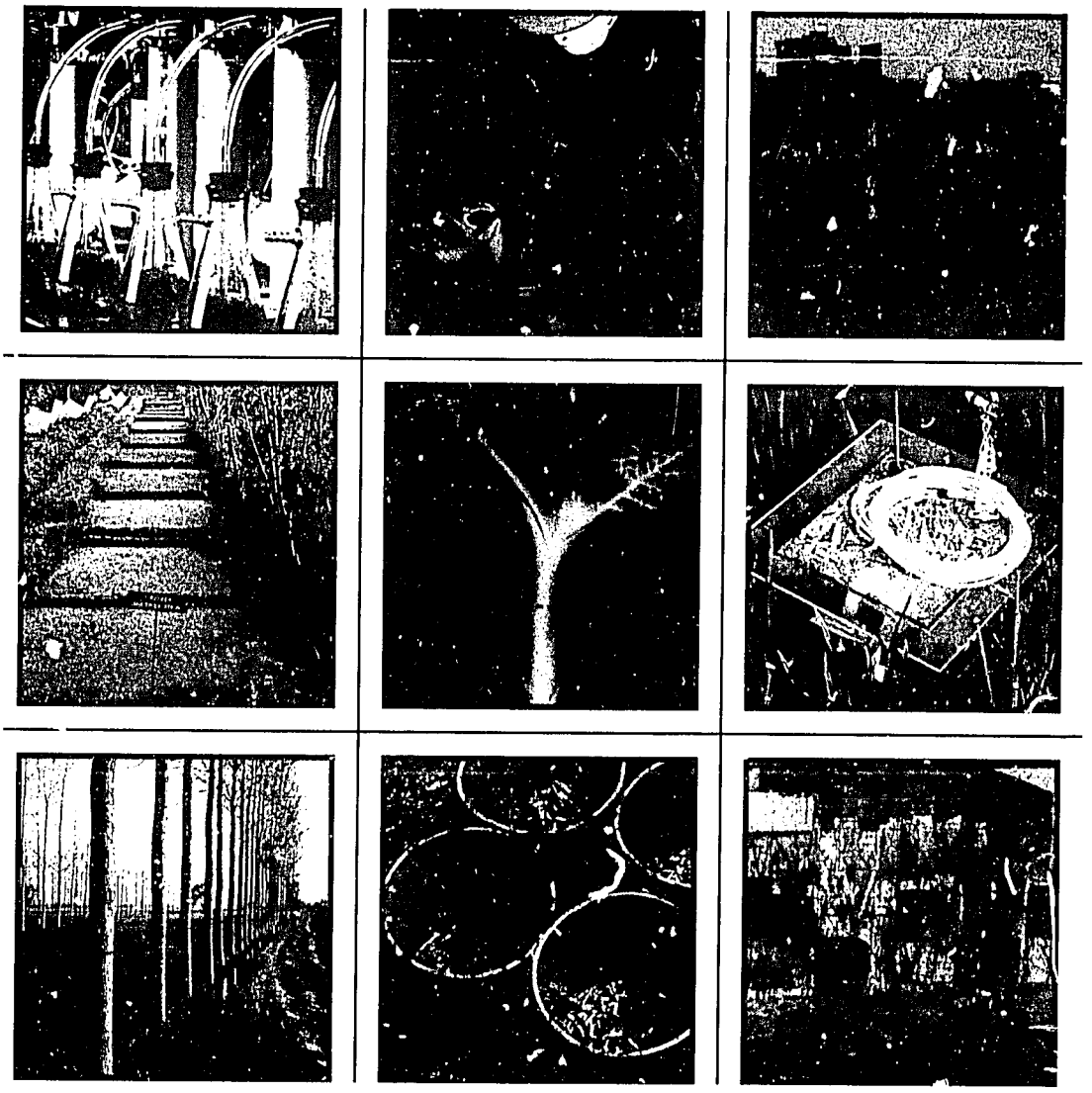
Indo-U.S. Collaboration on Agricultural Research



Partners to Feed a Hungry World

Indo-U.S. Collaboration on Agricultural Research

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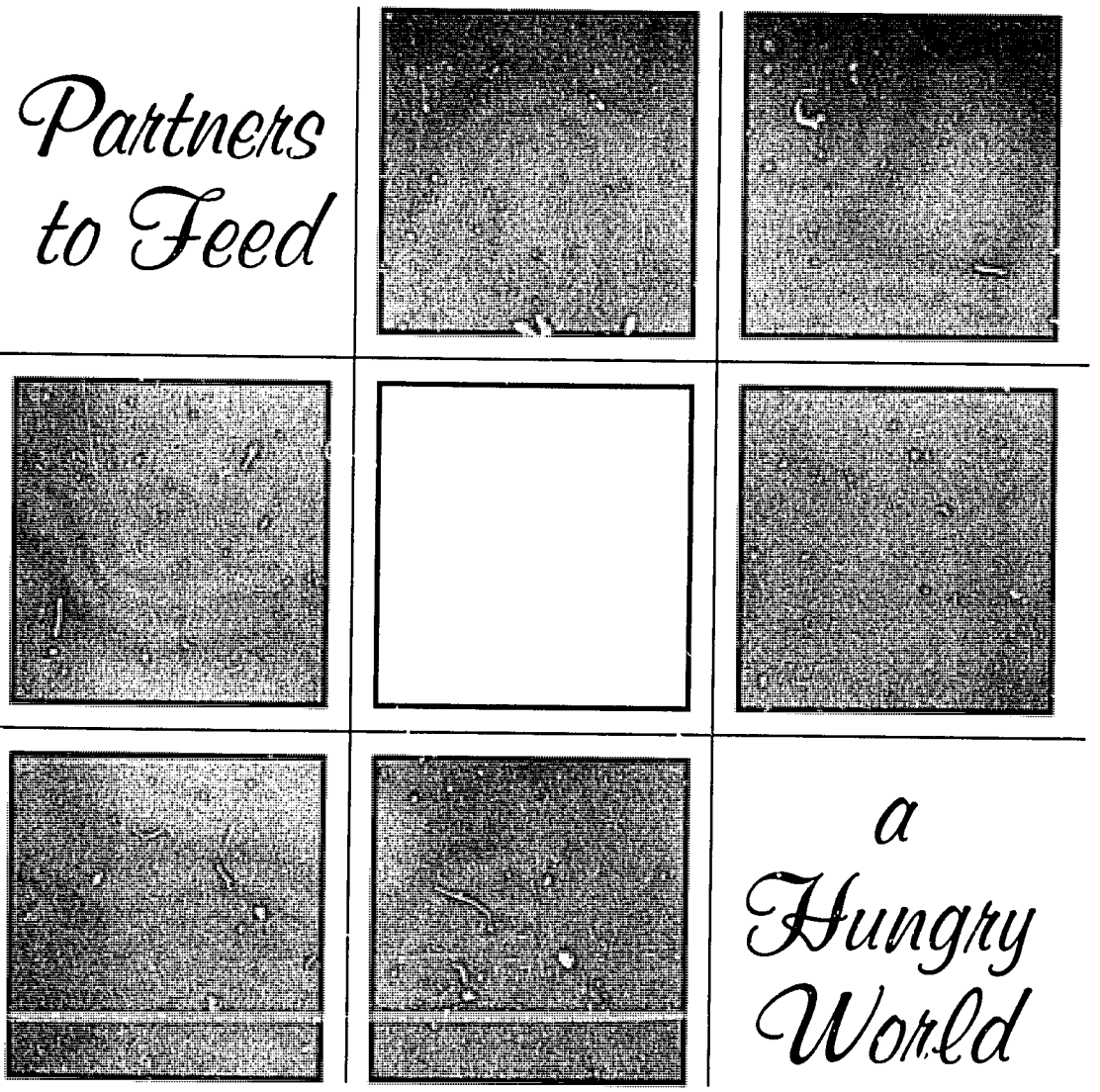

Acknowledgments

This publication describing the fruits of a collaboration between the United States and India in agricultural research came about because of the vision of Dr. Lloyd Frederick, a soil microbiologist who retired from the United States Agency for International Development (AID) in April, 1989. His collaborator at AID, Dr. John Malcolm, a soil and fertilizer specialist, carried to completion this Indo-United States Science and Technology Initiative (STI) book. Dr. Stanley Krugman, a plant geneticist with the United States Forest Service, United States Department of Agriculture, also offered invaluable guidance.

A primary source of information for this publication was the Indian Council for Agricultural Research (ICAR)'s "Indo-US SSP Programme (STI) in Agriculture: Progress Report of Work from July 1984 to March 1988."

Special thanks are due to the Indian coordinators of the STI agricultural project: in biological nitrogen fixation, Professor H. K. Das of Jawaharlal Nehru University, Professor Sushil Kumar, Dr. A. N. Sen, and Dr. G. S. Venkataraman of the Indian Agricultural Research Institute (IARI); in nitrogen fertilizer efficiency, Dr. N. N. Goswami of I.A.R.I.

Particular appreciation is also due to Dr. N. S. Randhawa, Director General, ICAR, without whose support there would have been no program, and Dr. U. Trivedi, Department of Science and Technology, who expedited travel and workshops, essential to such a complicated international collaboration.

On the United States side, special thanks are extended to all STI participating scientists who took the time to describe their work, review draft materials, and provide photographs for this publication.

The editors also want to thank Dr. Roger Doyon and Rose Bader of the National Science Foundation and Augustus Nasmith, Jr. of the National Academy of Sciences, National Research Council, for providing background information on STI; and Barbara Turner and Randy Casey of AID for providing essential statistical and historical information.

Angela Peebles of Research Assessment Management, Inc. planned, researched, and coordinated this publication. Freelance writers Jane and Tom Alexander provided overall editorial direction. Illustrations Unlimited, Inc. was responsible for the publication's graphic design.

Preface

Partners to Feed a Hungry World offers non-specialists in soil science and microbiology an overview of the accomplishments, scientific merit, and significance of the Indo-United States Science and Technology Initiative (STI) in agriculture. Interested specialists may find details of individual research projects in technical journals and institutional reports.

We hope that readers of this book will sense the excitement and commitment of scientists involved in STI. This publication illustrates that in scientific endeavors mutual cooperation between and among scientists is far more productive than isolated effort.

It is my sincere hope that each reader will share in a portion of the knowledge, rewards, and stimulation enjoyed by scientists who have participated in the fruitful STI collaboration.

John L. Malcolm
Senior Soil Specialist
Office of Agriculture
Bureau for Science and Technology
March 12, 1990

Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the editors and do not necessarily reflect the views of the United States Agency for International Development.

This publication was prepared by Research Assessment Management, Inc. for the Agency for International Development under Contract Number: DAN 1406-C-00-5112-00.

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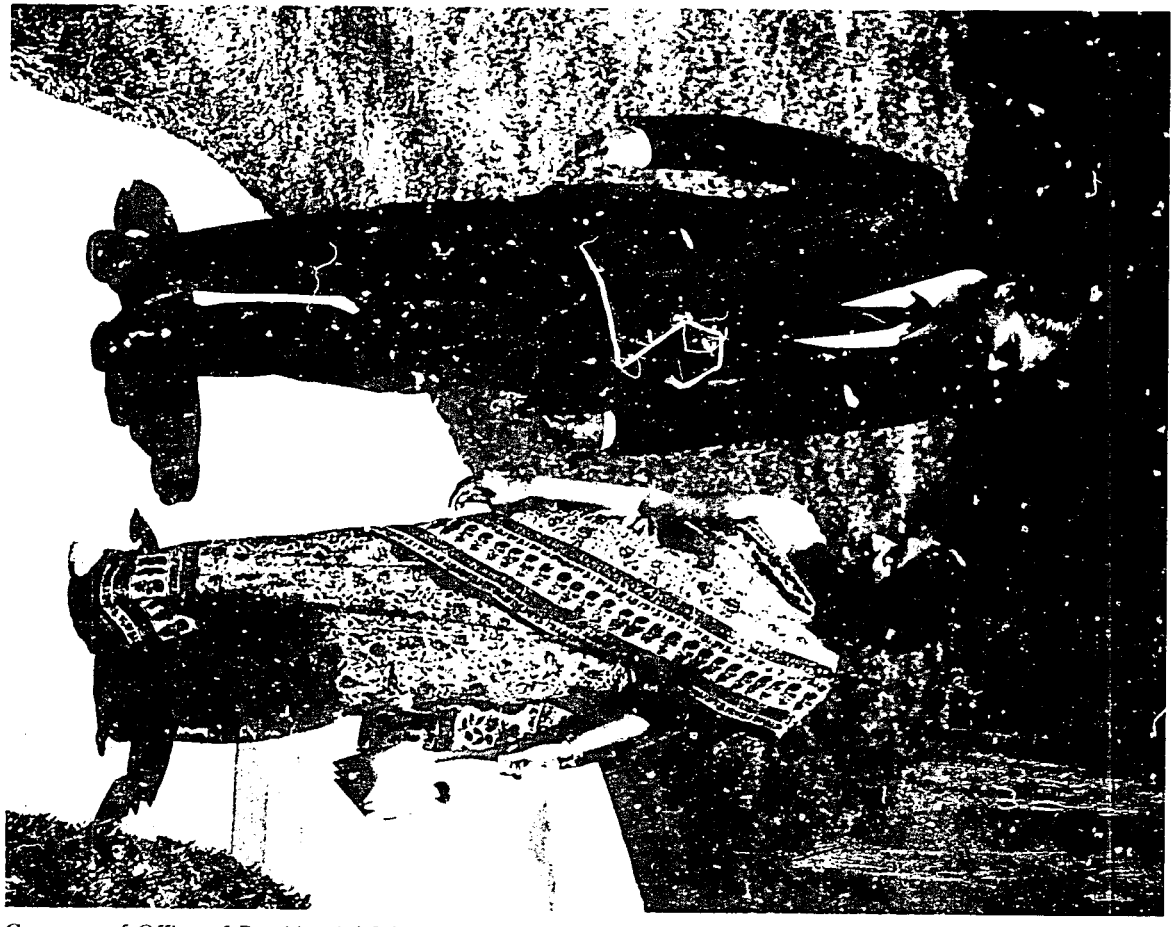

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Partners To Feed A Hungry World

The Indo-United States Science and Technology Initiative (STI) was designed to be a collaboration between equal partners that would bring considerable advantage to both. Of all the areas chosen for study, agriculture promises the largest benefits to both the research partners—and to the world at large—while conforming most closely to the equal-exchange ideal.

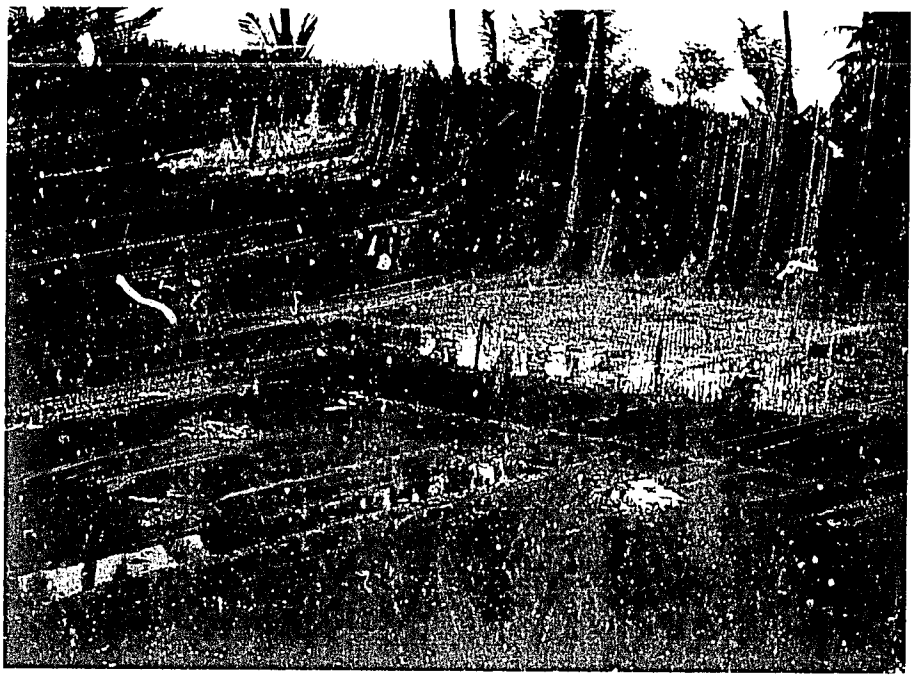
Mindful of the long and productive history of scientific and technological cooperation between their two countries, President Ronald Reagan and Prime Minister Indira Gandhi launched the Indo-United States Science and Technology Initiative (STI) in 1982 as a way of bringing their two great democracies closer together and reinforcing mutual interests. They proposed it as a collaboration between equal partners, each bringing complementary experience to bear on common problems, with considerable advantage to both—and to the world at large.

Of the four general areas they chose in which to conduct joint research—health, earth sciences, material sciences and agriculture—agriculture is, arguably, at least, the one that potentially promises the largest benefits to both the research partners and to the world community and that also conforms most closely to the equal-exchange ideal. Advances in agricultural technology may, in fact, be essential to human survival. To nourish the growing world population, food output must increase by about 60% during the next 20 years.

Furthermore, the United States and India have a lot to learn from each other about farming. The United States spearheaded the Green Revolution that helped transform once-hungry Third World countries into self-sufficient grain exporters. But the United States also has much to learn about things like long-term soil husbandry and energy-conscious farming from countries such as India with thousands of years of experience in such new-old practices as organic farming.

Bigger Harvests While Preserving Soil and Environment.

While India's main stake in STI agricultural research is to expand yield, a major United States concern is to preserve the soil and the environment. Awareness is growing that heavy reliance on fertilizers, lime, and synthetic chemicals, can, in the long run, damage the water, the air and farmers' ability to sustain high yields. Soils erode and lose their moisture-holding loam, and nitrates from artificial fertilizers pollute streams and ground-water with cancer-causing agents and contribute to green-house warming and stratospheric ozone-depletion. United States farmers look respectfully at their Indian counterparts who apply minimal amounts of chemical fertilizers, herbicides, and pesticides while coaxing five or six crops a year from fields long-ago depleted of topsoil and natural nutrients.



Searching for a way to substantially increase rice yields, STI researchers grow the nitrogen-fixing fern, azolla.

Improving on Nature's Nitrogen Fixation

Agricultural research projects under STI, managed on the United States side by the Agency for International Development (AID) and the United States Forest Service, fall into three main categories. One, biological nitrogen fixation (BNF), focuses on improving and extending the ability of certain microorganisms in soil and water to "fix" the atmosphere's gaseous nitrogen into mineral form, thereby making this critical nutrient for all living things available to growing crops. Another category, related to the first, is nitrogen fertilizer efficiency (NFE), which is concerned with finding ways to minimize the inevitable losses of soil nitrogen, with attendant effects on food costs and environmental degradation. The third area, biomass research, seeks to help reverse the worldwide trend toward deforestation whose economic and environmental consequences appear steadily more alarming.

Awareness is growing that heavy reliance on fertilizers, lime, and synthetic chemicals, can, in the long run, damage the water, the air and farmers' ability to sustain high yields.

Super Strains of Rhizobia

Much of the work in the BNF program is devoted to genetically engineering super strains of rhizobia, the nitrogen-fixing bacteria that create and inhabit nodules in the roots of legumes, major food-crops and dominant "green-manures" in the organic-farming community. Already researchers are designing new strains of rhizobia that combine desirable genes not only from other rhizobial species but even from non-rhizobial genera, with an eventual aim of extending nitrogen-fixing abilities to non-legume crops such as wheat or rice.

Researchers monitor how much fertilizer-nitrogen gets lost from rice plants.

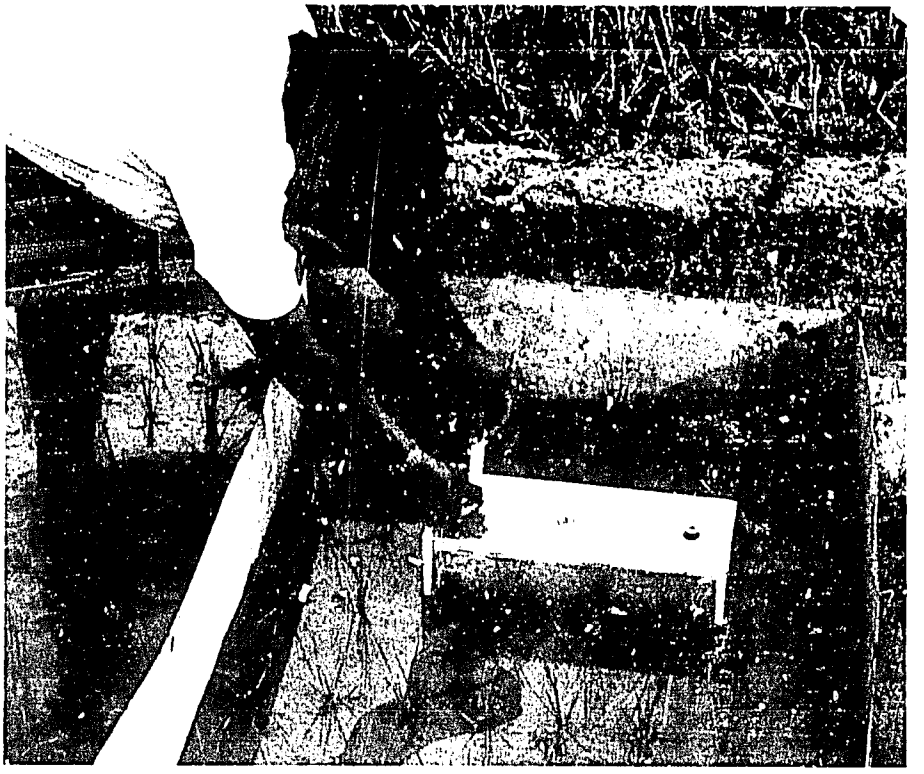
Scientists are combining competitiveness traits with improved nitrogen-fixing qualities to produce superbugs that can replace indigenous strains.

In one BNF program, for example, scientists are combining competitiveness traits with improved nitrogen-fixing qualities to produce superbugs that can replace indigenous strains. Researchers analyze the make-up of the long DNA molecule in organisms with desirable characteristics, identify and extract desirable genes, then insert them into the DNA strand of a target organism having other desirable characteristics.

Other STI researchers are working on newer, more direct gene manipulation techniques that involve extracting little DNA segments, or plasmids, from the bacterium, *Escherichia coli*, opening them up with the aid of chemical enzymes, splicing in foreign genes, then re-inserting them into a host to alter its biochemical behavior.

Hormones and Pesticides from Fungi?

Another fascinating interdependency under study is the one existing between most plants and various soil fungi known as mycorrhiza. These filamentlike fungi inhabit or surround plants' tiny rootlets, functioning as extensions of the root systems to increase uptake of nutrients and moisture, and in many cases supplying vital hormones, natural pesticides, and disease-fighting substances as well. Researchers are investigating the synergistic effects of inoculating seeds with both mycorrhiza and rhizobia to enhance nitrogen fixation and at the same time supply plants other chemical services they require.



At the Central Rice Research Institute in Cuttack, India, M. M. Panda collects gas samples from the first direct field measurements of denitrification ever conducted in India.

Still other STI researchers are investigating a symbiotic relationship widely exploited in the Orient—the water fern Azolla and its nitrogen-fixing blue-green algae called Anabaena—in an attempt to identify strains of fern and algae with greater salt-tolerance, pest-resistance, and pollution-removing talents. In their most recent report, the National Research Council's Overview Panel, which ensures that STI is on target, selected for special mention the work of STI researchers who have identified superior species of azolla, with greatly superior nitrogen-fixing abilities. It is hoped that the new symbionts can be sown between or with crops of rice to provide all the nitrogen rice crops need. Researchers hope that anabaena's little nitrogen-factories may eventually replace the chemical fertilizers used in United States rice cultivation, with enormous savings in both energy and environmental damage.

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Better Use of Fertilizer Nitrogen

Another approach to the same goal is simply to improve the efficiency with which plants utilize nitrogen from fertilizer, whatever its origins. Rice plants, for example, often recover as little as 20 percent of the available nitrogen in fertilizer. But if these losses could be better understood, researchers believe that they might be reduced to 30 percent or less.

N. K. Banerjee of the Indian Agricultural Research Institute in New Delhi collects gas samples in Fort Collins, Colorado. The gas samples monitor the effect of a new, relatively-cheap nitrification inhibitor, coated calcium carbide.

Every year the world loses an area of forest the size of California, most losses occurring in poor, tropical countries where the main source of energy is firewood.

STI scientists have found, for example, that applying fertilizer on wet soil greatly increases nitrogen loss; conversely, applying it a couple of days before a heavy rain decreases such losses. Other STI groups are exploring the practicality of coating fertilizer pellets with various substances to help inhibit nitrogen losses.

American and Indian investigators have collaboratively developed a computer program that allows various nitrogen management alternatives to be tested without expensive and time-consuming field experiments. By trading information, Indian and American scientists hope to discover for given crop species what types and amounts of fertilizer to apply, when to use them, and at what depths.

Reforestation of India's Wastelands

STI's biomass project aims to uncover useful tree species and improved reforestation techniques in order to provide renewable energy sources for rural populations, improve soil conditions for agriculture, and control floods.

Every year the world loses an area of forest the size of California. Most of the losses occur in poor, tropical countries where the main source of energy is firewood. With plenty of cheap labor, India has been in the forefront of countries trying to do something about the problem, each year planting 12.5 million acres to restore to woodland the one-third of India's area that is largely unproductive wasteland.

In northern India, researchers grow woody shrubs to replenish arid lands.

A major component of STI's biomass program involves scouring the world for woody species that can flourish in marginal lands unsuitable to agriculture. A promising candidate is the fast-growing American poplar tree, some species of which attain heights of 75 feet in just eight years.

In the United States where paper companies are growing concerned about an emerging scarcity of domestic wood pulp, STI researchers are identifying the fastest-growing poplar species and breeding or cloning hybrids suitable for short-rotation forestry under various growing conditions.

But poplar is not suited to India's more arid or mountainous lands. For these, STI researchers are trying out some of the tough shrubs from the American west, such as mesquite and saltbush, and collecting seeds and cloning Indian trees, such as neem and acacia as well as other hardy species from Africa's Sahel desert. Tissue cloning offers researchers opportunities to improve the species not only by selecting the very best specimens but also by transferring to the cloned cells beneficial genes from other plants, and even from bacteria.

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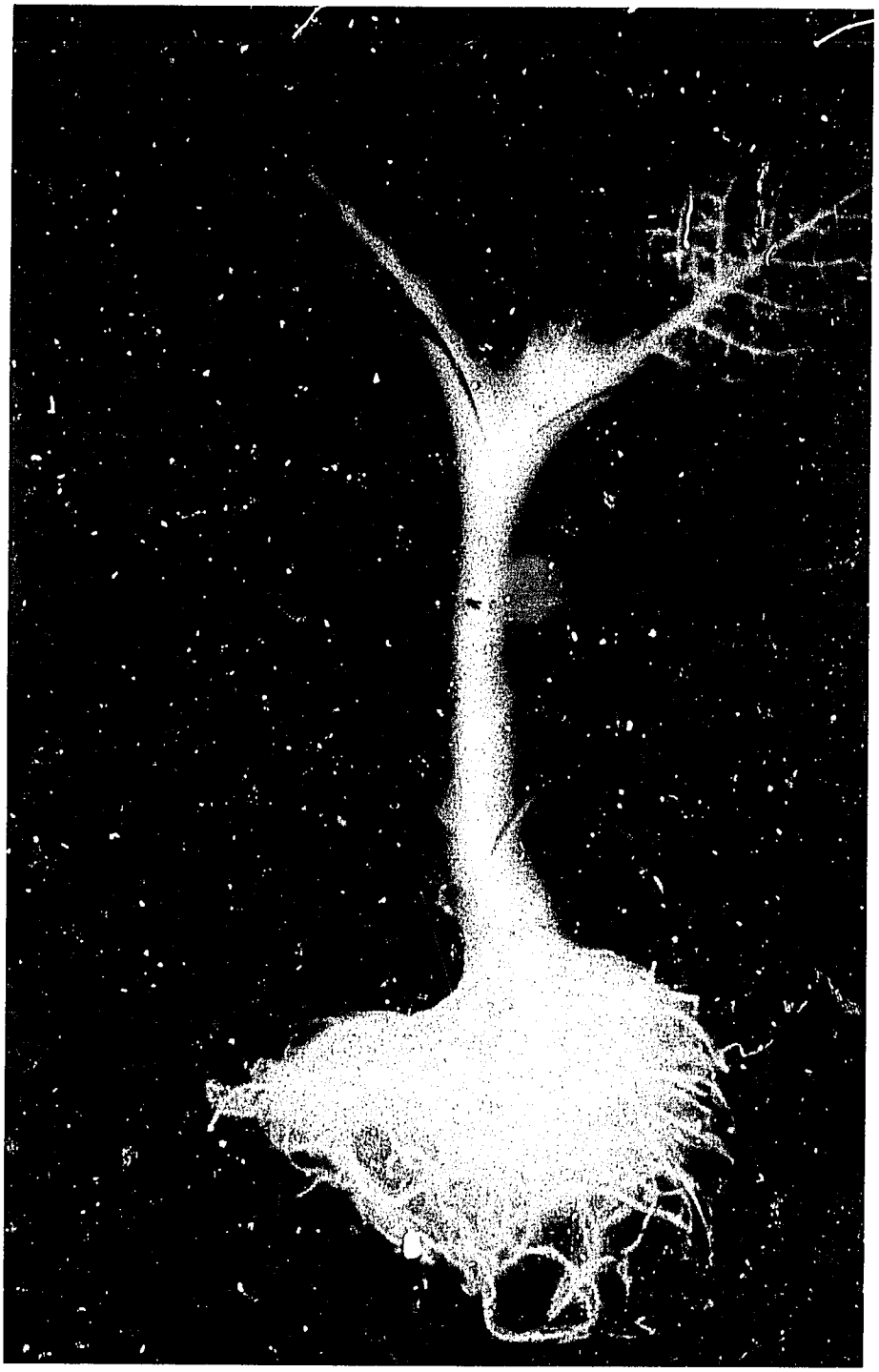
STI as a Model for Attractive New Projects

Replanting many millions of acres per year, as India contemplates, will take enormous manpower resources, so India is sponsoring an innovative "social forestry" to give millions of Indian villagers an economic interest in planting trees to provide the vital firewood and fodder villagers and their ubiquitous livestock require.

With these and other research ventures underway, it is hoped that STI will serve as a model for attractive new projects. By designing cooperative ventures, not aid programs, the partners invigorate their respective science and technology establishments, encourage the best talent in each country to come forward, and speed the progress of scientific discovery.

Courtesy of Office of Presidential Libraries



A luciferase gene responsible for a firefly's glow lights up an entire tobacco plant. Cloned in the lab of Donald Helinski and Sharon Stanfield at the University of California, San Diego, the luciferase gene may aid researchers in understanding the regulation of genes that enhance nitrogen fixation.

Redesigning Nature's Nitrogen Factories

The Indo-United States Science and Technology Initiative's Biological Nitrogen Fixation (BNF) program seeks to understand, improve, and harness natures nitrogen-fixing process to human agriculture, with an ultimate eye to replacing fuel-gobbling, polluting practices based on artificial fertilizers.

There's a finesse in Nature's chemistry that mocks mankind's brute-force methods, which rely on enormous pressures and temperatures to accomplish the same results. Cases in point are the still-mysterious but seemingly-effortless processes of photosynthesis and nitrogen-fixation, by which plant systems extract carbon and nitrogen—the two dominant constituents of living tissue. Abundant in the earth's atmosphere, primarily in the form of carbon-dioxide (CO_2) and molecular nitrogen (N_2), the two substances are bound so tightly as to challenge chemists' efforts to break them into their valuable constituents.

In photosynthesis, plants use solar energy and enzymes to break the carbon-oxygen bond. Nitrogen fixation is a more complex process in which plants get help from certain species of soil bacteria in a complex and delicate symbiosis that, from the standpoint of living things, is probably the most important division of labor on earth. The principal bacteria involved, encompassing a variety of strains known as rhizobia, inhabit nodules in the roots of legume plants, which include peas, beans, and clovers, and certain trees such as leucaenas, prosopises and acacias. Using a kind of molecular jujitsu, these bacteria tease tightly-bound nitrogen atoms apart with minimum outlay of energy, then combine them with hydrogen to make ammonia (NH_3). The rhizobia trade the ammonia to their plant hosts in return for the photosynthesized carbon fuel they need to keep the process going.

The Indo-United States Science and Technology Initiative's Biological Nitrogen Fixation (BNF) program seeks to understand, improve, and harness this natural nitrogen-fixing process to human agriculture, with an ultimate eye to replacing fuel-gobbling, polluting practices based on artificial fertilizers.

Traditional Farmers Harness Nature's Nitrogen

Since at least Roman times, farmers around the world have recognized the value of legumes in improving soil, planting them either in rotation or in conjunction with other crops both to maintain soil fertility and as foodstuffs in their own right. But in western countries after World War II, farmers largely abandoned these labor-intensive organic-farming practices for cheap artificial fertilizers, made in huge plants converted from manufacturing explosives to fertilizer-production. Subsequently, the nitrogen-hungry cereal crops developed under the Green Revolution increased yields sharply in response to large doses of nitrogen, so even many Third World farmers now rely on artificial fertilizers. Worldwide, nevertheless, most farmers still get most of their soil nitrogen through the natural symbiosis, and several Asian countries, notably China and India have developed a rich base of scientific knowledge about it.

STI researchers are studying the performance of rhizobia in the highly-weathered, infertile soils typical of upland farms in India. Despite continuous cropping with legumes, many of these soils lack sufficient rhizobia for maximum yields.

The Heavy Costs of Artificial Fertilizer

In recent years, new interest in Nature's elegant approach to nitrogen-fixation has emerged in the West as well. For it has become clear that the move to artificial fertilizer has entailed heavy costs, both in dwindling fossil fuels and in damage to soil, water and atmosphere. Soils have been losing topsoil and their moisture-holding loaminess, while nitrates from artificial fertilizers leach away to pollute streams and ground-water with cancer-causing agents or dissociate into gases that waft into the atmosphere, contributing to such problems as green-house warming and stratospheric ozone-depletion. STI's program focuses on improving the efficiency of BNF enough to make it as economically beneficial to farmers as it is environmentally beneficial to the world at large.

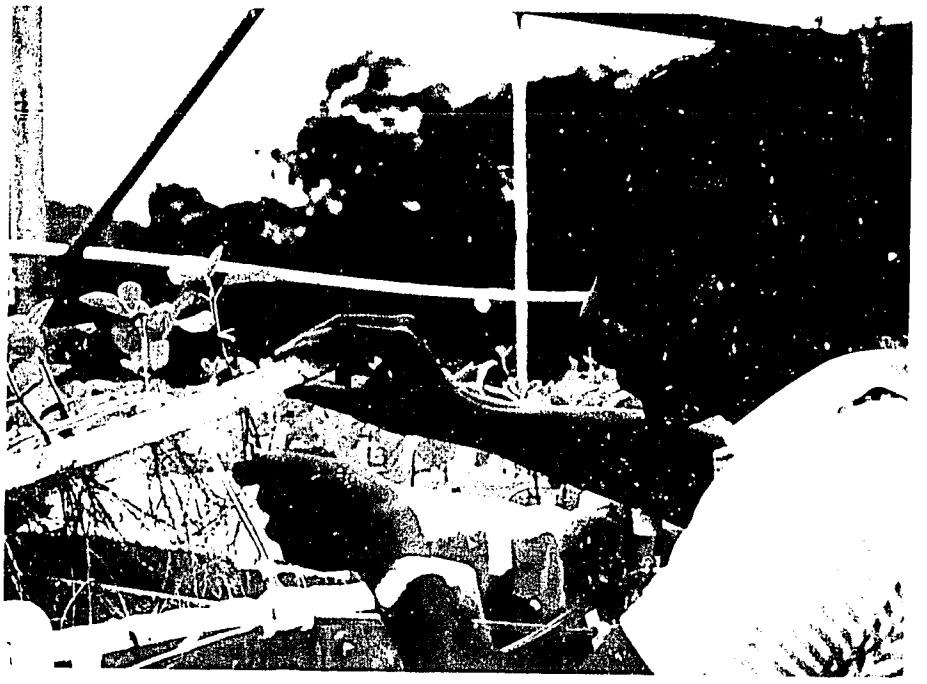
With its tradition and scientific investment in organic farming, its heavy dependence on legume foodstuffs and nitrogen-hungry grains, plus long growing-seasons that permit multiple crops, India is a natural partner in efforts to improve BNF. The United States brings to the STI partnership its special proficiency in agricultural research, and particularly in genetic engineering.

Nitrates from artificial fertilizers leach away to pollute streams and ground-water or dissociate into gases that waft into the atmosphere.

A Complex and Delicate System

For all its chemical elegance, biological nitrogen fixation is a complex and delicate system, not designed with an eye to human notions of economic efficiency. Legumes are widely distributed over Planet Earth and rhizobia are found wherever legumes flourish. Usually only specific rhizobium species are compatible with given legume species. Furthermore, each soil and climatic regime has rhizobium strains that have

An Indian graduate student works on a highly-controlled experiment to determine whether genetic differences in nitrate assimilation may be a useful characteristic for enhancing nitrogen fixation. Success in this project may enable breeders to increase the reliance of legumes on BNF and as a consequence, conserve soil nitrogen for other non-legume crops.



Each soil and climatic regime has its own rhizobia strains that may not be efficient nitrogen-fixers but outcompete newcomers for available nutrients.

adapted to that regime, strains that may not be particularly efficient as nitrogen-fixers but that can outcompete any newcomers for available nutrients. So, one of the aims of STI is to combine competitiveness traits with improved nitrogen-fixing traits to produce superbugs that can replace indigenous strains.

Such feats have become practical, or at least conceivable, thanks largely to developments in genetic engineering—modifications of the DNA molecules that constitute the genetic blueprints for all living things. Using various methods, scientists can analyze the make-up of the long DNA molecule in organisms, identify and extract desirable genes, then insert them into the DNA strand of a target organism having other desirable characteristics.

Designer Rhizobia

In one cooperative effort, an American team working under L. D. Kuykendall at the United States Department of Agriculture lab in Beltsville, Maryland, and an Indian team under Y.B. Gaur at the Indian Agricultural Research Institute, New Delhi, are concentrating on improving a rhizobium species that inhabits root nodules of the chickpea—a dominant foodstuff of hundreds of millions of people in Asia and elsewhere. The Americans have developed a strain of chickpea rhizobia with superior nitrogen-fixing abilities. Gaur's group has isolated chickpea rhizobia well-adapted to soil and climate conditions in India and brought them to Kuykendall's lab in the United States. There the team first cultures the United States rhizobia together with *E. coli*, a bacterium that has long served as the favorite transmission link in mankind's genetic manipulations.

STI participants sample soil from an Indian rice paddy, part of a large soil survey to evaluate how farm management affects rhizobial populations. Survey results will be used to make recommendations to farmers growing different crops about inoculation—coating seeds with materials containing living bacteria and nutrients to help them thrive.

Indian Bugs with American Genes

In addition to its main DNA molecule *E. coli* possesses short loops of DNA-like material, called plasmids, that it can exchange with other microbes through the process known as conjugation. Plasmids have the capacity to pick up genes from outside sources along with the viruslike ability to splice themselves into the main DNA molecule of the host, producing permanent mutations. In Kuykendall's lab, once the *E. coli* have acquired the superior nitrogen-fixing genes from the American rhizobia, the *E. coli* is cultured together with the Indian rhizobia. After acquiring the American genes, the Indian bugs can be returned to India as breeding stock whose descendants can be implanted in soils there.

Other STI researchers employ newer, more direct gene engineering techniques, involving the use of chemical enzymes to open up plasmids, splice in foreign genes, then implant them into a host. As yet, these enzyme methods often don't work as reliably to produce stable mutations as the older conjugation methods. Nevertheless, several labs think they have accomplished breakthroughs that will improve the enzyme methods, thereby making possible a greater range of gene manipulations. Several STI-funded teams, for instance, are surveying not only the universe of nitrogen-fixing bacteria for useful genes but also other organisms such as plants.

Other STI researchers employ more direct engineering techniques: opening up plasmids with chemical enzymes, splicing in foreign genes, then implanting them into a host.

C. S. Nautiyal from Lucknow, India, and Peter van Berkum from the United States Department of Agriculture's Nitrogen Fixation and Soybean Genetics Laboratory in Beltsville, Maryland, examine pigeon pea plants, effectively and ineffectively nodulated.

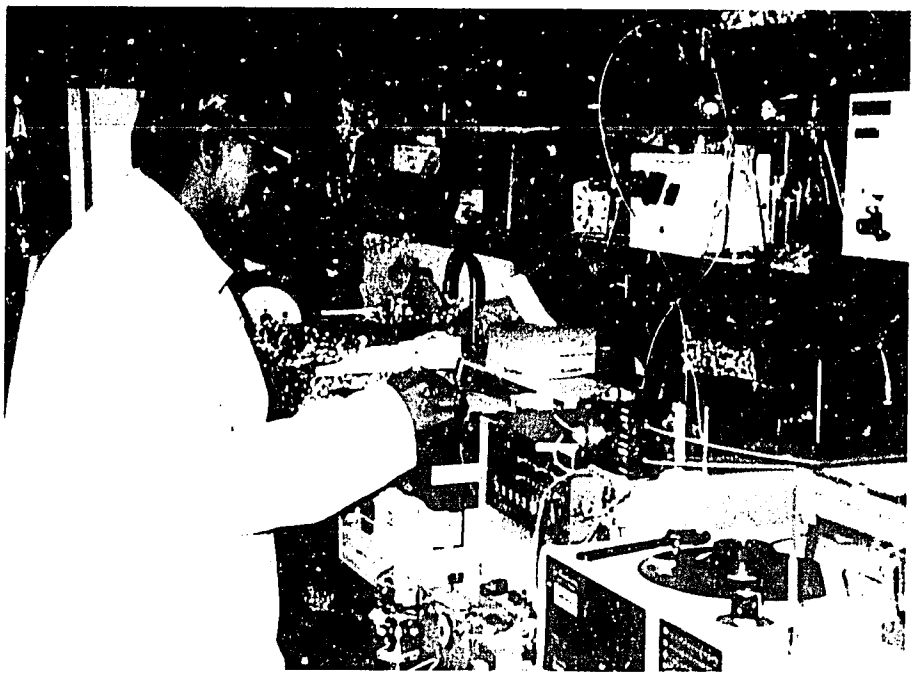
Soil microorganisms have complex nutritional requirements and limited capacities to survive the stresses and competition of the natural field environment.

One collaboration, which includes Donald R. Helinski and Sharon W. Stanfield of the University of California, San Diego (UCSD); Hiren Das of Jawaharlal Nehru University (JNU), and Sushil Kumar of the Indian Agricultural Research Institute (IARI) in New Delhi is "designing" rhizobia using desirable genes from various different species of rhizobium as well as non-rhizobial genera. Helinski and Stanfield have identified and extracted the nitrogen-fixing genes from a super-efficient *Rhizobium meliloti* that nodulates alfalfa roots. An Indian team under Kumar has cloned these same genes into *Rhizobium leguminosarum*, which inhabits nodules in pea-plants.

BNF for Wheat and Rice?

In another significant development, Das and his group have transferred the *R. meliloti* genes required for bacteria-plant interaction into two non-rhizobial, non-symbiotic species, the free-living soil bacteria *Azotobacter vinelandii* and *Azospirillum brasilense*. Potentially at least, equipping these bacteria with the ability to interact with plants might extend the benefits of BNF to non-legume crops such as wheat or rice, obviating the need to rotate cereal crops with legumes.

Several STI investigators are especially excited about a strain of *Azospirillum brasilense* that grows in association with certain grasses and stimulates their growth by excreting the plant-growth hormone, indoleacetic acid (IAA). In a turnabout, the collaborators have cloned azospirillum's IAA-producing genes into *Rhizobium meliloti*, enabling it to produce the growth-stimulator as well as to fix nitrogen. Das has also transferred the IAA-producing genes to another strain of azospirillum that grows in association with the cereal crop, millet, and has shown that it can enhance millet yields by thirty to forty percent—in laboratory experiments, at least.



Santosh K. Goyal of Indian Agricultural Research Institute in New Delhi works with high-pressure liquid chromatography equipment at in the lab of D. W. Rains at the University of California, Davis.

Still, a broad gulf divides controlled laboratory and greenhouse demonstrations from practical technologies for use down on the farm. Soil microorganisms have complex nutritional requirements and limited capacities to survive the stresses and competition of the natural field environment. Introducing improved bacterial strains, or for that matter new legume crops in soils where they have never been planted before, generally entails "inoculation"—coating seeds with materials containing living bacteria and nutrients to help them thrive. Once in the soil, the new strains compete with existing strains well-adapted to the climate and soil-conditions there, a competition the newcomers stand a good chance of losing. One stress that American rhizobia can't survive, for example, is the scorching temperatures—upwards of 120 degrees F.—characteristic of tropical soils.

"What we've done is create a new, low-technology fermentation system that can be used at the village level."

Low Technology for the Villages

Largely as an outgrowth of its hefty investment in soybean and peanut cultivation, the United States has developed an entire industry to make rhizobia inoculants. The industry uses enormous and sophisticated fermentation vessels in which bacteria reproduce under carefully controlled conditions. At the University of Hawaii's NifTAL project (for "nitrogen fixation by Tropical Agricultural Legumes"), STI-supported research is attempting to scale this technology down for use in countries such as India. "What we've done," says Ben Bohlool, director of NifTAL, "is create a new, low-technology fermentation system that can be used at the village level."

S. Kanaiyan of Tamil Nadu Agricultural University in Coimbatore and S. S. Goyal of the University of California, Davis, work together at Davis.

Soil scientists recognize that the azolla-anabaena combination improves water quality by removing phosphorous and nitrates.

In collaboration with NifTAL, Indian researchers at IARI are identifying the genes in rhizobium strains that enable them to thrive in particular crop/soil/climate regimes. Some strains, for example, tolerate highly saline soils, others can thrive in phosphorous-deficient soils, still others resist pesticides or herbicides, and so forth.

Some help in managing so much complexity may come from computers. In collaboration with NifTAL, Indian researchers working under S.V. Hedge at the University of Agricultural Research in Bangalore are developing a computer model into which farm agents or possibly even farmers might feed data about a specific locality—crop species, soil nutrients and temperatures, indigenous bacteria, etc.—plus the identity of a candidate replacement bacteria—and out of which would pop a prediction about whether the inoculation attempt is likely to succeed or fail.

While agricultural scientists have long emphasized the importance of the legume-rhizobium symbiosis, other types of symbiosis are now getting scientific attention in the new-old agricultural science pioneered by STI. Another nitrogen-producing system, widely exploited in the Orient, for instance, involves the water fern azolla and a nitrogen-fixing blue-green algae called anabaena that inhabits azolla's leaves. Indian and Chinese farmers have grown azolla as a green manure in their rice fields for hundreds of years, sowing pieces of the floating fern into flooded rice-paddies between crops, not only to provide all the nitrogen needed by the rice plants, but also to suppress weeds and provide fodder for animals. Recently, soil scientists have come to recognize that the azolla-anabaena combination also improves water quality by removing phosphorous and nitrates—a special benefit in countries troubled by water pollution from fertilizers and household detergents.

Greater Salt Tolerance and Pest Resistance

An STI project, involving scientists from more than twenty universities and institutes in the United States and India is attempting to improve the azolla-anabaena system by identifying the most efficient strains of fern and algae and creating hybrids with greater salt-tolerance, pest-resistance and pollution-removing talents.

Some researchers specialize in trying to understand the tricky combination of circumstances that induces azolla to reproduce sexually. Most strains of the fern reproduce almost exclusively from broken fragments, but the cost and difficulty of storing and sowing vulnerable bits of living water-fern discourage many farmers from exploiting the azolla-anabaena symbiosis. It would be far more practical if farmers could instead sow the hardy seed-like spores that are the fruits of sexual reproduction.

As with rhizobium, researchers in the azolla-anabaena project are developing a computer model to predict whether specific azolla strains can thrive in a given locale. One hope, of course, is that the solar-powered little nitrogen-factories inhabiting the fern may eventually replace the chemical fertilizers used in United States rice cultivation, with enormous savings in both fuel and environmental degradation.

How Soil Fungi Help Plants

Still another multi-organism system whose significance is becoming evident in the STI-BNF project involves the interdependence that exists between most plants and various soil fungi collectively known as mycorrhiza. These filament-like fungi inhabit or surround plants' tiny rootlets, not only functioning as extensions of the root systems to increase uptake of nutrients and moisture but in many cases supplying vital hormones, natural pesticides, and disease-fighting substances.

Under J. M. Trappe, with the United States Forestry Sciences Laboratory in Corvallis, Oregon, American researchers are collaborating with Indian counterparts under K. V. B. R. Tilak of IARI and D. J. Bagyaraj of the Indian Agricultural University to investigate possible synergistic effects of inoculating seeds with both mycorrhiza and rhizobia, not only to enhance nitrogen fixation but to supply other chemical services important to plants.

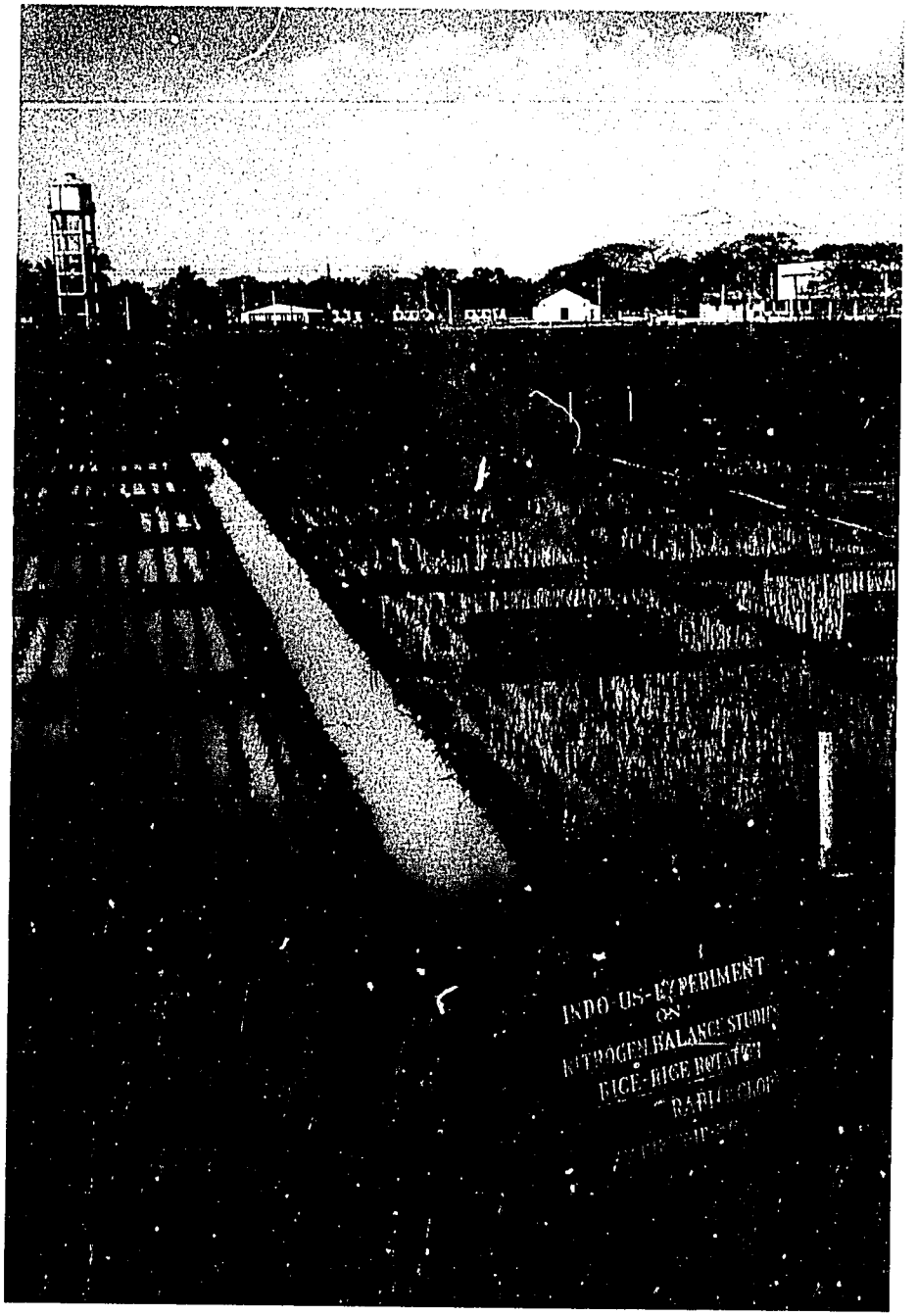
The synergistic effects of inoculating seeds with both mycorrhiza and rhizobia may enhance nitrogen fixation as well as supply other chemical services important to plants.

Complex Interdependencies

In the course of their mycorrhizal investigations, the researchers have uncovered a tripartite interaction with important implications for forestry. It turns out that some strains of long, hair-like mycorrhizal fungi that grow in association with certain nitrogen fixing legumes, called lupines, actually form interconnecting channels between the lupine roots and the roots of many species of trees. Apparently, important nutrients and other substances travel along these channels: unless the lupines and mycorrhizae are present, newly-planted trees frequently won't grow.

A common theme emerging from STI's BNF research is the recognition of the astonishingly rich ecology that flourishes just below the surface of the soil—an interdependence at least as complex and vital to life above ground as other ecologies more well-known to science. In fact, it now appears, no ecologist worthy of the name can leave these subterranean systems out of his calculations.

Searching for a way to substantially increase rice yields, STI researchers perform an azolla field experiment at the Tamil Nadu Agricultural University in Coimbatore, India.



Indian and American STI researchers are studying the fate of nitrogen in rice paddies that are kept flooded throughout the growing season.

Nitrogen Husbandry

Under STI's Nitrogen Fertilizer Efficiency project, various teams of U.S. and Indian researchers are attempting to discover the mechanisms that remove or sequester fertilizer nitrogen in paddy rice and upland wheat cultivation as well as devise modified farming practices or fertilizers to reduce these losses.

Scarcely a decade ago Asia faced such severe shortfalls in food production that many experts prophesied coming decades of disastrous famines. Since then momentous developments in agriculture commonly referred to as the Green Revolution not only rescued Asia from this fate but even transformed some countries there into net exporters of food. Recently, however, the old concerns about Asia's ability to feed itself have been reemerging. As the International Fertilizer Development Center reported in 1987, "Yields have leveled off in spite of increased application of nitrogen. A breakthrough in crop yields is needed if one accepts the prediction that the world's requirement for additional food will increase by about 60% during the next 20 years. Since 80% of Asia's arable land area is now under cultivation, its additional food requirements will have to come from increased yields."

The faltering progress of the Green Revolution reflects an economic/scientific predicament that a joint Indo-American research project under the Science and Technology Initiative is tackling. The primary achievement of the Green Revolution was development of new strains of grain, primarily rice and wheat, that could exploit intensive applications of nitrogen-rich fertilizers such as urea and ammonium nitrate. But a major shortcoming of that achievement is simply cost: the fertilizers are made in expensive plants from energy-rich feedstocks such as natural gas. While in principle, at least, a pound of urea, say, can yield as much as ten additional pounds of grain, farmers are reluctant to lay out the additional 45 cents that such a pound would cost.

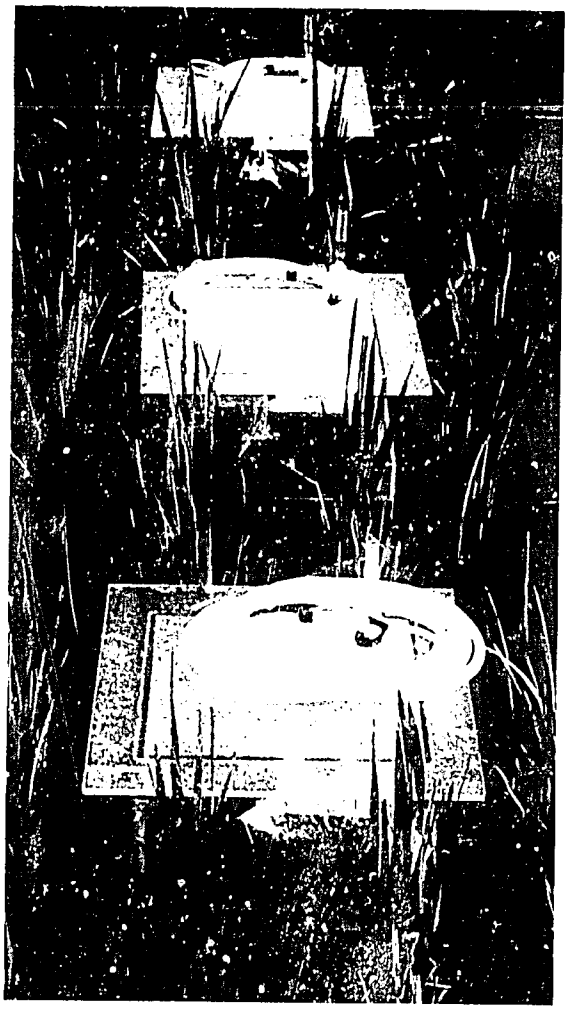
Puzzle of the Disappearing Nitrogen

Nevertheless, scientists are hopeful of finding ways around the cost barrier. Their hope is based largely on the fact that in actual practice much of that expensive fertilizer goes to waste: anywhere from 40 to 80 percent of its vital nitrogen disappears before reaching the plants for which it is intended. How and why this happens—and what can be done about it—are the puzzles that STI is addressing. What already seems clear is that much of the nitrogen gets leached, or washed, out of the soil, gets converted into gaseous nitrogen or ammonia and wafts away into the atmosphere, or gets stolen by competing life-forms.

What's at stake in solving the conundrum of the disappearing nitrogen also involves a lot more than the food problems of developing countries. The world as a whole now confronts problems of finite and dwindling supplies of energy. In addition, much of the fertilizer that goes to waste in developing and developed counties alike finds its way from farmers' fields to water courses and underground aquifers. The fugitive nitrogen and phosphates stimulate growth of waterborne plants and algae that block waterways and dams and deplete vital oxygen that fish require. Worse yet, nitrates pose risks of cancer. United States laws

limit their presence in drinking water to no more than ten parts per million. By now, in fact, such non-point sources of pollution as agricultural run-off constitute the most baffling challenge to efforts to clean up the world's waters.

In addition, nitrate fertilizers contribute both to the green-house effect —the global warming due to heat-trapping gases in the atmosphere —and to the depletion of the stratospheric ozone layer that shields the earth from cancer-causing ultraviolet rays. Finally, overuse of manmade fertilizers to the exclusion of manures and organic conditioners damages soil fertility by fostering erosion and reducing permeability and capacity for moisture retention.



Researchers monitor how much fertilizer nitrogen gets lost from rice plants growing in air-tight boxes near Crowley, Louisiana.

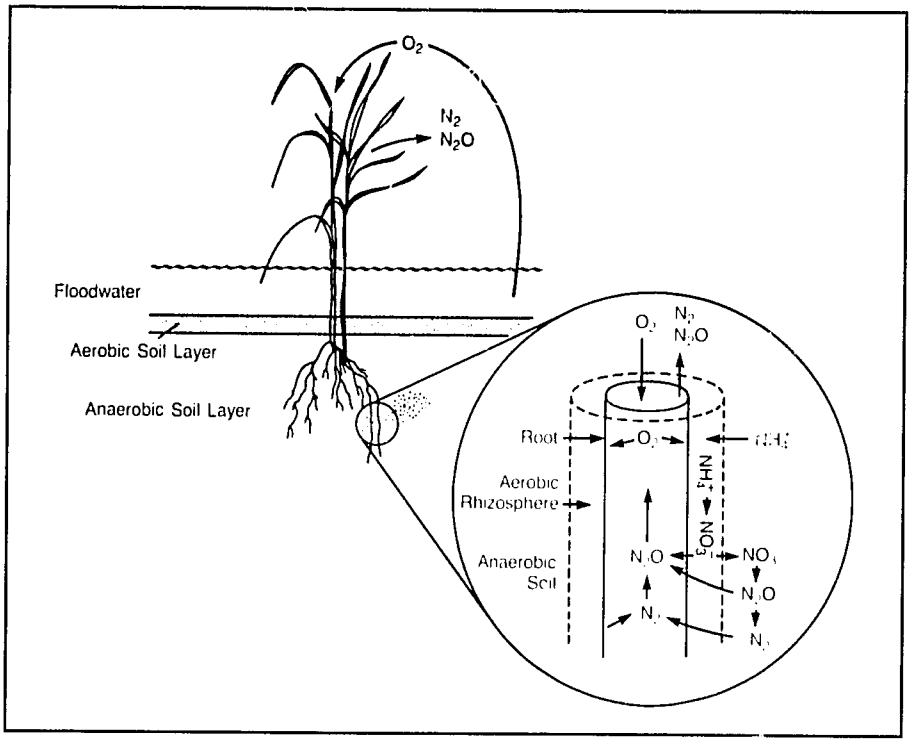
Much of the nitrogen leaches, or washes from the soil, gets converted into gaseous nitrogen or ammonia and wafts into the atmosphere, or gets stolen by competing life-forms.

Under STI's Nitrogen Fertilizer Efficiency project, various teams of NFE researchers, each drawn from both the United States and India, are attempting to discover not only the mechanisms that remove or sequester fertilizer nitrogen in paddy rice and upland wheat cultivation but also to devise modified farming practices or fertilizers to reduce the losses.

Isotopes Trace Nitrogen Losses

A key research technique employs the isotope nitrogen^{15} (^{15}N) as a tracer. Chemically identical to ordinary nitrogen, ^{14}N, in their effect on plants, ^{15}N atoms are nevertheless slightly heavier; therefore their presence can be detected by instruments called mass spectrometers. One United States contribution to the STI effort has been to assist in the installation and calibration of mass spectrometers in Indian laboratories. In many of their experiments, researchers employ special batches of fertilizer in which the proportion of ^{15}N has been augmented. By applying the enriched fertilizer and measuring the amount of ^{15}N that finds its way into plants, as well as into the water, soil, and atmosphere of the plants' environment, researchers can determine where all the nitrogen goes.

Scientists are trying to understand why rice plants utilize as little as 20 percent of the nitrogen available to them. As shown in this schematic representation, K.R. Reddy has found that the rice plant itself is largely to blame for nitrogen losses. In flooded soils, fertilizers get converted to ammonia or nitrogen gas in the root zones of the plant and simply flow up the hollow stems to the atmosphere.

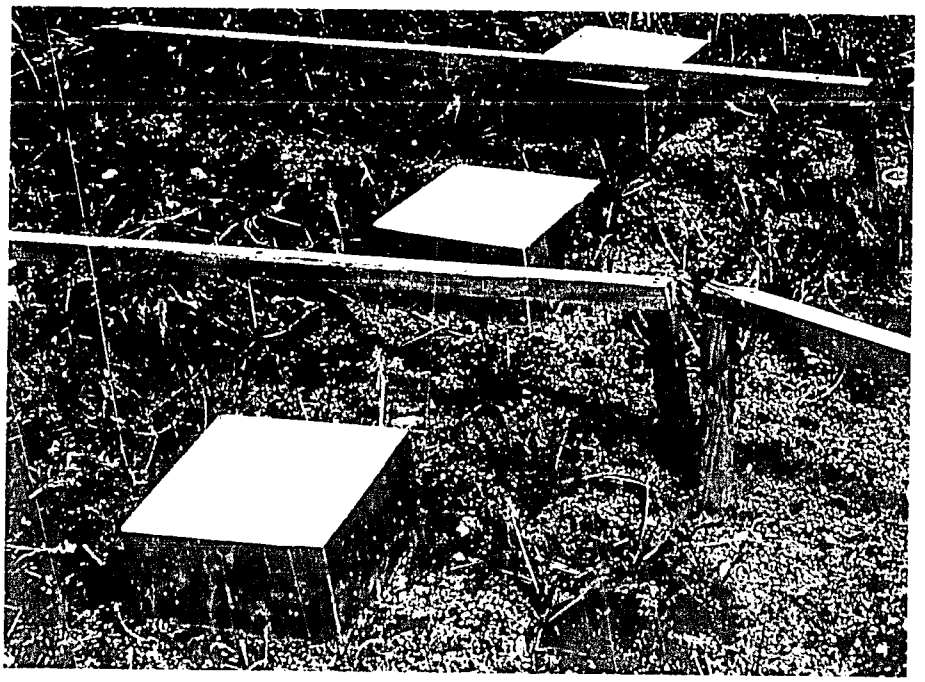


By applying enriched fertilizer and measuring the amount of ^{15}N that finds its way into plants, researchers can determine where all the nitrogen goes.

Competition for Nitrogen from Microbes

To be sure, perfecting the ^{15}N technique poses scientific puzzles of its own. Working under one STI grant, for example, soil scientist John M. Duxbury and his colleagues at Cornell have discovered that busy little microorganisms in the soil apparently have the ability to exchange the ^{14}N atoms naturally present in the soil with the ^{15}N atoms in ammonium fertilizer in such a way as to confound the scientists' careful measurements and calculations. In collaboration with Indian scientists at the Indian Agricultural Research Institute near New Delhi as well as at Tamil Nadu Agricultural University in Coimbatore, the Cornell researchers are trying to calibrate this effect and also to determine the extent to which these soil microbes compete with plants for nitrogen.

Further complicating the missing nitrogen puzzle is that different crops, different climates, and different farming methods seem to provoke wildly different mechanisms for nitrogen loss. Working under S.K. Mohanty, for example, researchers at the Central Rice Research Institute at Cuttack, India, are using the ^{15}N technique to measure the "denitrification" in dry-season, intermittently-flooded rice fields characteristic of India's uplands. Denitrification is the process whereby the mineralized, or chemically-bound, nitrogen that plants actually use gets transformed by various processes into gaseous nitrogen that then escapes to the atmosphere.



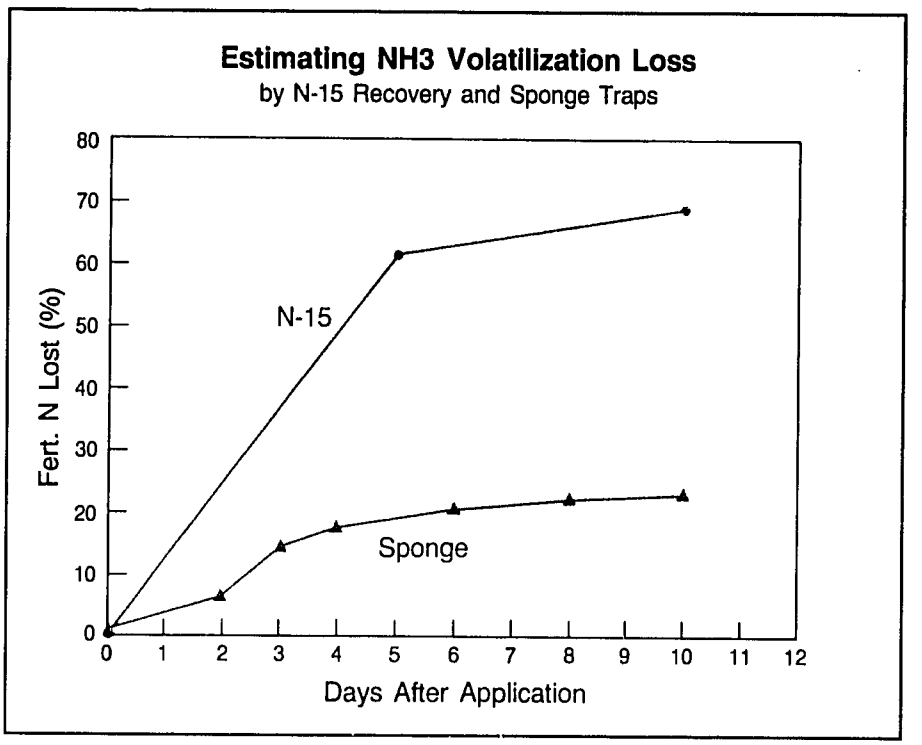
In a Penn State experiment, researchers compare two ways of measuring ammonia volatization from urea in the field — the ^{15}N recovery and sponge trap methods. As the graph shows, the ^{15}N recovery method registered a much greater ammonia loss than the sponge-trap method.

[illegible] for Flooded Rice Paddies

Meanwhile, American scientists working under William Patrick at the Laboratory for Wetland Soils and Sediments at Louisiana State University in Baton Rouge, Louisiana, are collaborating with Indian colleagues at Punjab Agricultural University in Ludhiana as well as at Central Rice Research Institute in studying the fate of nitrogen in rice paddies that are kept flooded throughout the growing season. For one thing, they find that less nitrogen—and less water—is wasted from this type of rice cultivation than from intermittently-flooded fields. They also find that the rice plant itself is largely to blame for the losses: fertilizers get converted to ammonia or nitrogen gas in the root zones of the plant and simply flow up the hollow stems to the atmosphere. The researchers conclude that one strategy for reducing losses involves delaying fertilizer application until the time when crops enter their period of maximum growth.

While in rice cultivation, keeping the soil as wet as possible seems to minimize nitrogen loss, in dryland crops such as wheat, the opposite seems called for. Soil scientist Richard Fox and his colleagues at Pennsylvania State University have found that applying urea fertilizer to moist soils dramatically increases the likelihood that urea will be transformed into ammonia and lost. But apparently it's not the presence of moisture alone that leads to the losses, but rather its timing: the Penn State researchers also discovered that with wheat, at least, a rainfall occurring shortly after fertilizer is applied actually reduces nitrogen loss.

Further complicating the puzzle is that different crops, climates, and farming methods seem to provoke wildly different mechanisms for nitrogen loss.



After feeding a computer data about crop species, soil types, and expected rainfall, out would pop advice about farming tactics.

Farming Advice from a Computer

In short, a principal lesson from STI research is that the explanations for nitrogen fertilizer losses are many, varying with crops, soils, climatic regimes—as are the prescriptions for preventing it. James Power, a soil scientist at the United States Department of Agriculture's research station in Lincoln, Nebraska, contends that one goal of research might be a computer model into which local farm agents could feed data about such variables as crop species, soil types, expected rainfall, and so forth and out of which would pop advice about farming tactics under these conditions.

Already, a collaboration involving American and Indian investigators from the University of California, the University of Florida and Punjab Agricultural University has produced a computer program that simulates what happens to fertilizer nitrogen in flooded soils such as rice paddies. Running this model will allow various management alternatives to be tested inexpensively without costly and time-consuming field experiments. Small experiments in a wind tunnel to simulate conditions, including wind-flows, occurring in actual rice paddies show that the computer model predicted the actual observed values with good accuracy. Field experiments in India have also confirmed the model's validity.

To find out about nitrogen dynamics, workers at Coimbatore add chopped up sesbania, labeled with ^{15}N as tracer, to rice plants. After flooding the microplots, they transplant rice plants at various times and analyze the distribution of ^{15}N between soil and plant. This close-up shows microplots before green manure residue was mixed in.

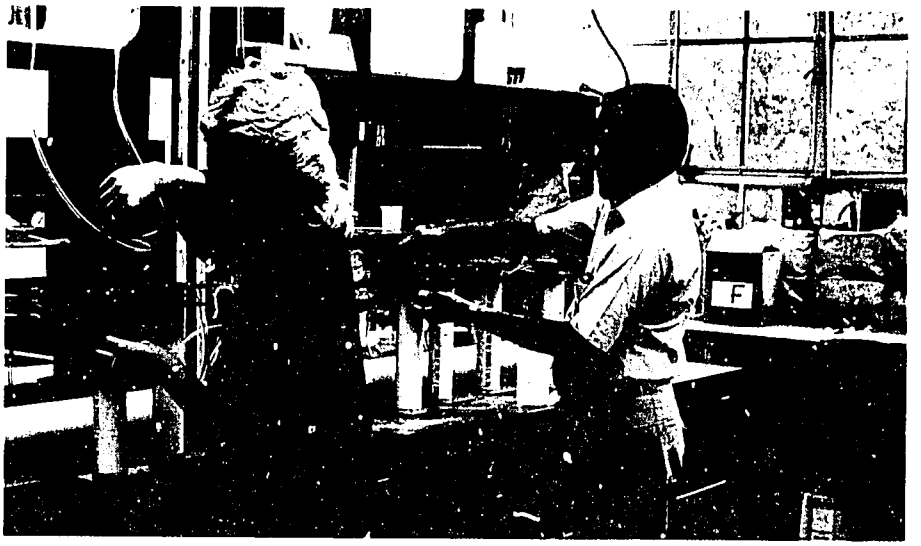
Tiny Time Pills Reduce Nitrogen Losses

Several STI groups are investigating prospects for coating or chemically modifying fertilizers to reduce nitrogen losses. One project, involving researchers from Louisiana State, the University of Florida, and Punjab University as well as from China's Rice Research Institute explores chemical additives such as phenylphosphorodiaidate (PPD) and N-(n-butyl)thiophosphoric triamide (NBT), which inhibit the tendency of urea to be transformed into ammonia. Urea is the fertilizer of choice in regions such as India but normally none of it remains in the soil within four or five days after it is applied. Inhibitors such as PPD and NBT have proven to be effective in stemming losses by 90 percent. As of now, unfortunately, these chemicals cost more than the nitrogen they save.

A more promising inhibitor, recently discovered, is calcium carbide, a chemical commonly employed to make acetylene gas for welding and miners' lamps. (Actually, it's the acetylene produced when calcium carbide mixes with water that furnishes the inhibiting action in the soil.) Working closely together, STI researchers N.K. Banerjee of the Indian Agricultural Research Institute and Arvin Mosier of the United States Department of Agriculture's research station in Fort Collins, Colorado, have found calcium carbide to be an effective, relatively-cheap nitrification inhibitor and have applied for a United States patent on an encapsulated form of it for this application. Other STI groups are exploring the practicality of coating fertilizer pellets with various substances that in the manner of tiny time pills might help delay chemical reactions leading to nitrogen loss. Researchers from the United States Department of Agriculture research station at Lincoln, Nebraska and from Punjab Agriculture University are testing urea pellets coated with neem cake, the abundant residue left after pressing oil from the fruit and seeds of the neem tree.

Other STI groups are coating fertilizer pellets with substances that might help delay chemical reactions leading to nitrogen loss.

In this flow-through experiment at Penn State, graduate student Nancy Vutz and Indian researcher Monickman from Tamil Nadu University measure the amount of ammonia lost from fertilizer. Air flowing over fertilizer mixed with soil in the white pipes bubbles into flasks containing boric acid. The researchers then measure how much ammonia is trapped in the flasks.

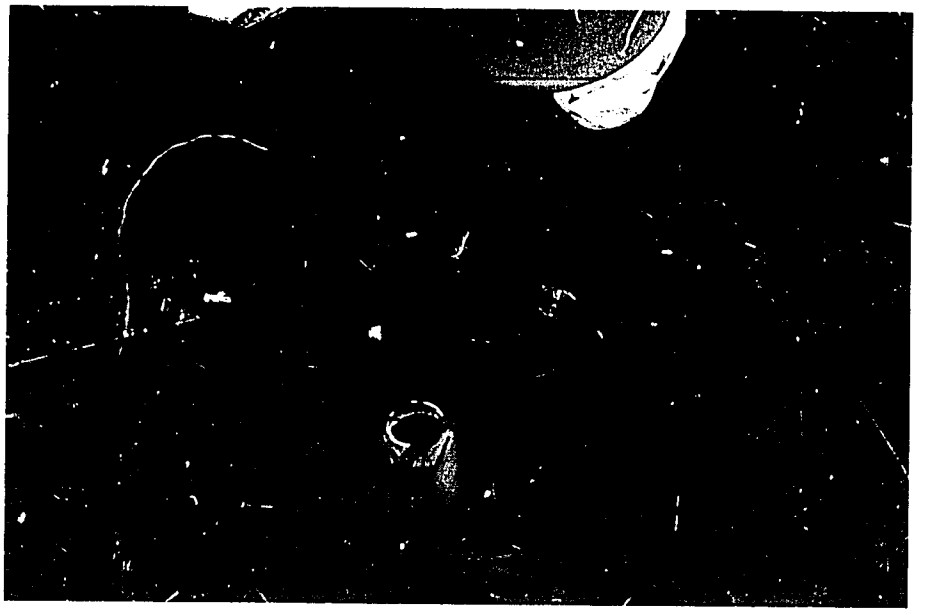


Lessons from Ancient Farmers

The U.S. has much to learn from India about the economic efficiency of no- or low-tillage farming, crop rotation, and use of green manures.

While India's main stake in fertilizer efficiency research is to expand agricultural yield, increasingly the major United States concern is preserving soil and the environment. Several STI researchers are convinced that American farmers could simultaneously reduce nitrogen waste and pollution and improve their soils by reverting to some of the age-old farming techniques still widely practiced by their Indian counterparts. The American farmer's reliance on single crops and his heavy dependence on artificial fertilizers, largely a post-World War II phenomenon, is now in question, what with the increasing cost of energy and the new comprehension of the costs to both soil and ecology.

Although United States farmers may have an edge on high-technology farming, there is much they may learn about economic efficiency from ancient practices of agricultural India, particularly in such realms as no- or low-tillage farming, crop rotation and use of organic fertilizers or "green manures" that reduce fertilizer requirements. These practices, validated by thousands of years of farming the world over, would reduce the rate of top soil erosion while increasing aeration and moisture retention and even improve crop quality if not yields. The use of crop residues as green manures and alternating crops between, say, wheat and any of a variety of nitrogen-producing legumes can restore the organic materials to soils that have been damaged by energy-intensive chemical fertilizers and single-crop cultivation. In some cases they increase soil nitrogen to the point of making manmade fertilizers unnecessary. Despite all the promise in these old-new methods, however, agricultural experts warn that there is nothing magical about them: exploiting them takes skill and careful management. James Power points out that it is often simpler to manage nitrogen-leaching with artificial fertilizers than through crop rotation, since the fertilizers can be applied at optimum times.



An Indian worker injects urea into soil around growing rice plants.

In cooperation with M. S. Maskina and others at Punjab University, Power's group at the Lincoln research station is exploring the effects on yield and nitrogen-efficiency of leaving varying quantities of corn and soybean residues in the field, both with and without tillage. Low-tillage use of crop residues is a common practice in much of India. These STI studies indicate that leaving more crop residues on the soil surface increases the efficiency with which plants use nitrogen from fertilizer. STI researchers have learned that the presence of some fertilizer nitrogen encourages plants to make greater use of the natural nitrogen from soil, a phenomenon they call the priming effect. Power speculates that the residue fosters soil, moisture, and temperature conditions in the soil that favor the microbial activity, converting atmospheric nitrogen to minerals plants can use.

These STI studies indicate that leaving more crop residues on the soil surface increases the efficiency with which plants use nitrogen from fertilizer.

Legumes as Cover Crops

In association with Punjab University and the Indian Agricultural Research Institute, the Nebraska team is also testing some two dozen different legumes as nitrogen-fixing cover crops to alternate with crops of corn, wheat or soybeans. A promising cover crop for the corn-belt is a bushy, low-growing legume known as hairy vetch. A focus of the Nebraska effort is to find legume candidates that don't deplete soil moisture in the already-dry central plains and upland states. One Indian import that has already shown promise in regions such as Oklahoma is the cowpea, a staple food crop in India similar to the blackeye pea.

STI researchers from Cornell University, the Indian Agricultural Research Institute, and Tamil Nadu University, are cooperatively exploring the potential of a variety of legume called Sesbania that originated in Africa. A tall, hemplike, moisture-loving plant, Sesbania can, in a

60-day growing season, fix as much as 200 kilograms of nitrogen per hectare—more than is needed for most crops. The plant is widely used in the Philippines as a cover crop in rice fields. Generally-speaking, rice cultivation wastes more nitrogen than dryland crops such as wheat. But Cornell's Duxbury argues that this disadvantage might be overcome if the source of nitrogen were legumes such as Sesbania, which may improve the structure and organic content of rice soils enough so that they hold more nitrogen. "We believe that legume green manure nitrogen, properly managed, may be used more efficiently in paddy-rice-based cropping systems than commercial fertilizer nitrogen, whereas the reverse is true for upland agriculture," says Duxbury.

Deep Fertilization à la Chinese

Meanwhile, a group at the University of California at Davis has torn a page from Asian rice-farmers' practice of deep fertilization. Chinese farm families often spend their winters rolling mud and fertilizer into balls, which are buried deeply into rice paddies at planting time. The Davis team finds that burying ammonia fertilizer only ten centimeters deep in flooded rice fields reduces nitrogen loss to only one or two percent of the surface loss while increasing rice yields.

Of all the STI programs, improvements in agricultural technology arguably promise the largest potential benefits not only for the United States and India, but for the world at large. For agriculture is the industry that involves simultaneously the greatest potential benefit to human survival and the greatest potential damage to the greatest portion of earth's surface. In even so mundane-seeming an inquiry as nitrogen fertilizer efficiency research, enormous stakes ride on getting it right.

At Tamil Nadu Agricultural University in India, green manure is grown for an experiment in which researchers measure the amount of nitrogen it provides rice paddies.

Four-year-old Stoneville, Mississippi poplars planted along the borders of a wheat field in Lalkua, India are already an impressive size. Relying on private and village initiatives to get trees planted, "social forestry" in India gives hundreds of millions of villagers an economic interest in planting trees. enormous manpower resources.

Reforesting India—And The World

The STI biomass program emphasizes reforestation, specifically restoring the one-third of India's area that is largely unproductive wasteland to woodland that can provide fuel, materials, and employment to villagers, while helping return the land to fertility and benefiting the environment at large.

In most less-developed countries, life at the village level is biomass-based. the inhabitants depend primarily on local plant-life for their food, fuel, fiber, fertilizer, shelter, and even medicine.

Unfortunately, these pressing needs often overwhelm the local and global interest in preserving forests. Lands are stripped of trees for firewood, cultivation, and grazing. Furthermore, the loss encompasses far more than local resources; it spawns water and wind erosion impoverishment of soils; far-flung flooding; damage to water-courses, lakes, and aquifers; eradication of animal and plant species—and, science has now concluded, ominous changes in the global climate. Forests are major sinks and potential sources of carbon dioxide—the otherwise-harmless gas that in the atmosphere acts like the glass in a greenhouse, admitting solar energy but inhibiting the return of heat from earth to space.

While the climatic consequences of global warming are still unclear, odds are that they won't be benign. Everywhere, human and natural systems are tuned to the climate that prevails. Growing forests act to soak up carbon dioxide, while burning or decaying wood augments it. Still, the world as a whole is better off to the extent that local energy comes from a renewable, self-sustaining source like managed forest growth than from imported fossil fuels.

The Indo-United States Science and Technology Initiative's Biomass Program proposes to help stem or reverse forest eradication. While India has yet to approve the program formally, a wide range of cooperative work is already underway in both countries. Presumably, the lessons learned will be applicable to other regions of the world where deforestation is a problem.

Wasteland to Woodland

The program emphasizes reforestation, specifically restoring the one-third of India's area that is largely unproductive wasteland—overgrazed, farmed-out, mined out, arid, salt-caked, or precipitous —to woodland that can provide fuel, materials, and employment to villagers, while helping return the land to fertility and benefiting the environment at large. The program aims to couple the short-term interests of local populations to environmental improvement by providing villagers with an economic interest in planting and maintaining woodlands.

American researchers were surprised to find that the eastern cottonwood, a variant of America's fast-growing poplar, thrives in India's arid, alkali-caked soils. At this nursery in Kalika India, researchers field test cottonwoods.

Righting Centuries of Abuse

In some cases, the strategy envisions very long-range payoffs. Much of the wasteland in India is the complex outcome of centuries of human abuse. Denuded slopes in the mountains of northern India, Nepal, and China, for instance, annually trigger not only local erosion but monsoonal flooding in lowland regions hundreds of miles away—often with enormous loss of human life. After many decades of repeated flooding, lowland soils have become semi-deserts—salt-caked hardpans where crops won't grow and where relentless grazing has damaged the root-systems of even the skimpy vegetation that remains.

In such instances, researchers would like to find not only trees with which to restore mountain slopes but others to help restore the soil in the wasted lowlands. A major component of the program involves scouring the world for woody species that can flourish in marginal lands unsuitable to agriculture. "In most of our projects, traditional methods of forestry don't apply," says Stanley Krugman, a plant geneticist with the United States Forest Service, and leader of the United States side of the STI biomass effort. "Our projects are designed mostly for disturbed, abused land with low fertility or alkalinity problems. We just want to get something that will grow there, maybe something lowly. Then, maybe we can work up."

At the same time, planners realize, if these plantings are to be preserved or renewed, they must also be of value to local inhabitants by supplying firewood, food, forage, or other benefits.

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A U.S. scientiest runs field tests on arid-land plant.

'oplars promise vastly reater output of pulp er acre per year than onventional species do.

The Versatile Poplar

A promising candidate for many areas seems to be the American poplar tree. In its hundreds of species and variants, which include the cotton-woods, poplars are to be found almost everywhere in the United States—a country that in sheer diversity of climate and soil regimes somewhat resembles India. Poplar is one of the fastest growing of trees; in average soils, with adequate moisture, some species attain a height of 75 feet in eight years.

Though lightweight, soft, and not particularly decay-resistant, poplar wood lends itself to many applications from burning to building. As firewood, it doesn't produce as much heat as heavier woods. Nevertheless, since poplar grows so fast, the actual energy production from a given piece of ground is generally greater than with other species.

Innovative Short-rotation Forestry

Already, India has numerous plantations growing some 300 families of American poplar. Many of these provide cuttings for plantings and experiments throughout India. The Indian experiments with fast-growing poplar have fostered an innovative "short-rotation forestry" that promises to find world-wide applications. In this approach, poplar trees are harvested at the age of only six to ten years, when the trees are past their period of maximum growth. By contrast, ordinary species commonly used for pulp, such as pines and other conifers generally aren't ready for harvesting until they are 15 to 20 years old or more. So, poplars promise vastly greater output of pulp per acre per year than conventional species do. Since wood is a good source of alcohol, fast-growing trees like poplar may over the long term offer promise as a renewable substitute for petroleum fuel.

A woman works in multi-purpose nursery in Jodhpur.

In consultation with Indian forest experts, a multi-disciplinary team from the University of Washington and Washington State University is seeking to perfect a poplar-based short-rotation forestry for application in the United States and elsewhere. According to Reinhard Stettler, a professor of forestry at the University of Washington, American paper companies are growing panicky about an emerging scarcity of domestic wood-pulp. India already has severe pulpwood shortages. So, research on large poplar plantations in both countries involves identifying the fastest-growing poplar species and trees and breeding or cloning hybrids suitable for short-rotation forestry under various growing conditions. Unlike pines and other conifers, poplars readily lend themselves to cloning and hybridizing.

American paper companies are growing panicky about an emerging scarcity of domestic wood-pulp.

Tough Shrubs from the American West

Adaptable as it is, poplar is not suited to some of the more arid or mountainous lands of India. For these, STI researchers from Texas Tech University's Arid Lands Institute are trying out some of the tough, pesky shrubs from the American West. These include mesquite and the saltbush, which, as its name implies, can thrive on salt-caked land. At the very least, these American "weed-trees" would provide the vital firewood and fodder that Indian villagers and their ubiquitous live-stock require. As a cooking fuel, saltbush leaves very low ash and has no odor. It has been successfully grown at the village level in India as part of a rural development project. Various saltbush varieties are being planted along drainage ditches and other unproductive areas, with villagers being instructed to try different techniques of maintaining them and of cooking with the wood.

Aside from the value of these scrub species as sources of fuel wood and fodder, researchers hope that over time they will absorb and remove the degrading salt, break up the hardpan soils, supply organic enrichment, and gradually restore lands to the point of sustaining more productive trees, grasses, or even crops.

At the Poplar Research Center in Pantnagar, newly planted seedlings from the United States will serve as future field plantings.

A Giant New Industry for Seed Production

These include sal, a source of high grade lumber, the lovely, spreading acacia, and the neem, which, along with lumber, furnishes edible fruit and oils. But unlike poplars, which sprout readily from simple cuttings stuck in the ground, many of the native species normally only sprout from seeds or seedlings. To make much of a dent in the mammoth task of reforesting India's planned 12.5 million acres of wasteland will require a gigantic new industry to collect or produce billions of seeds and seedlings annually.

For all the promise in such exotic imports, India still pins much of its reforestation hopes on the valuable trees native to the region.

Furthermore, foresters would ideally like to have these seeds and seedlings cloned from the best individual examples of the best species. India has long been a world leader in the tricky techniques of cloning plant tissue. More than 30 years ago, such institutions as the National Botanical Research Institute In Lucknow and the National Chemical Laboratory at Pune pioneered the cloning of commercially-valuable flowers. Since then, they as well as American botanists at Howard and other institutions have mastered the more difficult art of cloning woody plant tissue, such as fruit-trees.

Proud as they are of their laboratory successes, the Indians defer to the American genius for mass production. "We see America's role as helping convert that science into a technology," says T. N. Khoshoo, the ecologist who formerly headed India's Department of the Environment.

The Art of Cloning Indian Trees

One American laboratory pursuing this mission under STI funding is Howard University in Washington, D.C., which is cloning Indian trees such as neem and acacia as well as other hardy species from Africa's Sahel desert. Essentially, the art involves subjecting a few cells from a seed or growing shoot to a precise combination of hormones and nutrients at certain stages of the plant's growth cycle. Then, the culture is sterilized and transferred to an artificial growth medium and allowed to multiply under carefully-controlled conditions of light and temperature

emulating those of the tree's native habitat. At a certain stage, the cloned material may be packaged inside a nutrient capsule as a kind of artificial seed, plantable like any other. Sometimes, though, the culture is incubated until it reaches the size of a miniature seedling, at which point it is transferred to a nursery and raised as a mother tree from which more nursery stock is cloned.

John Rier, head of the Howard project, says that an advantage of the tissue-cloning technique is that it offers researchers opportunities to improve the species not only by selecting the very best specimens but also by transferring to the cloned cells beneficial genes from other plants—and even from bacteria. These genes might impart such desirable qualities as salt tolerance or resistance to drought, disease, or insects. Similar work with poplar tissue is underway at various other labs.

Social Forestry

Whatever species is involved, the work of replanting many millions of acres per year, as India contemplates, will take enormous manpower resources. So, India is sponsoring an innovative "social forestry," to give hundreds of millions of Indian villagers an economic interest in planting trees. Indian foresters accidentally discovered, for example, that certain crops planted in experimental tree nurseries actually benefited from the shade the young trees provided. One result is that many farmers are eager to acquire poplar cuttings to plant in their fields.

The self-appointed missions of STI's biomass project—finding suitable trees, learning to mass produce growing stock, and mobilizing millions of people for the planting operation—all seem to be essential keys to the reforestation of India. No doubt, similar approaches will be required when we finally undertake the vital task of reforesting the world.

An 11-year-old Indian poplar plantation is proof that this American tree adapts well to Indian climate and soils, some species attaining a height of 75 feet in eight years.