Chapter 1

The Potential of **Innovative Technologies**

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INTRODUCTION

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

Most LDCs, with their growing populations, are concentrated in a belt roughly 30 degrees north and south of the Equator. These tropical and subtropical lands contain diverse ecosystems: mountains, rainforests, semiarid regions, and deserts, and house some 45 percent of the Earth's people. The concentration of LDCs in the Tropics is not a coincidence but stems in large part from inherent physical limitations caused by climatic and soil constraints. As the populations of these nations have grown, many LDCs have come to face a myriad of severe resource problems: degraded soil fertility, deforestation, soil erosion, water pollution, and land-use conflicts, Concomitant social problems—including malnutrition, poverty, and political instability—are common as well.

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

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

Agriculture in tropical latitudes must contend with these and other physical dictates. It must work within increasingly severe economic constraints, too, as the costs of energy, water, equipment, and various other agricultural inputs, from seed to fertilizer, continue to rise,

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

The Agency for International Development (AID) is one mechanism by which the United States can help LDCs meet development and resource challenges. AID has been commended for many of its programs, but it also has been cited for its reluctance to change and for its lack of innovative vision at a time when innovation seems most necessary, This workshop reviewed a number of innovative biological technologies that might help LDCs enhance their agricultural productivity and it takes a special look at the role AID plays, and could play, in developing these technologies.

WHAT DO INNOVATIVE TECHNOL0GIES OFFER?

The innovative biological technologies chosen for discussion in the workshop represent only a sample of the diverse and adaptable approaches being studied by scientists here and abroad. The workshop examined the following:

- *promoting underexploited plant species, especially native species already adapted to local climates and conditions*. Nature is a storehouse of genetic possibilities including plants with potential as food, fodder, oil seeds, and export goods. Native plants can be integrated into cropping systems, reducing the need for fertilizer and water and enhancing resistance to pests and disease, There is also promise in plant breeding efforts and tissue culture, where native stocks are used to adapt crops to less than ideal environments, This reduces the need to alter the environment with fertilizer, irrigation, and other expensive inputs,
- *Developing multiple-cropping and inter-cropping systems suitable for specific tropical environments as a way to maximize land productivity*. Multiple cropping is intensive agriculture—growing two or more crops that share space and resources and can produce more per unit of land than monoculture. Proper design of the cropping pattern—e.g., using legumes—ensures and enhances soil quality while providing farmers with a range of products.
- *Designing integrated agricultural systems that take advantage of the special benefits provided by leguminous trees*. Various species of nitrogen-fixing trees (e. g., *Prosopis* and *Acacia]* could be used to revegetate deforested landscapes while providing food, fodder, cash crops, fuelwood, and increased soil fertility. Unlike legumes used in temperate agriculture (e. g., alfalfa), many of these tree species can fix nitrogen under arid conditions.
- *Cultivating "green" fertilizer for rice production*. Azolla, a small aquatic fern native to Asia, Africa, and the Americas, shows great promise as a green manure, The fern provides nutrients and a protective leaf cavity for a strain of blue-green algae, which in turn converts atmospheric nitrogen into a usable form. The nitrogen-rich azolla is grown in rice paddies, either before or along with the rice crop, It also can be harvested and transported to upland fields,
- *Using underexploited animal species to meet local needs for high protein food as well as to provide local populations with innovative cash crops*, For instance, in Peru, guinea pigs are being produced as an unconventional, but tasty and prolific, protein source for local diets. And in Papua, New Guinea, villagers are supplementing farm income by tending an additional garden crop—exotic butterflies for export.
- *Exploring the use of natural mineral soil amendments, e.g., zeolite minerals, that improve soil properties and extend fertilizer efficiency*. Because of their structure, zeolites have unique properties. They

are used today primarily as molecular sieves in industrial processes, but they show promise in agriculture. They seem able to help maintain nitrogen availability in soils and help plants resist water stress. More immediate benefits may show in animal agriculture, where zeolites can serve as feed additives and as decontaminants for feedlot wastes, and in fish farming. Zeolite deposits are thought to be widespread in many LDCs.

- *Reducing the need for commercial nitrogen fertilizer by inoculating suitable crops with beneficial soil bacteria—rhizobia—that biologically take nitrogen from the air and convert it to a usable form for the plant.* Legume rotations, of course, were fundamental to agriculture before the development of commercial fertilizers. These rotations relied on the natural abundance of rhizobia, but improved strains might garner even better results. Legume inoculants are used commercially in U.S. agriculture and suitable strains are being developed for LDC environments.
- *Increasing a plant's capacity to absorb nutrients by encouraging the growth of beneficial micro-organisms–mycorrhizal fungi—that live in association with some plants.* The mycorrhizae significantly increase the root's surface area—the part of the plant that assimilates nutrients from the soil.

THE WORKSHOP'S CONCLUSIONS

Workshop participants shared a general feeling that a range of promising, innovative technologies exists in various stages of development that could help LDCs sustain soil fertility with reduced fertilizer inputs. However, these technologies are underused and many important ones are being ignored by the development community. Many of the innovative approaches discussed are "technologies" in the broadest sense; they are new management systems, not new pieces of hardware.

Research on such innovative techniques generally is underfunded, perhaps because of technological complexity, human reluctance to stray too far from the norm, or well-intentioned skepticism about radically new or unproven approaches to agriculture. Thus, it is all the more difficult to document their worth. Most of the technologies, while promising, need pilot-scale testing in appropriate environments to determine potential problems or necessary alterations before they can be promoted on a wide scale. Also, workshop participants thought that much of the development of innovative technologies is occurring outside of, and perhaps in spite of, the national and international institutions normally considered responsible for maintaining natural resources and for dealing with problems of land quality and productivity.

A particularly interesting facet of these new technologies is that many of them could benefit not only LDC agriculture but also U.S. agriculture by providing opportunities for economic diversification, reducing soil degradation, and bolstering production while lowering capital costs.

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

INNOVATIVE BI0LOGICAL TECHNOLOGIES: HIGHLIGHTS OF THE WORKSHOP

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

It is clear that mankind could exploit more fully the range of botanical diversity found on Earth. In developing countries, various innovative uses of plant resources show great promise and could help enhance land productivity and increase food supplies. First, it is possible to expand the range of crops grown by using underexploited plant species, especially native species already adapted to local climates and conditions, Second, special attention could be devoted to the potentials of leguminous species, including leguminous trees, that are capable of converting atmospheric nitrogen into a usable form and thus enhancing soil fertility while reducing reliance on expensive commercial fertilizers. Further, innovative and conventional crops could be used together in multiple cropping or intercropping systems designed for specific tropical environments to maximize efficient resource use and land productivity.

The first day of the two-day OTA workshop was devoted to discussions of particular innovative biological technologies—their potential advantages for LDC users and problems limiting their use or development. Here are highlights of those discussions.

Underexploited Plant Resources

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

Now, however, there is renewed optimism about the agricultural potential of many of these plant resources. Native plants can be innovative sources of a wide range of goods—food for people and livestock, fuelwood for cooking and warmth, materials for homes and clothing, even oil seeds and other exports. The benefits provided are compounded because native plants can require fewer total inputs of fertilizer, herbicides, insecticides, energy, and in some cases water. This is because native species are adapted to local environmental conditions–soil type and quality, climate and terrain. Indigenous species often are more resilient to stress, as well; they have evolved defenses for local disease and pest organisms and evolved to be efficient users of available resources, whether water, soil nitrogen, or other necessary nutrients. The native plant concept is a reversal of the old philosophy of using inputs to change the soil to suit the crop. Here the crop is chosen to suit the soil. Examples of innovative plants include:

Winged bean (Psophocarpus tetragonolobus): Generally identified as a "poor people's crop" in developing countries, the winged bean's nutritional potential has been vastly underrated. Actually, this plant, sometimes called a "supermarket on a stalk, " has at least six edible parts. The leaves are used like spinach as a vegetable or salad; the flowers are edible, tasting somewhat like mushrooms; the pods, similar to green beans, are nutritious and palatable; the seeds are similar to soybeans and are composed of 17 percent oil and 42 percent protein; the tendrils are also edible and taste like asparagus; and the below-ground tubers contain four times the protein of potatoes.

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

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

Any change in the use of fertilizer, pesticides, irrigation, or machinery would depend entirely on the nature of the native plant chosen for cultivation—whether the particular plant could be used on an intensive or extensive basis, the degree to which the plant is susceptible to pests, and many other variables.

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

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

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

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

Multiple Cropping

Multiple cropping is intensive agriculture where two or more crops share space and resources, enhancing both land-use efficiency and long-term productivity. It is not a new technology but rather is at its roots an ancient technique that mimics the diversity of natural ecosystems.

Today's multiple cropping systems vary greatly depending on the character of the site being farmed. In general, multiple cropping systems are managed so that total crop production from a unit of land is achieved by growing single crops in close sequence, growing several crops simultaneously, or combining single and mixed crops in some sequence. Both "sequential cropping, " which is growing two or more crops in sequence on the same land, and "intercropping," which refers to various ways of growing two or more crops simultaneously on the land, are included in the broader term "multiple cropping."

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

It is important to point out that not all crop mixtures will produce better yields when multiple cropped. Certain combinations make better overall use of available resources and will be more successful; these crops are considered "complementary." One of the main ways to achieve such complementarily is by varying the crop components temporally—i.e., using sequential planting to achieve a multiple cropping system that avoids antagonistic interactions between the components. Such systems require special management—timely harvesting, the use of proper varieties, alteration of standard planting distances, special selection of herbicides so as not to create antagonisms or residual effects.

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

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

Agroforestry

Agroforestry is a multiple cropping management technology that combines tree crops with food crops, animal agriculture, or both. Like other multiple cropping systems, its goal is to optimize land productivity while maintaining long-term yields. In the past, small-scale traditional agriculture often included trees as part of the farm design, but interest in agroforestry's place in modern agriculture is just beginning. Agroforestry systems can be used to bring marginal lands into production—lands with steep slopes, poor soils, or widely fluctuating rainfall. But tree-crop combinations can also be used on prime agricultural or grazing land to further increase productivity. The main limitations to widespread use of agroforestry practices is lack of knowledge and expertise, and unwillingness in the agricultural establishment to accept the idea of long-term, diversified yields.

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

- more efficient use of vertical space and time, imitating natural ecological patterns and permitting more efficient capture of solar energy and nutrients;
- more biomass (organic matter) available to return to the soil;
- more efficient circulation of nutrients, including "pumping" them from deeper soil profiles when deep-rooted species are used;
- possible reduced wind erosion because of surface protection;
- promise for marginal areas because multiple cropping can take better advantage of variable soil types, topography, and steeper slopes;
- less susceptible to climatic variation [especially precipitation, wind, and temperature);
- reduced evaporation from soil surface;
- increased microbial activity in the soil;
- more efficient fertilizer use through the more diverse and deeper root structure in the system;
- improved soil structure, less 1ikelihood to form "hardpan, " and better aeration and infiltration;
- reduced fertilizer needs because legume components fix atmospheric nitrogen for themselves and associated nonlegumes;
- heavier mulch cover aids in weed control;
- better opportunities for biological control of insects and diseases because of component plant diversity; and
- potential benefits from mutualisms and beneficial interactions between organisms in crop mixture systems.

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

- competition for light, soil nutrients, or water;
- possibility of allelopathic influences between different crop plants caused by plant-produced toxins;
- potential to harm one crop component when harvesting other components;
- difficulty building a fallow period into multiple cropping systems, especially when long-lived tree species are included;
- difficulties in mechanizing various operations (tillage, planting, harvest, etc.);
- increases in evapotranspiration caused by greater root volume and larger leaf surface areas;
- possible overextraction of nutrients, followed by their subsequent loss from the agroecosystem if they are exported as agricultural or forest products;
- damage to shorter plants from leaf, branch, fruit or water-drop from taller plants;
- higher relative humidity in the air that can favor disease outbreak, especially of fungi; and
- possible proliferation of harmful animals (especially rodents and insects) in certain types of systems.

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

Reported lower yields, complexity of activities and management, higher labor demands, and difficulty mechanizing operations are all factors that discourage modern farmers from multiple cropping. Conventional agriculture is looking for short-term profits rather than at maintaining constant income over the long term, although it appears that the economics of farming may be changing to favor such innovative systems, especially in the LDCs.

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

Azolla/Algae Symbiosis

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

Azolla is a genus of small ferns that live naturally in lakes, swamps, streams, and other bodies of freshwater. Its tremendous agricultural potential lies in the fact that azolla lives in a symbiotic relationship with a nitrogen-fixing blue-green algae, *Anabaena*. The delicate azolla fern provides nutrients and a protective leaf cavity for the *Anabaena*. *In* turn, the algae produce enough nitrogen to meet the needs of both plants, plus some extra. Under the right conditions, the fern/algae combination can actually double in weight every 3 to 5 days and fix nitrogen at a higher rate than most legume *Rhizobium* symbionts. In 25 to 35 days, azolla can fix enough nitrogen for a 4 to 6 ton/ha rice crop during the rainy season or a 5 to 8 ton/ha crop under irrigation during the dry season. The nitrogen fixed by the fern/algae combination becomes available to the rice after the azolla mat is incorporated into the soil and its nitrogen is gradually released as the plants decay.

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

Azolla's ability to enhance soil fertility occurs both because it is an input of nitrogen and of organic matter. Nitrogen, of course, is a necessary plant nutrient. Humus, the rich organic material formed through plant decomposition, increases the water-holding capacity of the soil and promotes better aeration and drainage. Organic matter also can bind soil particles together, thereby improving the soil structure.

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

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

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

To be successful, azolla requires phosphorus fertilizer (0.5 to 1.0 kg P/ha/week), but this is not necessarily an increase over the fertilizer needed to produce a rice crop. Rice also requires phosphorus; so, rather than applying it directly to the rice the fertilizer can be given to the azolla in small weekly doses. Once the azolla is incorporated into the soil and begins to decompose, the phosphorus becomes available to the rice crop. Other inputs that enhance azolla growth in certain soils (e. g., potassium) are usually also applied for a high-yielding rice crop and so can be cycled in a similar way.

Water is the primary environmental constraint on azolla cultivation. As a freefloating, aquatic fern, azolla can only grow in areas with abundant, stable water supplies. Although it can last for months under refrigeration, the plant cannot survive for more than a few hours on a dry soil surface under direct summer sun. The azolla varieties available are not very stress tolerant; azolla cannot live in water outside a 0° to 400 range, and for adequate growth the daytime temperature should stay within 150 to 350°C. Humidity and pH also affect azolla growth.

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

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

Finally, social and political factors can work both for and against azolla's use, In some regions, especially where there are unfavorable land ownership patterns, low prices or other strong disincentives, farmers are not willing to shift from their immediate-subsistence, "plant and harvest" approach, because they do not see the long-term benefits. Political systems, too, can have an effect. The successful azolla programs in China and Vietnam depend heavily on specially trained "azolla teams" made possible by the structure of their farming communes and cooperatives. Societies less centrally organized could have difficulty adopting and transferring azolla cultivation techniques.

One of the major constraints on the development of azolla technologies is simply lack of information. Although it is an ancient agricultural system, its use has always been limited and it has not received much scientific attention. Research efforts are disorganized, scattered, and often repetitious. There has never been an international discussion of azolla research priorities. And once again, traditional segmented research approaches have proven inadequate because many of the problems that remain require a multidisciplinary approach.

As of 1980, azolla was cultivated as a green manure on about 2 percent of the harvested rice area of China and about 5 percent of the spring rice crop. In Vietnam, azolla grows as a winter green manure for 8 to 12 percent of the total harvested area, and about 40 to 60 percent of the irrigated spring rice in the Red River delta. But these two countries are only two of many that might tap azolla's potential. With research, strains could be found that are less sensitive to summer insects and temperature and cultivation could increase substantially. In essence, using azolla in rice production exchanges labor for nitrogen fertilizer. In countries with a shortage of cash but plentiful labor, azolla technology could be a step toward sustainable agriculture productivity.

Underexploited Animal Species

People interested in helping developing countries better their standards of living tend to promote resources and technologies with which they already have experience. One hears much, for example, of how genetic engineering can be expected to make possible self-fertilizing varieties of conventional crops such as wheat and corn. While understandable, this preoccupation with increasing the productivity of "mainstream" species overlooks a vast potential. Indigenous species often have the advantage of being relevant to the customs and values of local people.

Just as there are unfamiliar plants ripe for development as sources of food, feed, fiber, and fuel, so are there also unfamiliar animal species at least as promising. People traditionally have relied on a small number of animals that have been domesticated since prehistoric times. But domestication of some different species could pay tremendous dividends. In some countries, in fact, this is already beginning.

For instance, small animals are particularly suited to domestication in many developing countries because they require little space, they fit well into village or urban life, and they require no refrigeration since they can be eaten in one meal. Moreover, many of these species tolerate the climates of developing countries better than do sheep, cattle, and pigs, and they thrive on readily available diets. Thus, snail farming in Nigeria, giant toad farming in Chile, and guinea pig farming in Peru are all being developed to provide native people with much-needed high-quality protein at affordable costs.

In addition, at least some of these ventures can become the basis of new industries. Thanks to the efforts of researchers at the La Serena campus of the University of Chile, for example, intensive methods have been developed that furnish grocery stores, restaurants, and canneries with 10 to 15 tons of giant toad legs a year. Because the meat is an attractive white and tastes like a blend of chicken and lobster, it could prove to be a lucrative export as well. Giant toads are reportedly easy and inexpensive to rear. Kept in isolated ponds (so that they will not cannabilize other aquatic life) and supplied with insects attracted by flowers, shrubs, and rotten fruit, they require little attention and reach their market weight of about half a pound in 2 years.

The domestication of exotic species is, in fact, already producing foreign exchange for at least one poor country—Papua New Guinea. There, people who used to hunt crocodiles in the wild are now more profitably rearing hatchlings in captivity for the world skin market.

And in remote jungle villages butterflies are being raised on "farms without walls" to meet the rising international demand from museums, entomologists, private collectors, ordinary citizens, and the decorator trade.

Both the crocodile and butterfly projects demonstrate that development and the conservation of natural resources can go hand in hand. They also demonstrate something else: that to succeed, such projects need not only a concern for development but also a sensitivity to local environmental conditions and knowledgeable inputs of science and sociology.

In Papua New Guinea, for instance, the introduction of western-style cattle ranching could threaten the fragile tropical forest ecosystem. And such imported technologies would be completely unfamiliar to local people. By contrast, crocodile and butterfly farming that can be based on sound biological principles, would make it worthwhile for local people to use indigenous renewable resources wisely.

Zeolites

Zeolites are natural, three-dimensional, fine-grained silicate minerals composed of alkali and earth metals crystals that have an ability to separate gas molecules on the basis of size and shape. Over 100 forms have been synthesized and are now the mainstay of multimillion-dollar molecular sieve businesses that are important for industrial purposes in chemical and petrochemical firms in the United States and abroad.

Zeolites, however, also occur abundantly in nature, Almost 50 species have been identified from volcanic sedimentary deposits on every continent. Their widespread dispersion and special properties make them of interest to countries wishing to rely less on costly imported inputs to produce food because they appear promising as a means to improve animal husbandry, fish production, and crop yields. Zeolites have such promise primarily because they act as traps for nitrogen.

Zeolites get their name from the classical Greek words "boiling stones" because they froth when exposed to intense heat. Although their existence has been known to scientists since 1756 and they have been used since antiquity as building materials, their potential agricultural and aquacultural applications were virtually ignored until about 20 years ago. Even now this technology must be said to be suffering from neglect.

When added to animal feed, for example, zeolites have both inhibited the development of mold during storage and increased the growth rates of swine, rabbits, poultry, beef, and dairy cattle. Moreover animals raised on zeolite-enriched rations tend not to be subject to diarrhea or other ills. These minerals are thus a possible alternative to the controversial use of antibiotics in livestock feed.

Besides thriving on zeolite-supplemented diets, animals fed these minerals produce excrement that is at once almost odorless and exceptionally good fertilizer. This is because zeolites capture the ammonia ion from the feces and thus retain the biological availability of the nitrogen in animal wastes. Direct zeolite treatment of manure to reduce odor and improve its efficacy as fertilizer is also feasible, as is using the adsorption properties of natural zeolites to obtain pure methane for energy purposes from animal or other organic wastes.

In summary, the application of zeolites to animal husbandry holds some promise from the perspectives of livestock production, pollution control, crop yields, and energy alternatives.

Zeolite technology also has potential for the commercial fish breeding and farming. For one thing, the rations now fed to fish in such enterprises are quite expensive. As the nutritional requirements of fish are similar to those of poultry, the indications are that zeolite supplements could be expected to reduce feeding costs. For another, many fish species are raised in closed or recirculating water systems where the accumulations of nitrogen from their waste and the decay of uneaten food commonly causes sterility, stunted growth, and high mortality. Although various means already are used to deal with these problems, zeolite regulation of the nitrogen content of fish ponds has been reported to be cheaper and, under low temperature conditions, more reliable.

Similarly, the affinity of zeolites for nitrogen may be important in ponds and small lakes where eutrophication results in an oxygen-poor environment detrimental to fish life. Evidence suggests that the ability of these minerals to introduce free oxygen into stagnant water might increase the number of fish that can be raised or transported in a given volume of water.

The properties of zeolites also improve the performances of chemical fertilizers and pesticides, fungicides, and herbicides. For example, zeolite-treated soils retain the nutrients supplied by chemical fertilizers longer than soils treated with the fertilizers alone. The presence of zeolites as soil conditioners (also known as soil amendments) also has been found to regulate the release of critical nutrients from fertilizers. Improved yields of wheat, apples, eggplant, carrots, sorghum, radishes, chrysanthemums, and sugar beets have been reported.

Controlled release of micronutrients from the soil itself—e.g., iron, zinc, copper, manganese, and cobalt—has also been found when zeolites are used in conjunction with chemical fertilizers; this also prevents them from caking and hardening during storage.

Zeolites added to pesticides, herbicides, and fungicides seem to enhance their effectiveness. They can also be exploited to remove toxic heavy metals from the soil, thus preventing the toxic wastes from moving up the food chain from plants to animals and, ultimately, to people.

Nonetheless, the commercial use of zeolites in agriculture has generally been on only a relatively small scale and then predominately in Japan and other parts of the Far East. Even though a number of domestic companies have undertaken preliminary zeolite studies, little information is available on the long-term benefits or adverse impacts of these minerals on food production or the environment. Furthermore, even such information as has been developed is often proprietary. Though the desire of the private sector to keep its data confidential is understandable, this cannot help but lead to duplication of effort and slow progress.

Developing countries of course would be eager to reduce their costly dependence on imported fertilizers, fuels, and livestock feed. Cooperative ventures between the United States and these countries could improve knowledge of zeolite technology and, importantly, undertake long-term or large-scale testing projects under field conditions.

Biological Nitrogen Fixation

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

The use of legumes is not new; generations of farmers relied on rotations of legume plants to restore nitrogen in the soil long before the advent of cheap commercial fertilizers. Now, as energy costs skyrocket and fertilizer costs become prohibitive in many developing countries, legume use—green manure—may be the best remaining option for maintaining soil fertility and agriculture productivity.

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

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

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

Most soils harbor various native rhizobial populations and these strains will associate with sprouting legumes. But because these strains differ greatly in their effectiveness, it can be to the farmer's advantage to plant legume seeds that have been inoculated with proven strains of Rhizobium. The objective of inoculation technologies is to introduce sufficiently high numbers of preselected strains of rhizobia into the vicinity of the emerging root so that they have a competitive advantage over any indigenous soil strains of lesser nitrogen-fixing ability.

Commercial-scale inoculant use is common in the United States and Australia, Brazil, Uruguay, Argentina, India, and Egypt also produce inoculants. But while demand for inoculants is growing in many countries, it is not enough to simply import U.S. or other inoculants because they may not be suitably adapted to the LDCs climate, soils, and farming systems. BNF can be improved by selecting effective Rhizobium strains from the local environment and culturing these.

The major scientific constraint on developing BNF technologies is inadequate understanding of the interactions among specific host legumes, rhizobial strains, and various environments. This results in an inability to predict whether a given legume will respond to inoculation in a particular region. A lack of trained personnel in tropical regions also acts to limit research and development efforts, And because inoculant development and use requires some technical training, it may not be an easy technology for LDCs to adopt widely. But while legume use holds potential in all segments of agriculture, inoculant technology at present should only be advocated when there is a known need to inoculate.

Most legumes in the Tropics fix about 100 kg/ha/yr of nitrogen, although the forage tree leucaena can fix as much as 35o kg/ha/yr and some other species can fix as much as 800 kg/ha/yr. However, the benefit to nonlegumes is small when compared to the effects of nitrogenous fertilizer as applied in the intensive cereal production systems of the developed world. It is unrealistic to think that biologically fixed nitrogen will replace commercial fertilization of cereal and root crops. These crops are known to respond to levels of nitrogen far in excess of those that could currently be supplied through legume BNF. Thus, it would be profitable to determine ways to increase the contribution of legume BNF as a complement to nitrogen fertilizers rather than as an alternative.

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

Leguminous Plants: A great variety of leguminous plants—both food crops and species useful for fuelwood, fodder, and other needs—exist that could be cultivated in moist and arid/semiarid tropical climates, Winged bean is one extraordinarily valuable leguminous species. Tarwi, tepary bean, and yam beans are also nitrogen-fixing species with potential in moist tropical environments.

But not all leguminous species have high water requirements. Adapted plant species could be used in arid and semiarid regions as well, serving not only to enhance land productivity but also to stimulate depressed economies. For example, leguminous trees such as *Acacia, Leucaena,* and *Prosopis* could be important, fast-growing fuelwood sources. Because 80 percent of the wood consumed in the Third World is used as fuel, and wood shortages are of crisis proportions in some areas, the potential of agroforestry should not be underestimated,

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

Livestock fodder and cash crops, too, can be obtained from arid species. Arid-adapted, salt-tolerant shrubs (e.g., saltbush—Atriplex species), the pods of leguminous trees (e. g., *Acacia tortilis, Acacia albida,* and *Prosopis* species), and even cactus *(Opuntia* and *Cereus)* can expand the amount of forage available for local livestock while improving soil quality and enhancing the stability of the grazed ecosystems.

LDC farmers also could benefit from growing perennial, arid-adapted plants as cash crops, The species Jojoba is under development in southern California, Arizona, Mexico, and various semiarid LDCs. It produces seed that contains a rancidity-resistant, nonallergenic, liquid wax with lubricating properties equivalent to oil from the endangered sperm whale. Another desert plant, guayule, contains natural rubber and could become a major semiarid crop. Other potential lies with various species of drought-adapted leguminous trees that might be useful for the gums they exude, cacti that produce table-quality fruits, and a number of other innovative plant resources.

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

Optimal water-use efficiency in an arid/semiarid agroecosystem demands a mix of nitrogen-fixers and water-to-dry matter conversion specialist plants. For instance, cacti are a better supplier of the energy portion of livestock feed than legumes because they have a fivefold greater efficiency converting water to dry matter, However, legume leaf litter is important to create good soil fertility so the cactus can achieve its maximum water-use efficiency. Thus, a mix of plants is needed. And because livestock need both energy and protein, both energy- and protein-producing plants are required.

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

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

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

Other social influences also can make the acceptance and use of innovation all the more difficult. This is especially clear in research centers run by scientists either from or trained in developed countries; consciously or not, they often strive to promote their own cultural values and ignore the methods and effectiveness of native farming systems, As was the case with *Acacia albida,* the scientists may not be broadly trained—the agronomists failing to see the tree's food potential and the foresters underestimating its potential because it does not grow in forests and hence is not part of standard sylviculture concepts. It is not lack of concern that causes this problem. Rather, some agricultural scientists tend to be overspecialized and limited in their experience. Also, administrative structures often thwart attempts to develop integrated, innovative programs.

In practical terms, such innovative biological technologies offer real hope for LDC farmers. And the scale need not be big. A farmer, for instance, could plant *1* hectare with 200 *Prosopis* trees at 15 cents each for a total cost of *$30*. Land, a shovel, and buckets for watering the seedlings are the only prerequisites. With protein and nitrogen contents of *12,5* and *2,0* percent, respectively, pods from the trees could in 2 or 3 years produce *60* kg of nitrogen and return the *$30* initial investment.

Many of the innovative systems now receiving attention from the scientific community are actually widely used by subsistence farmers in the developing countries, However, the plants under cultivation now are of unselected genetic stock. It is comparable, in fact, to the use of unselected races of maize and wheat that were in use in the late 1800s in the United States and Europe. Subjecting the innovative species to a rigorous research and development effort could be expected to produce yield increases—perhaps twofold and threefold in 15 years—and other beneficial refinements of immense value to the people of the Third World. And yield increases in tree legume production, fuelwood production, cash crop production, soil fertility, and ensuing staple food production would have repercussions throughout the economy—more income; greater demands for goods; a larger tax base to support roads, schools, and health services; and increased employment. By working within the bounds of the ecosystems, innovative plant resources can help agrarian societies ensure sustainable and stable agriculture.

Mycorrhizal Fungi

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

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

There is another "biotic fertilizer" that might aid LDCs in their quest for sustainable agroecosystems. Mycorrhizal fungi are beneficial soil fungi that live symbiotically with a vast range of plants. Mycorrhizae are the structures formed—part plant, part fungus—by the symbiosis. These structures can extend up to 8 cm from the root into the surrounding soil, providing a bridge to transport nutrients back to the roots, The host obtains nutrients via the mycorrhizal fungi, while the fungus obtains sugars or other foods from the plant. The association results in a marked increase in the host plant's growth.

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

The fungi essentially increase the surface area of the plant's roots for absorbing nutrients. They actually can increase the plant's absorptive area by as much as *10* times. The fungi also extend the host plant's range of uptake; nutrient ions that do not readily diffuse through the soil—e.g., phosphorus, zinc, and copper—can be tapped from beyond the normal root zone by the fungi. Absorption of immobile elements can be increased by as much as 60 times by the plant-fungi symbiosis. perhaps the most important benefit provided by mycorrhizal fungi is increased phosphorus uptake. They also stimulate plant absorption of zinc, calcium, cooper, magnesium, and manganese. Plant uptake of mobile soil nutrients such as nitrogen and potassium is rarely improved because normal soil diffusion typically supplies adequate amounts of these regardless of root size.

Mycorrhizal fungi also can enhance water transport, prevent water stress under some conditions, enhance salt tolerance, and increase symbiotic nitrogen-fixing bacteria such as Rhizobium.

The potential offered by mycorrhizal fungi as biotic fertilizers, however, is not as vast as it might seem. Mycorrhizal fungi already occur in most soils and thus already grow in association with most agronomic crop plants. Because these fungi are so widespread, immediate needs for inoculation are limited. The inoculants currently available are for use on disturbed sites (strip-mined areas where indigenous mycorrhizal populations have been destroyed), on fumigated soils (any forest or crop nursery or plot that has been treated to remove soil-borne pests), and in greenhouses (because sterile soils lack native mycorrhizal fungi). In these situations, inoculation with mycorrhizal fungi has proven beneficial—e.g., in fumigated sand or soil, VA mycorrhizal fungi will increase the growth of citrus, soybeans pine, and peaches. Growth improvements also show in cotton, tomatoes, corn, wheat, clover, barley, potatoes, and many other crops.

But even though large-scale field inoculations with mycorrhizal fungi are rare because of adequate indigenous populations and because there is limited inoculum available, it seems likely that such applications might be much more valuable if, for instance, scientists develop mycorrhizal fungi inoculants that are superior to native populations. Because many indigenous mycorrhizae are relatively inefficient symbionts, improved strains of fungi could enhance plant growth, even in nonsterile soils. And because huge expanses of tropical soils (e.g., the Brazilian Cerrado) are either deficient in phosphorus or immobilize added phosphorus fertilizers, mycorrhizal fungi could improve the productivity of the marginal lands, if fungi having the ability to extract small quantities of fertilizer were developed and added to the soil.

Even though mycorrhizal fungi inoculants are used commercially in some circumstances, their importance is limited and many questions about their effectiveness remain unanswered.

For instance, fumigating fields with methyl bromide, a biocide that is extremely toxic to mycorrhizal fungi, often is followed by stunted growth in following crops. Yet little work has been done to determine the feasibility of field-scale application of inoculants. And even in nursery crops grown on sterile, nonmycorrhizal soils, inoculations receive limited use in part because detailed information regarding their value is lacking. For tree crops, however, some of the answers may be coming; the U.S. Forest Service is conducting a testing program using commercial inoculum on tree nursery sites throughout the country. When the tests are complete they should indicate the commercial feasibility of producing and using mycorrhizal inoculum in fumigated tree nurseries.

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

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