Chapter IX

Agrotechnologies Based on Symbiotic Systems That Fix Nitrogen

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Chapter IX

Agrotechnologies Based on Symbiotic Systems That Fix Nitrogen

ABSTRACT

When sustained productivity is sought from low-input farming systems, legume crops are especially attractive because of their ability to be self-sufficient for nitrogen supply. Life on Earth is dependent on transformations of atmospheric nitrogen to a form that can be absorbed from the soil by plants and used in protein synthesis. The process can be accomplished industrially, but at a very high energy cost, Biological nitrogen fixation (BNF) by symbiotic associations of plants with micro-organisms is more sound economically and environmentally than using nitrogen fertilizer in agriculture.

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

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

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

Legumes already are used widely and consistently, though as minor crops, in farming systems of the Tropics. Inoculant technology is used on a meaningful scale only in a few countries other than the United States and Australia. Great future potential rests in the development of:

- legume-based pastures and viable multiple-cropping systems including legumes for under-used savannahs;
- agroforestry systems that combine fast-growing, nitrogen-fixing trees, legumes, and other crops to meet the food and fuel requirements of the rural poor;
- fast-growing leguminous trees for reforesting water catchment areas following forest clearance;

- legume-based cropping systems to give sustained productivity in cleared jungle soils which typically exhibit a rapid decline in fertility under conventional cropping; and
- selection of deep-rooted, drought-tolerant leguminous tree-s that can serve as browse species in the world's dry lands.

The major constraints to full implementation of legume-based BNF technology in the Tropics relate to the delivery and acceptability of the technology at the farm level. The constraints are political, cultural, socioeconomic and, to a lesser extent, scientific. The major scientific constraint is inadequate understanding of host legume, rhizobial strain, and environment interactions. This results in an inability to predict whether a given legume will respond to inoculation in a particular region or not. A constraint on better understanding of these interactions is the lack of trained personnel to execute legume inoculation trials to determine the economic benefits. A lack of domestic inoculant production plants also constrains research, development, and production enterprises.

Legume-based BNF technology would benefit from:

- increasing economic and political pressure for greater energy efficiency in agriculture;
- increased recognition by decisionmakers in funding agencies and in governments of the potentials for exploiting BNF in developing country agriculture;
- an increase in trained professionals and technicians in tropical countries;
- improved integration of legume germplasm improvement programs and legume bacteriology programs;
- concerted application of international funding to establish a BNF Resource Center (this Center could be staffed, equipped, and budgeted to provide technical assistance; offer germplasm and information services; provide professional and technical training; conduct research necessary to adapt BNF technology to individual developing countries when it is beyond the capability of local researchers);
- improved opportunity to exchange findings from field research programs; and
- implementation of a sequence of standardized experiments designed to quantify the economic yield benefit attributable to legume inoculation under field conditions and followed by studies to quantify the nitrogen balance in multiple cropping systems that include legumes.

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

INTRODUCTION

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

Nitrogen is an essential component of all life forms; it is a cornerstone in the chemical structure of proteins, Ironically, nitrogen is abundant in the atmosphere—the air we breathe is 80 percent nitrogen. In its gaseous form, however, nitrogen occurs as dinitrogen molecules, each having two nitrogen atoms joined by a triple bond. This is among the most stable, inert molecules known and cannot be used directly, Thus, life on Earth is totally dependent on transformations of atmospheric nitrogen to a form in which it can be use readily by plants, and subsequently, by animals and man.

This process is referred to as "nitrogen fixation" and involves splitting dinitrogen into two nitrogen atoms that are then reacted with hydrogen (generated by splitting water molecules) to form first ammonia and subsequently a range of nitrogenous compounds. Nitrogen fixation can be accomplished industrially, but the process is one of the most energy demanding in today's agriculture. The energy cost of fixing nitrogen in the form of urea, ammonium sulfate, or ammonium nitrate is compounded by the additional costs involved in transport and application. Additionally, the rather small proportion of nitrogen-fertilizer actually taken up by the crop to which it is applied and the serious environmental pollution that can be caused by nitrogen lost from agricultural land through run-off are incentives for appraising alternate nitrogen-sources. Self-sufficiency for nitrogen supply as exemplified by the legumes is thus a highly desirable trait.

THE BIOLOGICAL NITROGEN FIXATION (BNF) PROCESS

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

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

AGROTECHNOLOGIES BASED ON BNF BY LEGUMES

Most farmers in the Tropics do not know that legumes fix nitrogen. Yet, traditional and modern farming systems of the Tropics almost invariably include legumes (52,59), Thus, legume cultivation happens because farmers over many centuries have recognized that legumes are valuable components in farming systems rather than from intentional exploitation of biological nitrogen fixation per se.

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

THE USE OF LEGUMES

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

Direct benefits from BNF by legumes in cropping systems arise from the multiple uses of plants in the legume family. Though known primarily for grain, forage, or feed production, legumes are also cultivated in the Tropics for timber, fuelwood, green manures, oils, fibers, gums, drugs, dyes, and resins. Additionally, they may be used as hedges; ground covers for weed, insect, and disease control; as soil stabilizers on terraced slopes; or simply for shade or as ornamental (59).

Indirect benefits accrue from the stability of performance and assurance of some economic return for at least one component under unfavorable conditions when legumes are intercropped with other crops. Stability is afforded, for example, in erratic rainfall zones when the components in the intercropping system are separated in time such as with sorghum/pigeon pea and groundnut/cotton (59,56). When there is an outbreak of pests or diseases, maize/beans and other intercrops afford stability of yields and income (3,32). Other indirect benefits accrue from the ability of legumes to make a net contribution of nitrogen to the soil under some circumstances, thereby reducing the nitrogen-fertilizer requirements for a companion or following nonleguminous crop.

INOCULANT TECHNOLOGY

There is a commonly held view (2) that tropical legumes are much more promiscuous than temperate legumes—that they nodulate freely with a wide range of tropical rhizobia and that tropical soils are laden with so many bacteria that effective modulation is virtually guaranteed without inoculation (49,30). This view is no longer well-founded. Some species and accessions from genera previously considered to be promiscuous (2) require specific strains of Rhizobium (9,28,26) or form highly effective symbioses with only a few out of the wide array of strains with which they nodulate (69, 16,22). Recent intensification of interest in the tropical legumes and their rhizobia is revealing much greater variation in genetic compatibility and nitrogen fixation effectiveness than has generally been acknowledged (38,23), A plea has been made for recognition that tropical legumes fall into one of three categories (23).

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

Just as with the temperate legumes, the likelihood that compatible, effective rhizobia will not always be present in sufficient numbers in the soil microflora is the rationale for using inoculation technology for tropical legumes (24). When a tropical legume seed is sown uninoculated in a tropical soil, a native rhizobial population of strains differing greatly in their symbiotic effectiveness compete for the finite number of modulation sites on the legume roots. Many forage legumes bear only 10 to 20 nodules on which they depend for nitrogen during the first three months of their establishment. Thus it becomes critically important that each of the nodules that form on the root contain a strain of *Rhizobium* that is fully effective in fixing nitrogen. The underlying objective in inoculation technology is to introduce sufficiently high numbers of preselected strains of rhizobia into the vicinity of the emerging root that they have a competitive advantage over any indigenous soil strains of lesser nitrogen-fixing ability in the formation of root-nodules.

Inoculation technology involves:

- selecting strains of rhizobia that are compatible and effective nitrogen-fixers with particular legumes;
- multiplying selected strains to high population densities in bulk cultures;
- incorporating the liquid rhizobial cultures into a carrier material (usually finely milled peat) for packaging and distribution; and
- finally, coating the seeds of legumes with the carrier or implanting the soil with the inoculant directly into the seed drill (64, 14,25).

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

The host genotype interacts with the infecting strain of *Rhizobium* in determining the level of nitrogen fixation, with the host playing the dominant role. Thus, two sources of variation (plant and *Rhizobium* strain) can be exploited in selection programs, Most commonly, though, the plant is selected independently and a suitable strain sought thereafter, thus allowing only for exploitation of strain variability. The range of specificities of host genotype interactions is well-illustrated by soybean (77) and in the African clovers (51).

Three approaches to select strains for inoculants exist: select numerous inoculants, each with a highly effective strain for individual species; select “wide-spectrum” strains that vary from good to excellent in nitrogen fixation with a range of legumes; or select multiple-strain inoculants containing the best strain for each host species. There may be a conflict between the option that would be chosen for commercial expediency and that which is scientifically preferred (25). In Australia, "wide-spectrum" strains are used when these are available, but there is increasing use of specialized inoculants with specific strains for individual hosts. Despite findings that suggest that multi-strain inoculant should be avoided because of possible antagonistic and competitive effects (46) and competition in nodule formation from the less effective strains (17) this is the approach used successfully by the U.S. inoculant industry.

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

Most legume inoculants are prepared by adding liquid cultures of rhizobium to a finely ground carrier base material such as peat. Although mixtures of peat with soil or compost mixtures, lignite, coir dust, and some other organic materials have been used, peat has proven to be the most acceptable carrier worldwide. Agar, broth, and lyophylized cultures are not recommended because survival rates for these forms are poor (20,21,72).

Peat cultures can be prepared in two ways. Either ground (milled) peat is mixed with a high viable count (more than 10^9 rhizobia / ml) broth culture in sufficient volume to provide the minimum number of rhizobium acceptable for use, or sterilized peat is inoculated with a small volume of culture and incubated to allow multiplication of the rhizobia. The choice of method will depend on two factors—the survival of the rhizobia in peat in numbers high enough to meet a minimum standard of quality, and the availability of suitable, sterilizable containers and sterilizing facilities. The two factors that most affect survival of rhizobia in peat are temperature of storage and sterility of the peat. There are differences among species and also between strains of the same species of *Rhizobium* in their ability to survive well in peat (63).

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

Although control of inoculant quality is primarily in the manufacturer's interest and therefore his responsibility, control by external bodies provides protection from less scrupulous operators and genuine failure of a strain outside manufacturer control. Not all countries back their control labs with legislation. A control group requires suitably qualified and experienced personnel with facilities to permit normal aseptic culture transfer and plant growth facilities suitable for legumes from many environments. Methods of assessment involve both qualitative and quantitative tests. The number and extent of these may vary according to competence and experience of manufacturers and the standards desired. In Australia, this control extends to holding stocks of the strains used in inoculants. This is not the case in the United States (29,70). In addition to assessment of quality throughout manufacture, it is important to monitor product quality in retail outlets. Standards acceptable at this level may vary between countries. It is important that standards be realistic and within the capability of manufacturers yet ensure that sufficient viable rhizobia are applied to the seed to provide a satisfactory inoculation. In many instances this can be as few as 100 rhizobia per seed but in cases of severe environmental stress as high as 10,000 or even 500,000 (1 1,12,21),

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

The first attempts at inoculation involved transferring soil from one field to the next, but when the organisms responsible for nodule formation were isolated, artificial cultures soon replaced the laborious soil transfer technique, The usual inoculation technique is to apply the inoculant to the seed just before sowing either as a dust or as a slurry with water or adhesive solution. Adhesives such as gum arabic or cellulose not only ensure that all the inoculum adheres to the seed but also provides a more favorable environment for survival of the inoculum. Pelleting of seed with finely ground coating materials such as lime, bentonite, rock phosphate, and even bauxite (11,12) have been used to protect rhizobia during their time on the seed coat. pelleting is a simple on-farm technique (11,50) but custom-pelleted (by seedsmen at farmer's request) and preinoculated seed is now more popular. This latter procedure is potentially able to provide high populations of rhizobia on the seed for a long period of time (one growing season to the next) but has not yet been fully developed or exploited.

Most preinoculation procedures arc based on multiple coatings, alternately of adhesive and finely ground pelleting materials as used in simple pelleting, The peat inoculant is included as one (or more) of these coating layers. Soaking seeds in a broth suspension and then exposing them to either high pressure or vacuum to impregnate the rhizobia into or below the seed coat has not proven successful. Theoretically, rhizobia introduced in this way would be protected from drying and other adverse environmental conditions, but the quality of products produced commercially has been variable to very poor (16,10,66). It is, in fact, an indictment of the research workers in this area that 25 years has yielded so little progress in an area where there is so much potential,

These production techniques are particularly applicable to less well-developed and inexperienced rural groups, If high-quality and reliable products were marketed by a manufacturer or seeds distributor, the farmer would not need to be involved in legume inoculation.

A recent alternative to pelleting and preinoculation has been the use of concentrated liquid or solid granular peat culture that can be sprayed or drilled directly into the soil with the seed during planting. Suspensions of rhizobia either as reconstituted frozen concentrates or suspensions of peat inoculant can be applied with conventional equipment. Similarly, granulated peat inoculants can be drilled in from separate hoppers on the drilling equipment. These methods have been especially successful for introducing inoculant strains into situations where there are large populations of competing naturally occurring soil rhizobia (6), in cases of adverse conditions such as hot-dry soils (68), and where insecticide or fungicide seed treatment precludes direct seed inoculation (67,12). Solid inoculant, also known as granular or "sod implant" inoculum, is advantageous also, where seeding rates for crop legumes of 70 to 100 kg/ha make on-the-farm inoculation logistically impracticable.

CURRENT USE OF LEGUME-BASED BNF TECHNOLOGY

The Use of Legumes

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

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

Production statistics for tropical grain legumes are seldom accurate. Most of the production is on a subsistence scale on small farms and the yields are seldom included in official statistics. Thus, a figure of 186 million tons (31) should be regarded as an understatement.

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

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

Inoculant Technology

Inoculant technology is used widely on a commercial scale in the developed countries. The United States and Australia have substantial industries to produce, distribute, and market legume inoculants. There is also commercial-scale production in Brazil, Uruguay, Argentina, India, and Egypt, Inoculants are available commercially in many other countries but they are produced in U.S. or Australian laboratories. Some research centers, such as CIAT and the University of Hawaii NifTAL Project, produce inoculants in pilot-scale plants as a service to researchers and occasionally to legume growers. Demands for inoculation technology are increasing, primarily because of the increased use of soybeans.

There are dangers in trying to satisfy this demand by importing inoculants developed in the United States or elsewhere. This is because present inoculation technology has not proven transferable. That is, strains of Rhizobium and inoculation methods developed for conditions at one location in a particular farming system do not perform equally well at another location in a different farming system. Furthermore, the viability of rhizobia in legume inoculants is greatly affected by storage conditions during shipment. Since producers are unable to control such factors, no guarantee can be given that the inoculants are of merchantable quality on arrival at their destination. For both these reasons inoculation failures are a common occurrence and this is harming consumer acceptance of the technology. An ideal scenario for improved implementation of BNF technology is described in a later section.

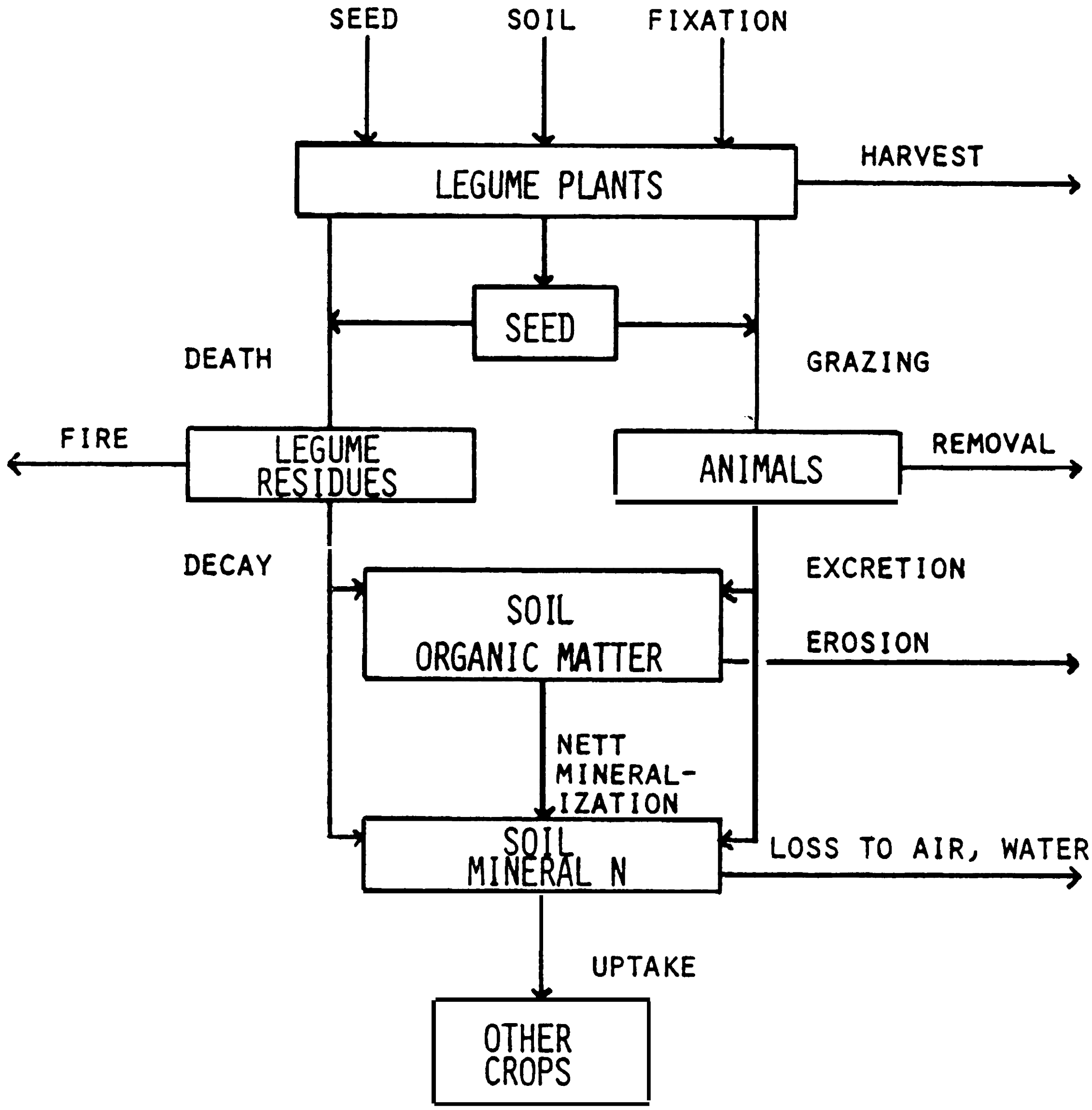
The organizations funding research to adapt inoculant technology to the circumstances where it will be used in tropical countries include: UNDP by its support to the IARCs through CGIAR and for a specific research program involving IITA and BTI/Cornell University; UNEP and UNESCO support inoculant technology under the MIRCEN Project; FAO is actively considering the role it might play in the adaptation of inoculant technology for use in developing country agriculture; USAID through its contracts with University of Hawaii (NifTAL Project) and USDA, Beltsville ARC (World Rhizobium Study and Collection Center) through grants under Section 211(d) to the U.S. Universities' Consortium on BNF in the Tropics, and through a portfolio of small grants administered by USDA SEA/CR; USAID and several governmental and nongovernmental agencies that support the CGIAR are thereby sponsoring work at CIAT, IITA, ICRISAT, and ICARDA on the adaptation of inoculant technology for use in the Tropics.

HOW BNF BY LEGUMES INCREASES CROP YIELDS AND SOIL FERTILITY

Consider the possible pathways to transfer nitrogen from legumes to other crops (figure 1), The relative importance of the transfer pathways of nitrogen from legumes to other crops and/or the soil can be estimated. Nitrogen gains per hectare per year entering the cycle as seeds (1 to 2 kg) (41) and in acid rainfall (1.5 to 3.5 kg) (78) are small compared to the nitrogen fixed biologically. About 50 percent of the nitrogen accumulated in legumes in fertile soils is attributed to BNF (71), though the proportion from fixed nitrogen will be greater in impoverished soils and lesser under nitrogen fertilization. Nitrogen accumulation in legume monocrops ranges from 50 to 350 kg/ha/year, It is generally accepted that nitrogen fixation of around 100 kg/ha can be expected from the majority of grain and forage legumes. Higher levels are possible for leucaena and other forage legumes with a 12-month growing season. Low levels are likely for bad nitrogen fixers with short growing seasons (e. g., Phaseolus *vulgaris).*

As an example, follow the fate of 100 kg of biologically fixed nitrogen entering the cycle. Between 60 and 90 percent of the nitrogen accumulated in legumes is removed as grain—depending on the species, harvest index, and harvesting practice, or as animal products depending on the intensity and selectivity of grazing. Thus, in an intercropping system only 10 to 40 kg nitrogen could potentially benefit other crops. Some of the organic nitrogen of the legume residues is mineralized rapidly. The rest is added to the soil organic matter pool and it

Figure 1.—Pathways for Flow of Nitrogen From Legumes to Other Crops (from Henzell, 1977)



is mineralized slowly over a much longer period, Studies show that 60 percent is probably the maximum portion of the nitrogen in the organic residue of a legume crop that could be mineralized in time to benefit a following crop.

If 50 percent of the nitrogen is used in the initial mineralization, in a cropping system where the legume fixes 100 kg/ha/year only 5 to 20 kg of nitrogen is likely to benefit the following crop, One practice that could substantially increase the contribution is green manuring. If one year's production were incorporated into the soil, it would leave a residual benefit of 50 kg/ha/year for the following crop. Experience has shown, however, that crops do not necessarily respond to exaggerated applications of green manures.

There are few farming systems where green manuring is economically feasible (41,8) since land is tied up without immediate economic return. Where green manuring is practiced, 5 tons of green matter per hectare is an accepted application rate (54). This would represent an addition of only 40 kg/ha of nitrogen to the soil, of which only about 20 kg would mineralize to the benefit of the crop. Green gram contributed 22 kg of nitrogen to following crops and calapo/stylo green manure contributed 15 kg (l).

The situation is more complex in mixed cropping systems where the legume and nonlegume are growing concurrently. Legumes usually take up less soil nitrogen in competition with nonlegumes and a greater fraction of the nitrogen they accumulate in a mixed crop is from fixed nitrogen. Somewhat surprisingly, the nitrogen fixation of intercropped beans (*Phaseolus vulgaris)* per hectare is not significantly different from beans raised in monoculture (36). This is attributed to competition between the maize and the bean for light and nutrients beginning after the decline in nitrogen-fixing activity in the bean's root nodules. Not all legumes shut down nodule function as early in the growth cycle as *Phaseolus vulgaris* but the effect of intercropping on nitrogen fixation may be detrimental in other intercropping systems.

It is a common misconception that there is substantial direct transfer of nitrogen from the legume to a nonlegume companion species in a mixed cropping system. There is no convincing evidence that actively growing, healthy legumes, whether grain or forage, excrete significant amounts of nitrogen from their roots or nodules. The hypothesis originally proposed by Virtanen and coworkers (73,74,75) that surface excretion of simple amino compounds from healthy, functioning legume root-nodules resulted in direct transfer of significant quantities of nitrogen to nonlegume companion species has found little support from other workers (45,7,47,80,81).

Subsequent research under carefully controlled conditions using the "fox box" technique (18) indicated that excretion of a wide range of substances from plant roots does occur, but that the quantities involved are small, less than 0.5 percent of the plant's nitrogen (65). Stated differently, a crop fixing 100 kg of nitrogen a year would excrete only 0.5 kg to the soil.

Nitrogen benefit to nonleguminous crops through association with companion legume species is considered to be of an indirect nature through loss and decay of shoot, root, and nodule tissue, or by recycling via the grazing animal, rather than by a direct pathway (76,15, 29,79),

Clearly then, mixed cropping systems that aim to use legume-fixed nitrogen for the benefit of a companion nonlegume species must match species so that the nonlegume is longer-lived than the legume. Nitrogen will be released in significant amounts only after cessation of active growth and decomposition of tissues of the legume. The maize/bean association used widely in Latin America shows this principal. Beans fix about 20 to 40 kg of nitrogen per growing cycle (34). Assuming 70 percent removal of nitrogen as protein in the legume grain, this leaves only 6 to 12 kg in legume residues, of which 3 to 6 kg (assuming 50 percent mineralization) will be mineralized in time to benefit the maize. Some estimates place the mineralization that can benefit a companion species as low as 20 percent. Consistent with this, it is not uncommon for there to be no detectable nitrogen benefit in companion crops that are intercropped with legumes.

It is evident that the BNF benefit to nonlegumes due to inclusion of legumes in a cropping system is small compared to the level of nitrogenous fertilizer used in the more intensive cereal production systems of the developed world. Thus, the principal contribution of BNF to human nutrition will continue to be via the protein in legume grains. Any suggestion of substantial replacement of nitrogen fertilization of cereals and root crops by biologically fixed nitrogen is unrealistic because these crops respond to levels of nitrogen fertilizer far greater than those currently supplied through BNF by legumes, Thus, there is an urgent need to devise ways to increase the contribution that BNF by legumes can make to cropping systems as a complement to nitrogen fertilizer-based production, rather than as an alternative to it.

Legumes can be managed to increase their nitrogen contribution. They vary in total nitrogen fixed, the proportion retained in non-harvested residues, the percentage nitrogen level in residual tissue, and the facility with which the organic nitrogen is mineralized. Thus, some species, managed in particular ways, will give greater residual nitrogen benefits. Given this, the priority now given in legume breeding programs to improving their harvest index, i.e., maximizing the fraction of each plant's total production that is removed as grain, should be called into question.

In summary, the principal benefits from BNF through the use of legumes in farming systems in the Tropics are derived from the dietary protein of the legume grain, the multiple uses that legumes serve for the subsistence farmer, and the greater stability of yield and financial return of intercrops over monocrops. The indirect benefits from contribution of biologically fixed nitrogen to companion or following species are small but are significant in the context of input levels in subsistence farming.

Insufficient reliable data exist on the potential benefits from enhancing, through inoculant technology, the nitrogen fixation in tropical legumes. It is tempting to recommend rhizobial inoculation of all legume sowings as an insurance measure against the risk of modulation failures that would otherwise occur. However, inoculant technology does represent a cost, albeit small, and does add a degree of complexity to the sowing practice. Thus, inoculant technology should only be advocated when there is a known need to inoculate and a demonstrable benefit. Additionally, the concept and practice of inoculant technology is so foreign to the farmer's normal practices that it should not be recommended lightly. A subsistence farmer can be forgiven for not comprehending nor accepting a technology that involves sticking black powder containing bacteria to his seeds. This contradicts concepts which he had only recently learned, namely, that bacteria are bad and clean seed is important. It is to be questioned whether inoculant technology in this form will ever be accepted widely among subsistence farmers in the Tropics and Subtropics.

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

FUTURE POTENTIAL OF LEGUME-BASED BNF TECHNOLOGY

Despite their seeming attractiveness for sustained productivity from low-input production systems, and despite also their consistent strategic use in many farming systems of the Tropics, legumes have remained minor crops in the systems where they occur (52). Why is this the case, and what factors would lead to greater use of nitrogen fixed biologically by legumes? A small-scale, subsistence farmer elects to raise those crops that best meet his household's needs but he also chooses one crop, at least, to sell or exchange for goods or services. Large-scale farmers consider the economic return and ease of management associated with the crops they plant. A grower preference for cereals over legumes, when the grain is to be marketed, would be understandable. It is usual for yields of cereal grains to be as much as four times higher than legumes (typically 3.0 t/ha vs. 0.7 t/ha), Although the protein content is much higher in legumes (30 percent) than in cereals (6 percent), the market value of legume grains, albeit higher than for cereals, does not compensate the grower for their low relative yield.

Many factors will contribute to an increase in the use of legumes. Cereals will continue to be the major source of protein and calories for human nutrition worldwide, but an increase in importance of root and tuber crops and plantains over the next two or three decades is anticipated (58). Legumes can be expected to be one means of complementing the dietary quality of these starchy protein-deficient foods.

Another factor that has already caused a reappraisal of biological nitrogen fixation through legumes is the cost and availability of energy to produce nitrogen fertilizers. Already, 20 percent of nitrogen fertilizer production in the United States is cost-ineffective because of the cost of energy (in the form of natural gas) for the process. Producer costs have been calculated as $160/ton (61) whereas the selling price is in the range of $85 to $105/ton. Thus, biological nitrogen fixation through the use of legumes may be resorted to increasingly, not only to reduce the cost of on-farm inputs, but also to save foreign exchange and avoid overdependence on foreign powers.

But economic pressure alone will not guarantee adoption of BNF-based technology without compelling demonstration of greater benefits from BNF by legumes. The dramatic increase in interest in BNF since the energy crises of 1973, 1974, and 1979 has brought it under the scrutiny of agencies and individuals whose concern is its viability as a productive agricultural technology now rather than its often acclaimed potentials for the future.

The agricultural research community needs to undertake a comprehensive program of technology development where the relative distribution of funding and manpower investment is realistically prioritized. Research to stabilize grain legume yields can increase the contribution of biological nitrogen fixation in tropical farming systems more than much of the research on the BNF process per se in grain legumes. Similarly, research to select forage legume germplasm that is adapted to the soils and climates of the world’s underused savannahs, and development of appropriate legume-based pasture management technology, can be expected to increase the use of biological nitrogen fixation even without further research on the BNF process. These statements assume that effective modulation can be guaranteed. Since this is not always the case, those specific aspects of BNF research that study the factors that limit modulation and nitrogen fixation in tropical soils should be given highest priority.

CONSTRAINTS ON IMPLEMENTATION OF BNF TECHNOLOGY

There are still many unknowns in the scientific understanding of BNF, and research into the biochemistry and genetics of the process is particularly intense and competitive. But few, if any, of these unknowns are really constraining the implementation of legume-based BNF technology. The basic principles of inoculant technology have been known for many years and have already made major contributions to agricultural production—initially in Australia and, more recently, worldwide as soybean cultivation has been increasing. The real constraints to fuller implementation of BNF technology relate to delivery of the technology, both to potential inoculant producers and to farmers, and acceptability of the technology.

There has not been adequate demonstration, under realistic conditions in the developing countries, of the yield increases and/or reduced fertilizer needs that are repeatedly stated to be the benefits of BNF technology. In some cases, inoculation trials have been performed and no response obtained. But these trials have been mainly with imported inoculants, the quality of which at the time of their use was not or could not be verified. Thus, a related constraint is the lack of trained personnel with the essential combination of agronomic and microbiological skills for executing production-oriented research on BNF technology.

Research is necessary to adapt BNF technology and develop appropriate *Rhizobium* strains and inoculation procedures for use in the Tropics and Subtropics. Current inoculation technology as used in the United States and Australia is suited to legumes grown under favorable conditions with relatively high complementary agronomic inputs. Transferability of this technology to situations where the legumes are grown under marginal conditions with minimal inputs, and confronted with one or more soil and climatic stresses, is in some doubt (37).

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

For example, in providing inoculant services in Latin America and Hawaii, it has been common to receive data from soil analysis together with requests for inoculants. Farmers expect the selection of legume inoculant to be made after consideration of local soil and climate, just as would be the choice of crop variety. Yet there are few instances in which an inoculant strain is recommended in commercial production because of the soil characteristics. *Rhizobium* strain CB 81 is recommended for *Leucaena leucocephala* sown in acid soil and NGR 8 for alkaline soils (48).

When soil characteristics are very different, the response to inoculation and the relative performance of rhizobial strains is also different. Even apparently similar soils can show different performances. Thus some authors advocate that simple "need-to-inoculate" trials always be performed at the local level due to the unpredictability of the response to inoculation (11,22,23). This suggestion would result in legume inoculation being tested, essentially by trial-and-error, at every site where legumes are to be grown. Inoculation technology needs to be more transferable than this, otherwise its value as an agrotechnology is questionable.

There are significant differences between sites in the size of their indigenous rhizobial populations (42,55) and in the range of strains of *Rhizobium* in the indigenous microflora (43,55). Such differences have been attributed to the effect of soil factors (43,5) though the possibility of widespread correlations between specific soil characteristics and rhizobial occurrence in tropical soils has not been critically examined.

The response by tropical legumes to inoculation with rhizobia also varies from site to site (11,22,34,35,44,16). Such variation has been attributed to: differences in number, effectiveness, and competitiveness of native strains (40, 27,55,38); variation in quality of the inoculant at its time of use (14); and variation in soil nitrate levels (57). The possibility that the response to inoculation could be predicted on the basis of a more thorough description of soil and environmental characteristics has not been tested.

The relative performance of strains selected under optimal conditions for a specific legume is variable, depending on the site where they are introduced (16). With inoculants that contain a mixture of strains of *Rhizobium,* it is common for one strain to dominate in the resulting nodule population (33,39). The possibility that rhizobial strains might be selected for adaptation to particular soil and environmental conditions is not now exploited in tropical agriculture.

A serious constraint to fuller implementation of BNF technology is the lack of domestically produced, high-quality inoculants in the Tropics and Subtropics, Thus, factors which deter government organizations or private enterprise from undertaking inoculant production in a particular country are also constraining BNF technology. Among these are: high capital cost of inoculant production plant (of the type used in the United States and mistakenly assumed to be needed in any production plant); high operational cost associated with retaining a professional and well-trained staff to run the plant; operational risks associated with losses due to such factors as contamination; absence in most developing countries of an adequate infrastructure that would permit marketing and distributing a biological product with notorious vulnerability to high temperatures; reticence to embark on an enterprise in advance of official control standards being established (compounded by official reticence to set standards until there is an industry to be controlled); and insufficient demand and uncertain future demand for inoculants.

The present nature of BNF technology meets considerable farmer resistance, i.e., the coating of seeds with peat inoculant. In Brazil, packets of inoculant are included “free” by some seed distributors with all seed sales. However, the inoculant is frequently discarded by farmers not only because of the nuisance associated with its use, but also in part because of an unfortunate impression that if inoculant is “free” it is of little value.

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

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

Furthermore, few of the senior administrators and decisionmakers who determine agricultural policy in the developing countries are fully aware of the applications for legume-based BNF technology. Most policy makers are aware of some of the attributes of legumes, Relatively few appreciate the role played by biological nitrogen fixation, and among those an even smaller number recognizes that it may be essential to employ specific technologies to ensure that maximum nitrogen fixation occurs. Thus, there is a need for educational material, specifically developed for decisionmakers, bringing to their attention the need to adapt available technology to the particular circumstances where it is to be employed.

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

The large number of competent researchers who expend their energies and resources researching aspects of BNF other than limiting factors such as the examples cited above is also a constraint on fuller implementation of BNF technology. Funding agencies do not always recognize a distinction between applied and less practical research in the area of biological nitrogen fixation. Biological nitrogen fixation has great pertinence to agriculture production in developing countries, but not all research conducted under the BNF umbrella is applicable in agriculture.

SCENARIO FOR FULL IMPLEMENTATION ON BNF TECHNOLOGY

The constraints on fuller implementation of BNF technology are not solely scientific, but include cultural, socio-economic, and political factors. Thus, the scenario where BNF might realize its potential would necessarily be multifaceted and comprehensive.

The current trend toward energy-efficient farming systems to reduce capital outlay for imported fertilizers can be expected to continue and intensify. Manufacture of nitrogen fertilizers requires high energy consumption, so their price and availability is influenced increasingly by oil-rich nations. There is added attractiveness in alternate nitrogen sources to avoid further dependence on foreign powers. Legume-based BNF technology is the major option available and is likely to be resorted to more and more.

The use of legumes and appropriate inoculant technology has the potential to increase the amount of biologically fixed nitrogen entering agricultural production systems. Given that the main value of legumes is their high-protein grain, rather than their nitrogen contribution to nonleguminous food crops such as cereals and root crops, the scenario for full realization of BNF technology's potential would need to include a swing in consumer preferences away from crops that depend so heavily on nitrogen fertilizer. Thus, in the gambit of BNF research priorities, attention will need to be given to learning the cultural and scientific bases for these preferences and to alleviating the constraints to greater consumer acceptance of legumes.

The major increases in benefits from legume-based BNF technology will arise through an increase in the total acreage in legume production; innovative use of legumes in roles they have not previously occupied; and by ensuring that biological nitrogen fixation in legumes is maximum through appropriate inoculation technology. Much remains to be done to improve the role now played by biological nitrogen fixation components. There is a wide discrepancy between farmers' yields and the known yield potential of grain legumes. Furthermore, it is disconcerting that in the majority of legume trials that include nitrogen fertilizer application, the legumes responded to nitrogen fertilization. This is disconcerting because it means that even when legumes were grown under favorable management in experiments, let alone in farmers' fields, the symbiotic association of the legume with rhizobium was defective. Therefore, the potential to double or triple the nitrogen benefits described in this report exists through development of technology that would assure establishment of maximally effective rhizobial symbioses in tropical legumes under tropical conditions.

Greatest future potential would appear to rest in developing:

- legume-based pastures and viable multiple-cropping systems including legumes for underused savannahs;
- agroforestry systems that combine fast-growing, nitrogen-fixing trees, legumes, and other crops to meet the food and fuel requirements of the rural poor;
- fast-growing leguminous trees for reforesting water catchment areas following forest clearance;
- legume-based cropping systems to give sustained productivity in tropical soils following jungle clearance; and
- selection of deep-rooted, drought-tolerant leguminous trees that can serve as browse species in the world's dry lands.

Reference has already been made to the need to exploit fully the variation in host plant, rhizobial strain, and environment interaction when selecting the optimal BNF package for each circumstance. Legume programs should retain the services of a professional microbiologist, but this suggestion is not practical. First, few legume programs can afford the luxury of a full-time microbiology position and second, there is a worldwide shortage of professional soil microbiologists that is unlikely to be alleviated significantly for about 10 years. The world's major multidisciplinary legume programs should, however, have their own microbiologists. This is already the case with the IARC programs for beans, cowpeas, pigeon peas, groundnuts, chickpea, and tropical forages. INTSOY, working with soybean, has its own soil microbiologist. Also, there are several national legume programs where microbiological support is integrated through a participating institute with expertise in the BNF area (e.g., Brazil, India).

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

The BNF Resource Center(s) would best be located at universities in developed countries, and preferably in the Tropics. A university site would help provide professional training, important if national institutions in developing countries are to be able to sustain their own BNF programs. Short-term, non-degree training programs in BNF technology should be offered to key personnel working on research programs involving the legume/rhizobium symbiosis. This is more effective in the short term than Ph.D. or M.S. programs which tend to be a passport out of research into better paid administrative positions for many graduates returning to their home country. The short courses should be offered in cooperation with developing country institutes to generate a regional capability for offering such courses. They should be complemented by on-the-job training tailored to the needs of selected individuals that would be conducted at the BNF Resource Center and include visits to pertinent industry facilities.

Such BNF Resource Centers would engage information specialists to develop communications materials suitable for the many clientele groups. This would range from newsletters for administrators to pamphlets for extension agents and include providing information for developing country researchers, who often do not have access to libraries.

Agricultural research tends to focus manpower and resources on improvement of single commodities. Some organizations, like IARCs, are characterized by multidisciplinary teams with specific crop and/or geographic mandates. Establishing a BNF Resource Center would be considered by some as a return to discipline-oriented research. This author contends that the key element in the success of commodity programs such as some of those in the IARCs has been that they are *highly focused* and *actively managed* in pursuit of well-*defined research priorities* rather than attributable to the commodity approach per se. A program investing manpower and financial resources in an actively managed BNF program that is sharply focused on the constraints to full implementation can be expected to make real progress. The specialized and sophisticated nature of rhizobium bacteriological expertise and the scarcity of experienced manpower is further justification for assembling a critical mass of rhizobiologists in a single BNF Resource Center.

An additional advantage in the existence of such a BNF Resource Center would be a capability to extend BNF technology developed at a particular place to other crops and regions. Staff of the BNF Resource Centers would travel as required and undertake short (1 to 3 months) or longer (3 months to 3 years) assignments in support of specific outreach activities when warranted. Only travel would help the personnel of the BNF Resource Centers focus their attention on researchable constraints in real agricultural situations in the developing countries. Additionally, the Resource Centers would work closely with other universities and research organizations where specific research on factors limiting BNF use could be referred under subcontract.

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

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

The BNF Resource Center would take a major organizational responsibility for calling workshops and scientific meetings to coordinate international experimentation and disseminate results.

The major activity to be undertaken by the BNF Resource Center would be the coordination of competent, standardized experiments designed to generate the data necessary to quantify the economic yield benefit attributable to legume inoculation under field conditions. Such trials would also serve as local demonstrations of the benefits from legume inoculation.

The core budget for such a BNF Resource Center should be guaranteed by the host government through its agency responsible for international development. The host institution (university) cannot realistically be expected to provide direct financial support for such a Center given that the Center staff will not have conventional instructional responsibility and that the research will aid mainly foreign nations with only minor benefits for agriculture where the Center is located. The mandate of a BNF Resource Center is international and therefore, the support should be international.

There is understandable reticence on the part of international funding agencies to expend resources in a center located in a developed country. The author contends that it is in the best interests of the developing countries that BNF programs be conducted by a Center located in the Tropics but sited in a developed country where it can receive unimpeded logistic support for its sophisticated operations and enjoy continuity of service from high calibre professional staff. Such a Center would be ultimately more cost effective than fragmented support to a myriad of in-country programs, an approach that often causes wasteful duplication of effort. Furthermore, support of a BNF Resource Center, for example in the United States with funding by USAID, would be prudent use of public funds. A large share of the budget would be expended in the United States sustaining employment of U.S. residents and strengthening a U.S. institution without lessening the support for the developing countries. Additionally, a greater degree of control could be exercised over the activities of a U.S.-based Center than is possible with grants to foreign institutions.

Agencies that could be anticipated to contribute to a BNF Resource Center would be: FAO, UNEP, UNESCO, and UNDP. Technical assistance on a continuing basis to any specific country ought to be funded externally as a special project with funding arranged by that country from its national budget and international development assistance grants or loans.

As a hypothetical estimate, the author suggests the following distribution of $10 million toward the implementation of legume-based BNF technology (table 1). It is assumed that the $10 million is additional to current support for BNF.

Table 1.—Allocating Funds for a BNF Resource Center (How to Spend $10 million on BNF)

Salaries (6 professional and 12 subprofessionals)	$3,000,000
African network of trials/demonstrations	200,000
American network of trtals/demonstrations	200,000
Asian network of trials/demonstrations	200000
Training programs in technology	500,000
Professional (M.S., Ph.D.) training	150,000
Information services	120,000
Germplasm services	100,000
Workshops/conferences (3 regional, 1 global)	270.000
Research	
Simplification of inoculant production	90,000
Innovative inoculation methods	90,000
Stress tolerance in inoculant strains	150,000
Quantifying N fixation/cycling in cropping systems in the tropics	220,000
Advisory services	200,000
Contingency fund	60,000
Indirect costs	1,350,000
BNF Resource Center sub-total	$7,000,000'
Pilot Inoculant Plants	
Zambia (year one)	250,600
Ivory Coast (year one)	100,000
Others (beginning third year)	1,000,000
Nitrogen-Fixing Tree Research (initially in Haiti/Thailand/Senegal).	500,000
Socio-economic Evaluation of BNF Technology	250,000
Outreach Programs of BNF Resource Center (beginning year 3)	
Zambia	300,000
Bangkok	300,000
Peru	300,000
GRAND TOTAL	$10,000,000

%This figure is low for the level of operations envisioned and is possible because a center with appropriate equipment and buildings has already been established and is operating in the proposed BNF Resource Center mode (i. e. University of Hawaii NifTAL Project)

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Acronyms

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