Cranfield UNIVERSITY Silsoe

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Review of technologies being evaluated for the Forest/Agriculture Interface

Final Report[1]

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Executive Summary

1. Forest/agriculture interface (FAI) production systems are characterised by interactions between cultivation of crops, adjoining forests, and possibly livestock. These interactions may be temporal or spatial in nature. There is concern that these systems are leading to undesirable clearing and degradation of the world's forests, and that to reduce this, there is a need to stabilise such systems.

2. Projects in the DFID-NRSP FAI portfolio have attempted to address this issue by testing methodologies aimed at improving management of soil organic matter, nitrogen, phosphorus, and weeds, with the objective of improving crop yields and reducing fallow periods. However, there is concern that there may be fundamental technical reasons why these methodologies are not being taken up by farmers.

3. A number of these projects in Brazil, Bolivia, Ghana and Nepal were reviewed, and the techniques being evaluated in these projects were analysed in terms of their biophysical and socio-economic characteristics in relation to the likelihood of their uptake. These techniques included alley-cropping, biomass transfer, cover crops, multi-purpose tree species, animal manure, *Tithonia diversifolia*, improved and enriched fallows, and legume intercrops.

4. It is unlikely that any of the techniques reviewed will contribute significantly to increasing soil organic matter levels in soils at the FAI, due to both the relatively low quantities of biomass that can be produced by the resources available to FAI farmers (i.e. land, labour), and the relatively high rates of organic matter decomposition in the warmer temperatures of the tropics. However, it is possible that there are other benefits obtained by incorporation of organic matter that are appreciated by farmers, such as improved workability of the soil.

5. Similarly, it is unlikely that the quantities of other nutrients, such as nitrogen and phosphorus, that can be supplied through biological nitrogen fixation or phosphorus mobilisation by root exudation, will be sufficient to meet crop needs alone. They may, however, be a partial solution as a component of an integrated nutrient management strategy involving judicious use of inorganic fertiliser.

6. In the projects reviewed, the use of cover crops in various combinations helped to control the density of weed populations, but had no significant effect on subsequent crop yields. There was some evidence that integrated strategies involving cover crops, herbicides and burning, were able to control *Imperata contracta* in banana plantations after 2-3 years. Reports from other countries (e.g. Honduras) indicate that cover crops alone can be successful in reducing weed populations and increasing crop yields.

7. Potential improved interventions should be evaluated on their ability to meet farmer perspectives such as increased food security, improved cash generation, reduced risk, and enhanced quality of life, rather than researchers' perspectives of

improved soil fertility or weed control. This fits in with the school of thought that stabilisation of cultivation systems at the forest/agriculture interface can be achieved by developing means of improving the livelihoods of the people involved, so that there is less need for them to move on and clear new forested areas. People should be seen as part of the solution rather than part of the problem.

8. This is not an argument for 'holistic' versus 'reductionist' approaches. We would argue that both are necessary, i.e. that the starting point should be from a holistic viewpoint, that the analysis of problems in the system is reductionist, and that solutions to the problems are evaluated holistically again. However, care does need to be taken that the reductionist analysis does not restrict thinking to biophysical processes of the system, as has been done in the past, but that socio-economic processes are also taken into account.

9. There is, therefore, a clear need to take a systems approach when considering options for stabilising forest/agriculture interface systems. However, many of the processes, both biophysical and socio-economic and their interactions, are poorly understood, and it is essential that future research addresses this. Bio-economic simulation modelling is proposed as a way of integrating these processes at the system level to provide a means to evaluate different pathways of transition to more settled systems of agriculture.

10. It must also be recognised that the so-called forest/agriculture interface production system is very heterogeneous, both at the system level with different cultivation systems in the different countries, and also at the individual farm level with between-farm variability in terms of farmer aspirations and attitudes, and within-farm variability in resources. Problems tend to be location-specific, and improved techniques must be matched to individual niches.

11. Further investigation into the 'phenomenon' of low uptake should make use of a more sophisticated scheme of terminology in order to differentiate more clearly the actual basis of concern.

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Structure of the Report

Our task in this review was to provide an analysis and synthesis of technologies currently being evaluated in DFID projects in Forest/Agriculture Interface (FAI) production systems. Chapter 1 introduces the reader to the topic and provides the background context, the 'analysis' is undertaken in Chapters 2 to 6, whilst the 'synthesis' is undertaken in Chapter 7, and ideas on the way forward are presented in Chapter 8.

Because many of the socio-economic considerations are generic and common to all of the technologies, we have discussed these first of all (Chapter 2). It is essential to appreciate that existing practices are deeply interlocked with socio-cultural structures that have evolved over long periods of time to aid survival in difficult conditions, and it is often possible that the introduction of new techniques may disturb this larger context. Clearly, the utility or otherwise of a technique to resource-poor farmers may be influenced by criteria that are wider than their biophysical impact on crops. Even though a particular technique may be successful in addressing the biophysical problem it was designed to, it may still not be adopted by farmers as it does not fit into their socio-economic environment.

In line with our remit to carry out a technical review, we then group and evaluate the techniques in terms of the biophysical problems they are designed to address. Thus, we have considered their ability to improve soil organic matter (Chapter 3), nitrogen supply (Chapter 4), phosphorus supply (Chapter 5), and weed control (Chapter 6). During this analysis, we have considered both the specific biophysical and socio-economic factors that may limit their success to address these problems and hence their adoption by farmers. A major aim has been to build a 'database' of limiting biophysical factors and by implication, the biophysical requirements, for each technique.

However, while this reductionist outlook provides important insights, it is also important that the techniques are looked at 'holistically' in terms of possible overall benefits to farmers, that is, of how they contribute to enhancing farmers' livelihoods, and it is for this reason that we have attempted to provide a synthesis in Chapter 7 to examine wider issues. The lessons learnt in the previous chapters are summarised both generically and with regards to specific techniques.

In the Appendix, we have attempted to summarise information relating to each technique in tables, which it is hoped will allow a broader understanding of the requirements and limitations of each one. Whilst this in itself may be a step forwards, we would like to emphasise that the tools we provide are simply a possible model and need further development. Additionally, as those areas designated as FAI production systems are complex and heterogeneous, the use of these tools needs to be accompanied by a proper understanding of the context of the technique and the limitations of such tools. Although these tools synthesis the understanding of the previous chapters, they clearly cannot encompass everything.

1 Introduction

1.1 The forest/agriculture interface

1.1.1 General characteristics

On a world-wide scale, the greatest historical cause of deforestation has been due to the conversion of forest land to agriculture (Bajracharya, 1983; Myers, 1984; Shepherd *et al*., 1996). Areas in which this is now occurring, the so-called forest/agriculture interface (FAI), are often of great ecological importance and need to be managed wisely to avoid unnecessary destruction of forests, and at the same time meet the livelihood requirements of those that live there. The FAI is characterised by temporally and spatially transient changes in land use following conversion of primary forest to settled agriculture. Two distinct land-use processes can be identified, the first involving initial forest conversion to agricultural use, and the second involving the development of characteristics related to more settled agriculture. Although features of the FAI vary between geographic regions, a common feature is that there is significant interdependency between tree-based systems and arable crops. In some cases, livestock may also be an important component (Figure 1.1).

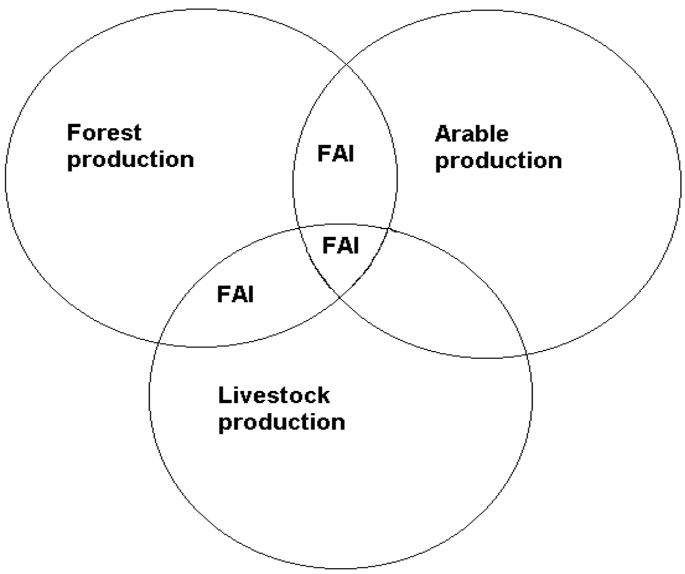


Figure 1.1. Schematic representation of the FAI.

These interactions may be separated in time or space, leading, on one hand, to FAI systems where temporal interactions predominate (e.g. in Ghana, Figure 1.2), or, on the other hand, systems where spatial interactions predominate (e.g. in Nepal, Figure 1.3).

Some FAI systems may exhibit both spatial and temporal dimensions (e.g. in Bolivia). These interactions between components have an important influence on the stability of the FAI boundary, typically in relation to soil fertility, but also by giving people access to a wider range of natural resources and services. For example, the value of non-timber resources (bush meat, fruit, medicine, and nuts) in certain tropical forests may be several times the value of the timber component (Peters *et al*., 1989). The forest component may also be an important source of food that provides a buffer against variations in yield from the cropped component of the system (Shepherd *et al*., 1996), and may also be a source of nutrients for the latter (Pilbeam *et al*., 1999). Interactions in time are also important. A fallow period, for example, performs the important functions of suppressing the build-up of weeds and other pests, and of accumulation of nutrients in the vegetation which can be released when the fallow vegetation is cut or burnt, benefits which are all the more significant in the absence of agrochemical inputs and/or if there are labour constraints (Brady, 1990).

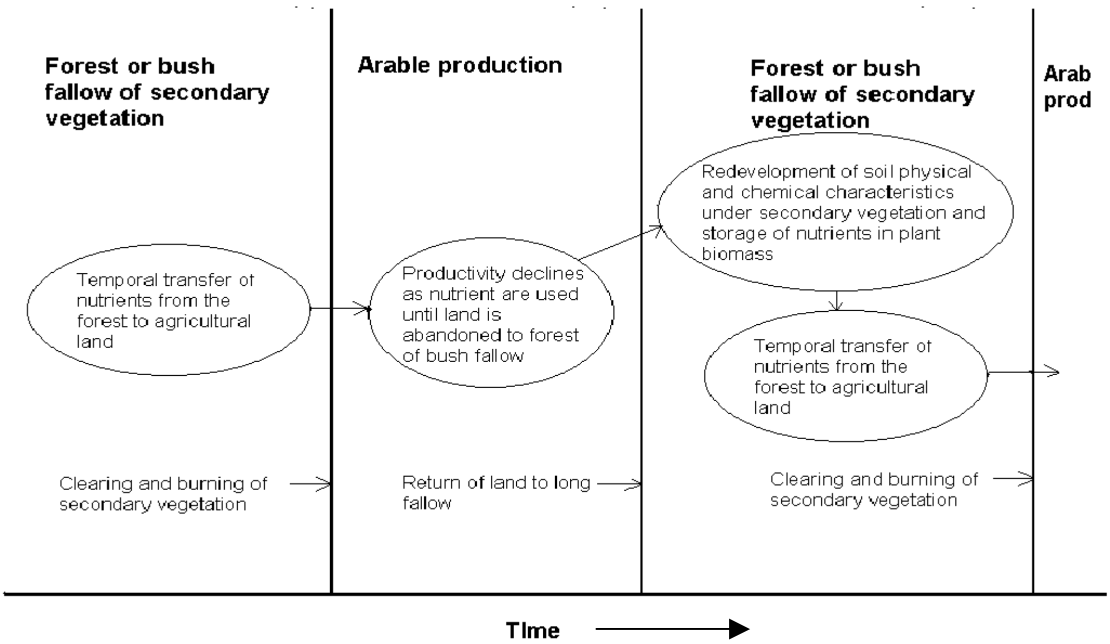


Figure 1.2. Typical FAI dynamics where temporal dynamics predominate.

In many parts of the world, population growth may increase the pressure on these FAI systems, resulting in a move towards intensification, which often cannot be sustained with traditional cultivation methods. This, in turn, may cause a build-up of weeds and other pests, and rapid depletion of soil fertility. Losses of soil organic matter and nutrients are often high just after the initial clearing of the forest. During the cropping period, further losses of soil fertility through leaching, erosion, and structural deterioration may also occur. If soils degrade, there is also likely to be a concomitant degradation of water resources (Brady, 1996). For this reason, most of the biophysical research aimed at stabilising forest/agriculture interface systems, including that reviewed in this report, has focused on addressing the problems of soil fertility and weed control. Further problems are related to the sustainability of the new land use arising due to remoteness, lack of social and agricultural services, absence of capital to finance inputs or improvements, and difficulties in marketing produce. The situation is often further complicated by the fact that most agriculture in the FAI is practised by disadvantaged social groups who do not have permanent rights to land, and as such have little incentive to expend the extra effort required to develop more sustainable systems.

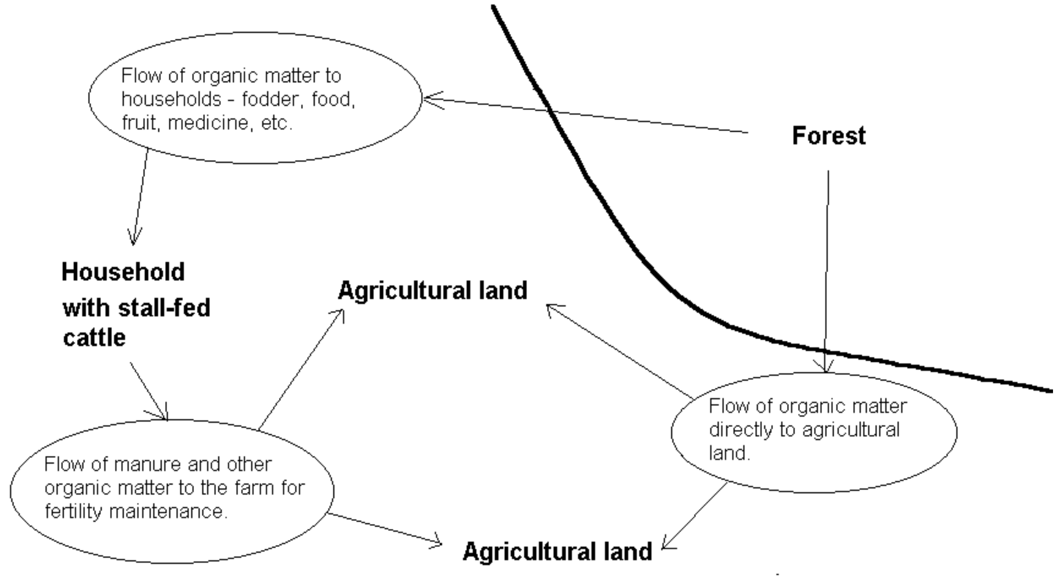


Figure 1.3. Typical FAI dynamics where spatial dynamics predominate.

There is mounting national and international concern over the effects of farming at the FAI. From the perspective of many development organisations, this concern stems from the large numbers of poor people who already live at the FAI, or who are displaced there, often as a result of social or political marginalisation. From the perspective of many environmental groups and individuals, concern stems from the impact that farming at the FAI might have on the environment, in particular on the quantity and quality of tropical forests that are being degraded. Loss of biodiversity , loss of O_2 production, increased atmospheric pollution and greenhouse gas emissions as a result of burning, and changes to local hydrology and precipitation, are all issues derived from degradation and loss of forests (Fujisaka & Escobar, 1995; Brady, 1996; Tinker *et al*., 1996; Tomoch *et al*., 1998; Clerck *et al*., 2000).

1.1.2 The FAI in the context of agricultural systems development

It is useful to consider how the forest/agriculture interface systems in each of the focus countries is placed in the overall context of the evolution of agricultural systems. Boserup (1981) classified countries according to population density, technology level (based on indicators such as energy consumption, life expectancy, literacy, and the number of telephones per unit of population), and main agricultural system. Six major agricultural systems were identified, in increasing level of intensity: (1) gathering technologies, where wild plants, roots, fruits and nuts predominated, (2) forest fallow, where fallow rotations were between 15-25 years, (3) bush fallow where rotations were shorter than for forest fallow, (4) short fallow with domestic animals, (5) annual cropping, and (6) multi-cropping systems (Figure 1.4). There was a strong correlation between the intensity of the main agricultural system in each country and its technological level and density of population. Thus, at low population densities and technological levels, long fallow rotation systems as a means of building up soil fertility tend to predominate, and the use of industrial inputs is virtually zero. In countries with intermediate population and technological levels, short fallow systems are more common, and increasing use is made of organic nutrient sources. Where there are high population densities but low technological levels, labour-intensive ways of dealing with soil fertility, soil conservation, and weeds are used. In countries with high population densities and technological levels, annual cropping or multi-cropping technologies are the norm, and are mainly achieved through the use of capital intensive industrial inputs. Boserup (1981) concluded from all this that change in agricultural systems was driven by population density through the influence it has on the availability of land and labour.

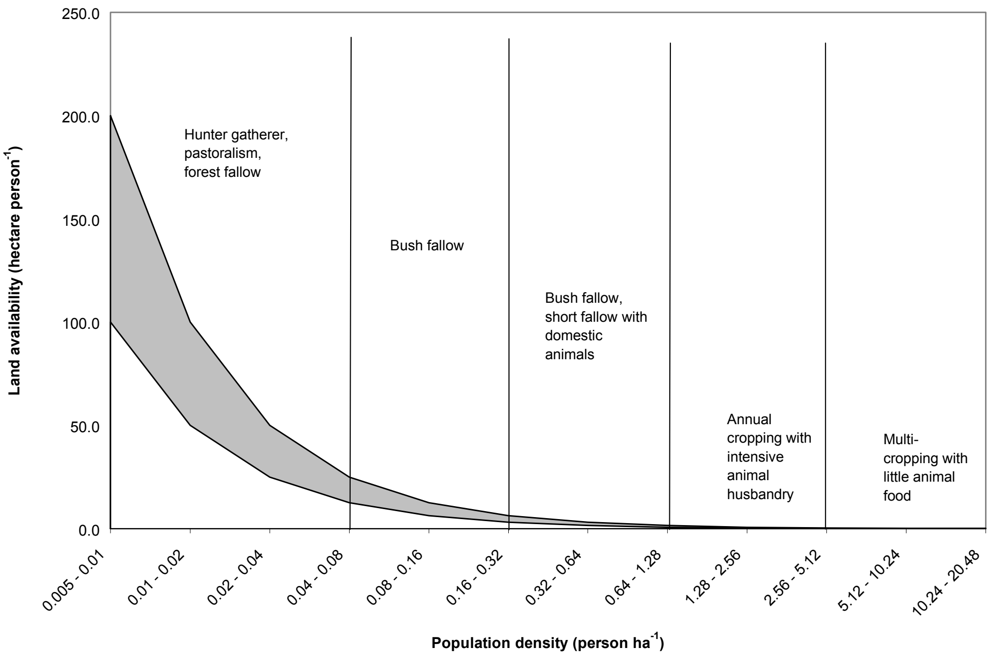


Figure 1.4: Land availability and predominant agricultural systems as determined from population pressure. (Developed from Boserup, 1981).

Thus, according to Boserup (1981), there are three different ways to deal with the problems of soil fertility, weeds, water control, and erosion brought about by agricultural intensification: (1) fallowing, as in sparsely populated countries; (2) the use of labour-intensive practices, as in densely populated countries at low technological levels, and (3) the use of industrial inputs, as in high technology countries. As population density and technological level increases, there is a natural progression from the use of fallow through to an intensification of firstly labour, and then capital, inputs.

The forest/agriculture interface systems we are dealing with range from bush fallow systems, such as in Ghana, through to annual cropping with intensive animal husbandry, such as in Nepal.

1.2 Forest/agriculture interface cultivation systems

1.2.1 Traditional shifting cultivation and bush fallow systems

Shifting cultivation and bush fallow systems are temporal FAI systems in that regeneration of nutrient status is achieved over time rather than spatial transfer of nutrients from one part of the landscape to another. Such systems have been practised for hundreds of years by indigenous farmers, and, provided the population density is low, have proven to be sustainable. One of the major advantages of shifting cultivation and bush-fallow systems is their productivity in terms of yield per unit of labour (Brown & Schreckenberg, 1998). The nutrient status of the land under secondary forest or bush fallow gradually improves due to weathering of the parent rock material and atmospheric deposition. The slashing and burning of the secondary vegetation produces ash, helping to neutralise acidic *p*H and provide nutrients (Jou & Manu, 1996) so that the land can support crops for a few years. Burning the land prior to cultivation also destroys weed seeds (Gallagher *et al*., 1999) and helps to retard the development of weeds during the cropping period (Brady, 1990). Eventually, yields eventually decline to such a level that the farmer allows the land to regenerate again under a fallow of natural vegetation whilst moving cropping activities to a new plot of land which has been rejuvenated by several years of fallow vegetation. A single farm may consist of several plots of land in various stages of cultivation or regeneration of secondary forest or bush fallow. In an ideal situation, where each plot of land is farmed for only a few years and there is sufficient land to fallow, soil degradation is low. Provided that populations are low and there is sufficient land to fallow, the shifting cultivation and bush fallow systems can, and have been, sustained indefinitely. The technical ingenuity of shifting cultivation and bush fallow systems within the ecological constraints of the tropics should not be underestimated. Brady (1990) argues that modern agricultural methods have, as yet, generally failed to provide better alternatives where land is plentiful and labour is scarce.

Managed fallow systems are generally viewed as a development of the shifting cultivation system, with the fallow period of the rotation being planted with selected species of trees. Using selected trees allows the farmer the option of planting a tree that increases the regeneration rate of the plot (e.g. by fixing nitrogen), or a tree that provides some short-term economic benefit, or a tree that can do both. However, examples of such indigenous systems appear to be rare (Nair, 1993).

The spatial dimension of shifting cultivation systems can also be important. The forest can provide a continuous supply of fruit, nuts and medicines to the farmers as well as a habitat for animals that may also be exploited for food. Even a short rotation bush-fallow can provide a considerable quantity of goods that are rarely considered by farming systems experts. Such goods may include the residual germination of main crop species as well as the more typical species and animals associated with the fallow period. These may be termed ‘the invisible harvest’, by those who consider them at all (IIED, 1995). These resources may be particularly important to the poor and vulnerable and to communities as a whole, for example in times of drought or famine. However, there are risks associated with economic over-dependence on such extractivist activities - any income generated is subject to market fluctuations, and stocks of products in high demand may be severely depleted in a short time. Nevertheless, they are clearly an important component of the livelihood strategy of many resource-poor farmers.

1.2.2 Spatial agroforestry systems

Spatial agroforestry systems make use of the beneficial interactions that occur between crops and trees to improve the productivity and sustainability of the cropping system. In an on-farm situation, such systems may benefit from the ability of trees and woody shrubs to utilise nutrients and moisture from lower depths and make it available to crops through tree litter, or to fix nitrogen. On a larger scale, spatial agroforestry systems may also provide the benefits associated with extractivist activities, such as food, medicine, bush-meat, construction material, and cash needs.

Other important services performed by forest for resource poor farmers, include the supply of nutrients to farming systems in biomass transfer (Pilbeam *et al*., 1999), or the protection of agricultural land from erosion by runoff (Martens, 1983). Such functions may be typical of areas where the FAI is relatively stable as in Nepal, where forests are often found on the steep land above agricultural land, ensuring to some extent that that rainfall does not runoff into the fields at speeds that induce erosion.

Livestock are often an important part of spatial agroforestry systems. For example, nutrients from the forest may often be transferred to agricultural land via cattle. This has the added advantage of providing the farmer with a supply of dairy products (and meat) for cash income and subsistence. However, it is worth noting that without good manure management, many of the nutrients in the biomass supplied to the animals may be lost to the farming system through the urine - up to 70% of N and the majority of K excreted by cattle may be in the urine (Lekasi *et al*., 1998).

1.2.3 Forest plantations

Forest plantation systems are part of a larger family of plantation systems that include perennial field crops such as sisal, sugar cane, bananas, pineapples and shrub crops such as tea and coffee. Forest plantation crops can also include tree crops such as rubber, cocoa, coconut and oil palm. Forest plantations are defined as ‘large farms that are typically mono-cropped with perennial crops’, producing tropical or subtropical products that commonly require prompt initial processing and for which there is an export market (Stephens *et al*., 1998). Plantation production systems generally require large amounts of fixed capital investment on planting material, processing/packaging equipment and infrastructure such as roads and housing (Stephens *et al*., 1998). Clearly resource poor farmers may find it difficult to compete with forest plantations for the production of forest plantation crops, although there are areas where typical plantation crops are farmed by smallholders. Cocoa production in Ghana is a case in point.

1.3 Forest/agriculture interface systems in Brazil, Bolivia, Ghana and Nepal

The aim of DFID’s Natural Resources Systems Programme portfolio for the FAI is ‘to increase the productivity and productive potential in the forest/agriculture interface production systems through the application of systems-based approaches’ thereby encouraging greater stability of livelihoods. So far, DFID-NRSP research in the FAI has focused on three regions - the margins of the high rainforest in South America (Brazil and Bolivia), and the more densely populated forest margins in West Africa (Ghana) and Asia (Nepal).

In Brazil and Bolivia, the forest/agriculture interface is frequently occupied by disadvantaged social groups driven from their home areas by poverty or other problems. As such, they are new to the area with limited understanding of the forest margins, they have no enforceable rights over the land they clear, and so their livelihood strategies focus on short-term survival rather than long-term sustainability. In West Africa, on the other hand, the forest margins are more densely inhabited, and extensively used for crop production, forest products, grazing of livestock, and settlement. Communities are more stable, but shortening rotation cycles mean that their cultivation systems are still characterised by low productivity and declining soil fertility. In Nepal, the FAI is more stable, but there is a flow of resources from the forest to the adjacent agricultural land as people and their animals harvest grasses, leaves and tree cuttings.

These different systems are discussed in more detail below.

1.3.1 Brazil & Bolivia

In Brazil and Bolivia, expansion of the agricultural frontier is being driven by demand for land by large farmers and ranchers taking advantage of government subsidies (Brown & Muchagata, 1999; Pound *et al.*, 1999). In Brazil, the opening of the Trans-Amazonian highway in the 1970s is an added impetus. Poorer farmers find themselves under pressure to sell their land for an immediate cash return, after which they move to the frontier to start new farms. Although there is considerable diversity in farming systems, three broad phases can be distinguished (Brown & Muchagata, 1999):

- Phase I: A colonist farmer will move into the area and clear ~3 ha of forest by slashing and burning, and plant rice. During this phase, there is a dependence by his household on forest products for subsistence (food, fuel, raw materials for construction/utensils, medicines) and revenue (source of cash when the farm can't provide this, e.g. before planting). As transport is unreliable and infrequent, these colonists rely predominantly on middle-men for access to markets. Some may sell their labour to neighbours. Land tenure is not secure, and most farmers try to establish pasture to add value to land.
- Phase II: After 4-5 years, pasture is usually established, and the farmer has acquired a number of cattle. Homestead gardens established in which cassava, beans, and maize are grown for household consumption. Forest products are still important, but less so than in Phase I. Land under pasture commands a price that is several times higher than that commanded by land under forest.
- Phase III: The farm is now dominated by pasture, and cattle have become main productive activity. Cash is generated through sales of milk and cheese. Rice and cassava are still grown for subsistence, and the forest remains a nutrient reserve. The ingress of weeds into the pasture is becoming a major problem for sustainability in many cases.

Stabilisation has occurred in the 'old' frontier regions, but there is still a rapid turnover of families in 'new' frontier colonies - this is partly due to the continuing pressure to sell land to the large ranchers, and partly related to the sustainability of the farming systems due to declining soil fertility and increasing weed problems. Nutrient cycling is poor - there is little use of manure, and no external inputs of fertiliser.

Weed control is often more limiting than soil fertility. A number of DFID projects (R6675, R6165, R6382, R6774, R6008; R6447) have attempted to address these problems by evaluating technologies such as perennial crops, cover crops, and agroforestry.

1.3.2 Ghana

Although there are some large farms and plantations of cocoa, rubber, oil-palm, coconut, rice, and maize, agriculture in Ghana is predominantly on a smallholder basis (Sarris & Shams, 1991). In the Brong-Ahafo region, which is typical of the transition belt between forest and agriculture, 87% of holdings are less than 2 ha. In the savannah-forest mosaic areas of this region, farmers have moved toward ploughing, permanent cultivation, and use of chemical fertilisers. However, problems still faced by these rural households include poor access to markets resulting in low crop prices; limited access to draught power; limited access to credit facilities; and particularly for women, limited access to land and the confidence to take on their own projects. Migrants have particular problems, as they cannot buy land freehold. Uncontrolled bush-fires are also perceived as a threat by many people. Improving incomes is a priority for all groups. Until recently, resources have been developed to support the development of food staples, but there is now a move by farmers towards vegetable production for income generation and food security. However, vegetables are grown mainly during the dry season in valley bottoms, where the predominantly sandy soils have a minimum of organic matter in the top few centimetres. Underneath this layer, there is usually pure sand with poor water-holding capacity and minimal plant nutrients. A current DFID project (R6789) is looking at the possibilities of increasing soil organic matter through the use of green manures and animal manure.

Forest farmers in the transitional zone, on the other hand, continue to use low inputs within a cycle of bush farming, with the use of traditional hand tools such as the hoe and cutlass being still widespread. Similarly, in the savannah region further north, farms are composed of two spatially disaggregated components: the compound farm and the bush farm. While the compound farm close to the homestead is permanently cropped and fertilised with animal manure and household wastes, the bush plots are rarely fertilised but allowed to regenerate under periodical fallow. Over the past decades, due to intensification, bush-fallow strategies have undergone change in their management of land, cropping system, and duration of fallowing, resulting in more rapid cycling of land between cropping and fallow periods. Many farmers have integrated intercropping systems (e.g. maize/cassava) into their cropping systems. A DFID project just commissioned (R7446) to help improve these systems is evaluating other technologies such as cover crops, agroforestry, crop rotations, relay cropping, cut-and-carry grasses, forage alleys, mulches, and fast-growing timber, etc. Another project just completed (R6517) has looked at ways in which farmers make decisions regarding new technologies such as agroforestry.

1.3.3 Nepal

Forests are a crucial component of the hill-farming systems in the mid-hills of Nepal (Soussan *et al.*, 1999), providing fuel, fodder, bedding materials, medicines, timber, and construction materials. In addition, they provide a source of off-farm income through sale of products, and services such as water catchment, grazing, and recreational and religious use. Moreover, the livelihoods of a number of other nonfarming people, such as firewood sellers, blacksmiths, and liquor distillers, are also dependent on the forest. The sustainability of these hill-farming systems in terms of soil fertility depends on the transfer of nutrients from the forests through grazing, fodder, bedding, and litter collection. However, the majority of farmers perceive that soil fertility is declining - the reasons for this are complex, but do seem to be affected by proximity to roads and markets. The reduced availability of fodder in recent years, due to demand outstripping supply, means poorer people are keeping less livestock, so that there is less manure for maintaining soil fertility, which in turn is leading to a growth in the use of inorganic fertilisers. A number of DFID projects (e.g. R6447, R6757, R6994, R7154, R6881) have attempted to address these problems by evaluating methodologies such as cover crops, on-farm fodder production, agroforestry, and the use of trees to improve phosphorus availability.

1.4 Potential improved methodologies to address these problems

1.4.1 Terminology used in this report

Before we start, it is useful to clarify what is meant by a technology. Reece & Sumberg (2000), in a related study to this one, have defined a technology as knowledge about how to do things, or the application of scientific knowledge. For the purposes of this review, we have found it useful to develop this idea further into a hierarchical framework, in which knowledge is our understanding of the way that the world works, usually derived from experimentation and observation, and a technology is the application of this knowledge to address a particular problem, in our case, relating to agricultural production. This technology could consist of a number of related techniques, or practical and specific ways of doing something; a technology, therefore, can be seen as a 'family' of techniques. Finally, we can think about a practice as relating to the specific details of the way that a particular technique is implemented. When we refer to improved techniques or practices developed by research, and not yet adopted by farmers, it may be more appropriate to think of these as 'packages' or 'products'. We have also used the generic term methodology to refer to a technology, technique, or practice.

An example may serve to make this hierarchy clearer. Our knowledge includes the understanding that atmospheric N is fixed by *rhizobia* bacteria in association with legume plants. A technology would be the application of this knowledge to improve the N status in a cropping system, such as the use of legumes in cropping systems. There may be a number of techniques whereby this technology is implemented, such as alley cropping or crop rotations. Finally, a practice would include details of the particular combinations of legume species and strain of *rhizobia*, time of planting, planting arrangement and so on.

In the following analysis, therefore, we have defined technologies as families of techniques linked by the broad problem areas that they address. These technologies are (a) organic matter management for soil physical improvement, (b) the management of nitrogen supply to crops, (c) the management of phosphorus supply, and (d) the control of weeds. Within each of these, there are a number of techniques aimed at addressing the broad problem. It is quite possible that a particular technique may fall into more than one technology group – many techniques aimed at improving soil organic matter status, for example, also help to improve nitrogen availability.

Thus, what are commonly thought of as technologies, such as alley-cropping, we will refer to as a technique within the technologies of organic matter management or nitrogen availability management.

1.4.2 Potential improved methodologies for the FAI

Within DFID's Renewable Natural Resources Strategy, the main thrust of projects within FAI production systems has been to address resource degradation. This has been done both through projects aimed at ameliorating the biophysical problems associated with the FAI, in particular declining soil fertility and weed encroachment, and through projects aimed at examining the socio-economic reasons for resource degradation, in recognition of the fact that the biophysical degradation of the environment has much to do with issues of resource control. In this review, as is our remit, we have focused on methodologies falling into the first of these two approaches.

The methodologies that have been evaluated for the FAI (in both DFID-NRSP projects and other work) are generally based on the manipulation of plant and animal processes to improve the fertility of the soil (Pieri, 1995). Examples of such methodologies include the use of plants to enhance soil microbial activities to increase the decomposition rate of organic matter (OM), the uptake of nutrients through mycorrhizal associations, and the fixing of nutrients from the atmosphere by *rhizobia* (Snapp *et al*., 1998). Using these natural processes to improve resource-poor farming systems has several potential advantages, most notably the minimisation of capital requirement for expensive external inputs such as farm machinery and fertiliser.

Given the nature of the FAI, it might be expected that techniques used would generally aim to manipulate the interactions of perennial and annual plants in the agroforestry tradition. However, techniques evaluated for the FAI have not been limited to agroforestry interventions. Where stabilisation and productive increases are a priority, it is clearly important to consider the role of a wider group of techniques. This is particularly important, as with current trends of population growth and diminishing forest resources, many FAI systems are likely to develop into 'high potential' or 'hillside' systems (DFID & NRSP, 1999).

In the following sections, we describe briefly the various techniques that have been evaluated in FAI projects before discussing them in more detail in Chapters 3-7.

1.4.2.1 <u>On farm biomass banks</u>

Cut and carry grasses, alley cropping, fodder trees, full or relay intercrops are examples of on-farm biomass banks. These are used to accumulate organic matter and nutrients on one part of the farm for transfer to another part. Such technologies may use leguminous or non-leguminous plants and annual or perennial plants. Deep-rooted plants may provide nutrients from below the crop root zone, although the utility of this will depend on sub-soil fertility levels and the rate of weathering of the parent material. Additionally, deeper-rooted plants may enable some of the nutrients leached or deposited below the crop root zone to be recycled. However, unless leguminous plants are used, there is no net increase in nutrients at the overall farm level, although there may be net nutrient increase in localised areas on the farm.

1.4.2.2 Off farm biomass banks

These are used to transfer organic matter from off-farm areas, such as forests, to the farm. In principle, they are similar to on farm biomass transfer technologies, except that they may provide the basis for net increases in nutrient and organic matter at the farm level. The length of time for which this can be achieved depends largely on the extent of off-farm biomass sources and the quantity of organic matter imported onto the farm itself. Off-farm biomass banks may be useful in a wide variety of biophysical conditions, provided adequate labour is available is available for biomass transfer.

1.4.2.3 Animal manure

Animal manure is most useful as a technique where animals are stall-fed, or where manure can simply be purchased. Often, land scarcity will tend to be high and animals will not be allowed to roam free. Where animals do roam free, the collection of manure is difficult, and farmers may have to rely on cropping land on which animals have grazed to benefit from manure derived improvements. Such systems are likely to be more effective where land is more plentiful or where nomadic pastoralism is still practised. Animal manure improves soil physical and soil chemical conditions, especially if well prepared. It may also potentially provide a net increase to the nutrient status of the farm, if large amounts of off-farm biomass are collected for fodder, or concentrates are used as feed. However, substantial amounts of N can be lost in the urine of the animal, and badly stored manure may be subject to leaching or volatilisation losses. Other animal manures, such as that of poultry, may contain N in even higher proportions than cattle manure, and it is certainly worth considering their use where appropriate. Animal manure also contains phosphorus and may be used to increase net farm levels of P, particularly if most of the fodder is from off-farm sources and concentrates are also used to feed the cattle. As most of the P is held in the faeces of the animal, there is little loss in the urine and the P is relatively stable.

Where on-farm sources of fodder, such as crop residues and cut-and-carry grasses, are used, there is only a recycling of nutrients. The animal's rumen provides an ideal environment for the decomposition of organic matter, and may provide a means by which farmers can improve the speed of organic matter decomposition in difficult environmental conditions, such as low temperatures or dry conditions, provided the animal is kept healthy.

1.4.2.4 Crop residues

Crop residues are commonly used as a source of organic matter. These are most commonly incorporated into the soil at some point after harvesting and before the planting of the next main crop. Crop residues may also be imported from other areas, although this clearly requires labour and possibly capital. The major problem with the use of crop residues is supplying enough organic matter and nutrients, particularly as they tend to be naturally low in N and P and high in lignins and polyphenols. A possible solution to this may be composting with higher quality organic matter. The major benefits of crop residues alone may, therefore, be to improve soil physical structure.

1.4.2.5 Compost

Compost is defined as the 'aerobic, thermophilic decomposition of organic wastes to a relatively stable humus' (Farrall, 1979). During the process, much heat, CO_2 and water is released. Although composting makes use of the same decomposition processes occurring naturally, the aim is to control the conditions to a level that allows faster decomposition (Rynk, 1992). The biophysical conditions that are required for effective composting are generally those that are required by the micro-organisms at various stages of the composting process. These are the mesophilic, thermophilic, cooling-down and maturing stages. In general, good moisture levels, moderate temperatures, mixed quality organic matter, and fairly neutral pH ranges are required. Limitations to compost production may include finding enough organic material to compost, labour requirements for building compost windrows, turning the compost during production, managing the compost to ensure that leaching and volatilisation losses of N are not excessive, and transporting the compost to the field.

1.4.2.6 Agroforestry

Agroforestry is the growing of woody perennials on the same unit of land as agricultural crops and/or animals, either in some form of spatial mixture or sequence, such that there is interaction (preferably positive) between the woody and non-woody components of the system, either ecologically and/or economically (Nair, 1993).

Agroforestry technologies may be either temporal or spatial. In temporal agroforestry systems, trees and crops interact with each other in sequence. For example, the fallow of secondary perennial vegetation may build up organic matter, N and P levels, soil moisture, reduce erosion, and suppress weed and pest development, as in shifting cultivation. The following crops benefit from these when the fallow period is long enough. With spatial agroforestry systems, such as alley cropping, perennial plants and crops are grown on the same area at the same time, with the perennials possibly supplying the main crop with nutrients from deeper in the soil profile or through biologically fixed N, although competition between the main crop and the perennial for other resources may offset any advantage this provides.

Most agroforestry technologies suggested for use by resource poor farmers tend to be spatial. However, some efforts have been made to improve temporal agroforestry systems by improving fertility regeneration during the fallow period with leguminous trees, or using trees of some economic value. In terms of N fixation, the improved fallow technologies have not been found to outperform the natural fallow to an extent that might result in widespread uptake. Such technologies may also require more labour and inputs than might be the case with natural fallow.

1.4.2.7 Using legume crops in the cropping system

Leguminous plants may be herbaceous, woody, annuals, or perennials. Most technologies involving legumes aim to improve the supply of N to the system by making use of the ability of legumes to fix atmospheric N. This depends on the ability of host plants to form root nodules in association with *rhizobia*. It is important therefore that the biophysical conditions are conducive to the growth and development of *rhizobia*. Optimal growing conditions for *rhizobia* are similar to those for leguminous plants in general. However, to obtain the maximum benefit from the ability of legumes to fix atmospheric N requires a deficiency of N in the soil, provided other conditions are kept optimal, as this stimulates biological nitrogen fixation.

Herbaceous legumes may be used in a sequential system to provide N for a following crop. Generally a window of opportunity, such as an existing fallow period, is required for the planting of a sequential legume crop. Herbaceous legumes may also be fully- or relay-intercropped, where climatic conditions are suitable. Full and relay intercropping may result in improved main crop growth from N fixed biologically by the legume, provided competition for other resources does not take place. This N may be transferred from the legume to the main crop through leaf senescence, biomass incorporation, and some direct transfer of biologically fixed N to the main crop through legume root decay. The advantage of relay over full intercropping is that competition between the legume and main crop is reduced. Legume intercrops are most likely to be used where land is relatively scarce, or where the legume provides a secondary benefit, as is the case with grain legumes.

Grain legumes have the advantage of producing grain that is often of subsistence or economic value. Where a grain legume is rotated or sequenced, biophysical conditions may be less than optimal for plant growth, as this is often towards the end of or after the main cropping season. Where the grain legume is full or relay intercropped, it is again important that competition does not reduce main crop yields below what could be expected in a monocrop of the main crop. The major problem with grain legumes is that due to the loss of N in the harvested grain there is usually a relatively low overall net benefit of N, even when the rest of the biomass is incorporated into the soil.

1.4.2.8 Phosphorus mobilisation with *Tithonia diversifolia*

Tithonia diversifolia has gained interest as a potential way of improving phosphorus supply, largely as a result of its ability to extract relatively high quantities of P from the soil. It could be used both in an on-farm or off-farm context, although only the latter will result in a net increase of P in the farm as a whole. The main problem is in the quantity of biomass that needs to be collected, transported and incorporated into the soil in order to make any appreciable contribution to crop P requirements.

1.4.2.9 Cover crops

The use of cover crops is a potential way of suppressing weeds in low-input agricultural systems. Ideally, cover crop plants used for weed suppression need to grow quickly, and provide good spatial coverage. Cover crops also have the added benefit of potentially improving soil moisture levels, reducing soil erosion, as well as improving soil physical and soil chemical conditions through N fixation or providing soil organic matter.

The use of cover crops may be either temporal or spatial. In a temporal context, they are grown during fallow periods so that weed growth is suppressed before the planting of the main crop. Other benefits may also be important, such as the provision of biologically fixed N or soil organic matter for soil physical improvement. The cover crop will, however, need to outperform a natural fallow, which may be difficult if labour and inputs as well as weed suppression are considered. In a spatial context, cover crops intercropped with the main crop can also help to suppress weed growth during the main growing season. The difficulty is in providing the correct degree of weed suppression, thereby facilitating main crop growth, without offsetting this advantage through competition with the main crop.

1.4.3 Criteria for analysis of FAI technologies

There is concern within DFID-NRSP documentation that the techniques described above are not being taken up by farmers. Although some of this may be ascribed to inadequate attention to promotion pathways and dissemination, there is some concern that there may be more fundamental reasons responsible. We were commissioned to carry out a major technical review of the techniques to attempt to understand inherent limitations to their uptake.

As the techniques being evaluated in DFID-NRSP projects were generally aimed at addressing particular natural resource management problems such as organic matter management, nitrogen supply management, phosphorus supply management, or weed control, we have analysed the success of each technique in the first instance in terms of its ability to contribute to solving these problems. Table 1.1 shows how each technique is classified according to technology. We discuss the implications and usefulness of this classification later in Section 8.1. It should be noted that a number of these techniques fall into more than one technology. For example, a technique such as a leguminous cover crop may be used to fix N and augment N supply, but may also have an important impact on improving soil organic matter levels, or may also be used as a weed suppressing technique. In the following analysis, after discussing general socio-economic considerations common to all the technologies, we have discussed each technique under their respective technology, focusing only on the characteristics that are relevant to that technology. The technologies are researcher, and to some extent farmer, defined. To many farmers, weed control may be a major issue, whilst to researchers soil fertility, particularly the level of soil organic matter and the supply of nitrogen and phosphorus, are central issues. Projects in the FAI portfolio reflect these technologies. Later, in Section 7, we look at the different techniques in a more ‘holistic’ way to see where they have been successful, and whether this is due to other characteristics apart from their ability to address the technologies in Table 1.1.

Table 1.1: Classification of potential improved techniques for the forest/agriculture interface production system according to technology.

Technology	Potential improved techniques
Soil organic matter management	Cover crops Animal manure Crop residues Compost Agroforestry
Nitrogen management	Cover crops Woody legumes Grain legumes Perennial legumes Agroforestry
Phosphorus management	*Tithonia diversifolia* Plant biomass Animal manure
Weed control	Cover crops

2 General socio-economic issues

2.1 Introduction

Although the techniques being evaluated for use at the FAI may address different agricultural problems, such as low soil organic matter, soil nitrogen deficiency, or weed growth, for example, they share many socio-economic constraints with each other. In this section, we take a generic look at the socio-economic factors limiting the adoption of techniques being evaluated. Insecure tenure rights or lack of access to markets, for example, are likely to limit the adoption of any of the techniques to be used at the FAI, whether they are aimed at increasing SOM, N and P levels, or whatever. Socio-economic limitations specific to the techniques will be examined under their respective headings.

Socio-economic limitations can be divided up into several major categories. In particular, it is evident that the farmer's control of and access to land, markets and labour are major factors limiting the uptake of methodologies at the FAI. Additionally, both receivers and providers of potentially improved methodologies work in specific cultural settings that may not match. For example, farmers may be unwilling to use a certain methodology because it is thought to be old fashioned or retrograde. Scientists, on the other hand, may concentrate on the technical aspects of the agricultural system, ignoring the obvious importance of the farmer's socio-economic limitations. This often produces methodologies that cannot function effectively within the socio-economic context of the farmer. Many techniques, for example, are inherently labour intensive, and farmers often struggle to supply this labour. Alternatively, a technique may be expected to function in a socio-economic context that discourages the adoption of new ideas.

Resource-poor farmers are, by definition, limited by their lack of access to and control of resources, which is often why new methodologies are difficult to integrate into an existing farming context that survives, within the biophysical limitations of the land and the socio-economic limitations of the farmer. The blanket adoption of low-input methodologies to improve the socio-economic circumstances of farmers at the FAI is therefore unlikely. Techniques have very specific socio-economic requirements as well as specific biophysical requirements. For example, legume rotations may work where land is plentiful and labour scarce. Legume intercrops may work where land is scarce and labour is plentiful. A single farmer may also perceive a niche application for both on a single farm. Once the socio-economic and biophysical limitations of the techniques are understood, the importance of these techniques may be in their niche applicability, both in spatial and temporal terms.

It is important, therefore, to recognise that new methodologies exert new and different pressures on the socio-economic and cultural fabric of society. It is also important to perceive the depth to which existing methodologies may be embedded in the fabric of existing societies. This fabric may often be important in people's survival strategies and where a new methodology disrupts or causes excessive strain on this fabric, it may jeopardise a whole means of survival. New methodologies have very much to be understood in the context in which they are expected to work and this may extend far beyond the limits of the agricultural system as we see it (Corner, 1987).

2.2 Labour

2.2.1 Labour as a limiting resource

For many farmers, labour is often a major limiting resource, so that they will only change their traditional practices where the alternatives represent a more rational use of their labour time (Brown & Schreckenberg, 1998). There are various demographic changes taking place in rural areas that contribute to labour shortages. Men may be migrating to cities in search of wage labour, or children may be increasingly going to school. This influences the amount of household labour available for farming operations.

The introduction of a methodology that increases the workload on a farmer, such as alley-cropping, in the interests of a long term soil fertility, without addressing the immediate problem of increasing output per unit labour, or reducing labour requirements, is unlikely to be adopted by the farmer. Farming operations are hard work, often in difficult physical conditions, and the wisdom of increasing this burden is questionable, unless the benefits of the extra labour input are immediately evident to the farmer.

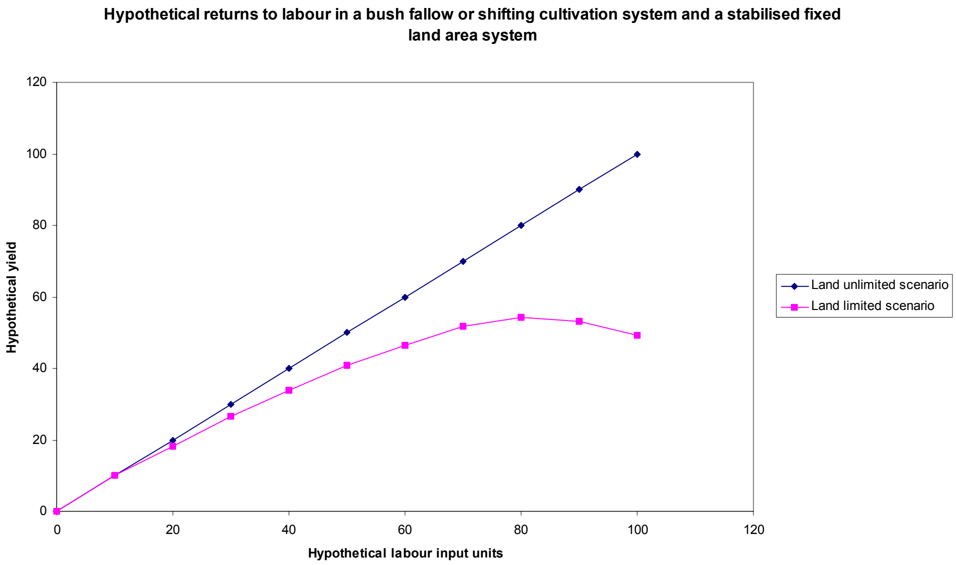


Figure 2.1 Hypothetical yield returns from a land limited and land unlimited scenario.

Traditional bush fallow systems or shifting cultivation systems, for example, maximise the marginal return to labour. For the farmer, it is usually more efficient to use extra labour to bring fallow land into production than to use the same amount of labour intensifying production to obtain higher yields from the same area of land (Figure 2.1). More importantly, bush fallow and shifting cultivation systems do not require labour to be used for the improvement of soil fertility. The land is simply left to fallow and regenerate naturally. However, many of the techniques being evaluated for the FAI may require relatively high inputs of labour to maintain soil fertility. The use of agroforestry techniques, for example, alley cropping or biomass transfer may, require high inputs of labour that clash with other important farm activities (Carter, 1995; Nelson *et al.*, 1996; Rao & Mathuva, 2000), as may compost (Dalzell *et al.*, 1979) and use of animal manure (Onduru *et al.*, 1999; Slingerland & Stork, 2000). Brady suggests that for tropical conditions it may be difficult to develop soil regeneration techniques that are more effective than bush fallow and shifting cultivation systems (Brady, 1990).

2.2.2 Maximising returns to labour

Economists have observed in many production systems that as a rule the quantity of physical output tends to decrease with each increasing unit of input. This is known as the 'Law of Diminishing Marginal Returns'.

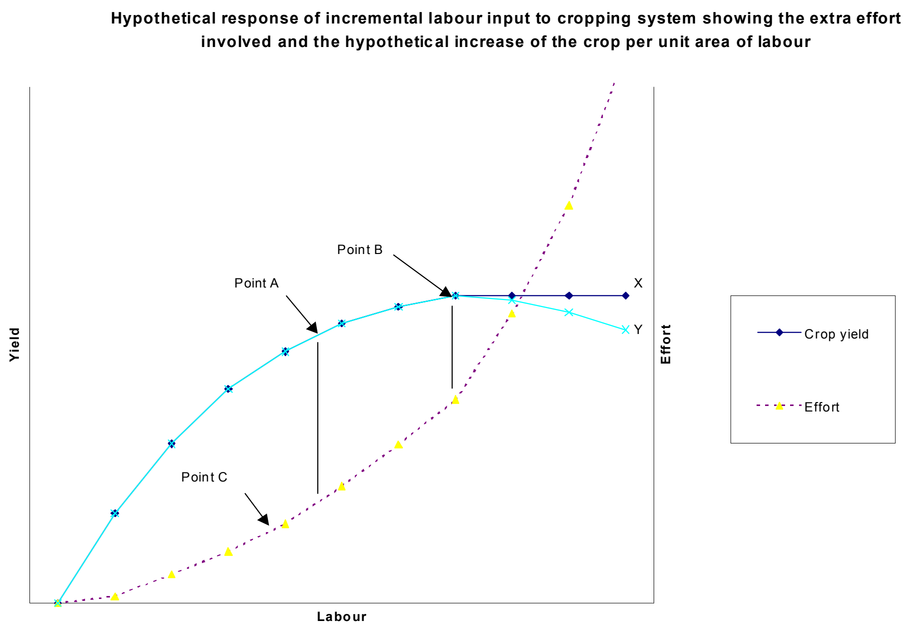


Figure 2.2. Hypothetical representation of difficulty that farmers may have with supplying extra labour to farm operations and the hypothetical impact of labour on the value of the crop.

Figure 2.2 shows that although there are large marginal returns to labour when little labour is applied, there is a diminishing marginal return as the amount of input labour increases (Line B). This may particularly be the case where extra labour cannot be expended on cultivating additional areas of land. There may come a point where the use of large amounts of labour becomes at best ineffectual with very little impact (X), and at worst counterproductive, causing a decline in yields (Y).

The effort of supplying labour increases as the amount of labour supplied rises. There comes a point where the farmer may judge that it is not worth supplying extra labour to the farming system, particularly as the marginal return to his/her labour is decreasing with each extra unit of labour that is invested. It may also be possible that the maximum return to the farmer's labour (Point A) is somewhere below the maximum possible production from the farming system (Point B). This makes it irrational to increase labour input, unless subsistence requirements have not been met, or unless there are very obvious market incentives for doing so. In some cases, the farmer may not even have the available labour to increase output to the optimum level and can only supply labour to a point below the optimum possible (for example Point C). In such cases, it is unlikely that the adoption of a new technique will be acceptable to the farmer unless it greatly increases the marginal return to labour, or unless it can reduce labour requirements altogether, without reducing yields.

2.2.3 Increased labour requirements

Many techniques increase the requirement for labour. In the worst case, this may occur when there is already a peak demand for farm labour, and there is an absolute necessity of completing other farming operations. In Nepal, for example, manure is often left in heaps outside for long periods of time while other farm operations are being carried out, resulting in the loss of N through volatilisation, and reducing the beneficial effect of the manure when it is eventually applied. However, other farming operations take precedence at this time and the farmer has no available labour for the proper management of the manure resource (Pandy, *pers. comm.*).

In Ghana, the constant operations needed for the successful management of the alley cropping species, *Leucaena*, was a constant drain on the resources of the farmer increasing the demand for labour (Abeney, Quashie-Sam, Cobinnah, *pers. comm.*). In the absence of sufficient labour, *Leucaena* was more trouble than it was worth, and often came to be seen as a weed by farmers (Ososu-Bennoah, *pers. comm.*). It had the tendency to seed and invade the main crop, and the stumps were difficult to dig out with hand hoes, whilst lateral roots would make land preparation difficult (Danso, *pers. comm.*). In addition, farmers found it difficult to view the constant requirement for pruning, trimming and mulching as acceptable farming operations (Abenney, *pers. comm.*). Ngambeki (1985) estimated that alley-cropping in general required up to 50% more labour per unit area than sole cropping.

In short, techniques that increase the burden of labour will not be easily acceptable to farmers, particularly if the benefits only become evident in the distant future.

2.2.4 Gender and division of labour in households

In many households, there may often be a division of labour, which can limit the uptake of techniques. Access to labour varies not just between households, but also within households. For example, husbands and wives may often farm different areas of land, with wives specialising in subsistence crops, and husbands specialising in cash crops (Cobbinah, 1996). Thus, for example, men may be unwilling to transport large amounts of organic matter for the improvement of the subsistence crops grown by their wives. Even if the same area of land is farmed by both husband and wife, there may be a gender specialisation of farming operations. If a new technique straddles the gender division of labour, one of the partners may be unwilling to adopt it, if this involves an increase in their own burden of labour primarily to the benefit of the other partner (Olivia, *pers. comm.*).

In Ghana, men often do the heavier farming operations, such as the clearing of fallow land for cultivation, or the transporting of inputs. The deprivation of this source of labour, either through bereavement, or because the men may be working elsewhere, causes labour shortages in the household in these particular areas (Ahmed, *pers. comm.*). In such a situation, women may be unwilling or unable to adopt methodologies that involve carrying large amounts of compost or manure to the field, unless they are in a position to be able to pay for labour to do it.

Labour in the household is also divided according to age. Children may be responsible for certain farming operations. The fact that so many are increasingly going to school in developing countries results in labour shortages for these farming operations. In Nepal, children may contribute to transferring biomass or be responsible for grazing animals. Without them, there is a reduced labour input into the farming system and this may make a family unable to adopt a methodology that requires labour, of the kind that has traditionally been catered for by the children of the household. Clearly, various structures within the household may limit the ability of the household labour pool to adopt to the labour requirements of new methodologies.

Certain techniques may also be inherently more difficult for women to use than for men, particularly if they involve heavy work. In Ghana, some farmers suggested that labour intensive techniques such as green manure might be more accessible to men, as the work would be too heavy for women (Jackson *et al*., 1999). For example, women might have to hire labourers to be able to use green manure, whereas men would be able to do the work themselves (Jackson *et al*., 1999). Thus, for women the benefits of green manure might be evaluated in relation to the opportunity cost of capital, whereas for men undertaking the work themselves, it might be evaluated in relation to the opportunity cost of labour.

In some areas of Africa, women may also be traditionally barred from planting trees (Chavangi & Chavangi, 1991), and this may for example restrict access of women to agroforestry projects. Ownership and access of tree resources and decision making may often be controlled by men, also reducing the scope for agroforestry projects (Sturmheit, 1990; Chavangi *et al*., 1992). In certain areas of the Gambia, the closure of tree canopies, may bring to an end the usufruct right of women to farm horticultural crops on the land of predominantly male landlords (Schroeder, 1993). As the landlords have for reasons of ecological stability, been encouraged to plant trees for orchard development, taking advantage of the water supplied by women for their horticultural crops, women have found themselves increasingly disenfranchised, partly through such development efforts (Schroeder, 1993). Where women do take an active role in planting trees, and have rights of access and ownership to tree resources, it is worth noting that their requirements may often be quite different from the requirements of men (Rocheleau & Rocheleau, 1990). Women play a particularly important role in subsistence, for example, and it may be worth considering how far a new technique meets the needs defined by women and their particular circumstances.

2.3 Land

2.3.1 Insecure tenure rights

Brown & Schreckenberg (1998) suggest that improving land-tenure rights could do more than anything else to improve the productivity of many subsistence farming systems. Evidence from many parts of the world suggests that lack of control over resources is one of the major reasons for the degradation of natural resources. The farmer’s willingness to invest in methodologies that may demand extra input and effort on their part is limited by insecurity of tenure. Certain techniques such as agroforestry are inherently long-term, requiring security of tenure over land for an extended period of time. Many resource-poor farmers at the FAI may lack this security of tenure, and feel unable to invest in the technique as a result.

Local communities often lack management control over the common resources that they use. However, evidence suggests that their involvement in common resource management is essential to prevent the degradation of that resource. The issue of control is especially important at the FAI, and in many situations may well do more to reduce land degradation than the development of techniques for on-farm fertility improvement. In Ghana and Nepal, the ability of the Forestry Departments to control the extraction of forest resources from a centralised location has been shown to be extremely limited. Local communities exploit the forest as there is no agent of control. However, when communities are given control of the resource, the management of the forest is localised, making control over common property resources easier. Additionally there is a vested interest in using common resources more carefully, as the link between the effort made by the community to manage the resource, and the benefits from those efforts, are more easily perceived. Where implemented, such strategies have often had the effect of stabilising the FAI and improving the resource base of the rural population.

In Nepal, the importance of devolving control over common resources has been demonstrated by Community Forestry Projects and Leasehold Forestry Projects, where forest user groups have been set up to manage the access to, and exploitation of, the forest land. Usually this is the most degraded land in the area that can be identified. The regeneration of vegetation on land that is given over to leasehold forestry is rapid, primarily because grazing is prohibited, but also because people have been prepared to protect and invest in the land and in new methodologies (Shastri, Gamrakear, *pers. comm.*).

Under the Leasehold Forestry Project, government land is leased to small groups of people for a period of 40 years. The usual consequence of this appears to have been a far greater investment in the land and in methodologies for the land (Gamrakear, *pers. comm.*). Community Forestry Projects have devolved control of government forests to local communities. This has normally resulted in the improvement and stabilisation of the FAI (Shastri, *pers. comm.*). Singh (*pers. comm.*) points out that farmers often invest in soil organic matter (SOM) or biological nitrogen (BNF) techniques such as cut-and-carry grasses on land that they have acquired under leasehold schemes. Security of tenure appears to give farmers an incentive to invest in improved techniques, whilst insecurity of tenure is clearly a disincentive.

In Ghana, where such initiatives are much more recent, similar experiences have been obtained under the Collaborative Forest Management project, suggesting that the devolution of control to local people is an important component of stabilising the FAI (Boakye-Boating, *pers. comm.*). There is, however, some disparity in opinion as to the impact of land-tenure rights on the adoption of techniques by Ghanaian farmers. Most of the land is allocated by stool chiefs to farmers, and access is based on usufruct (i.e. its use without ownership). While some people in Ghana believe the current land-tenure arrangement is detrimental to the poorer farming community as a whole (Cobbinah; Poku; Owosu-Bennoah, *pers. comm.*), others suggest that the system is at least stable enough to allow everyone access to land (Boakye-Boating, *pers. comm.*).

Those who maintain that the land-tenure system in Ghana may limit the adoption of new techniques believe that farmers feel that there is little benefit to be derived from investing in long term methodologies when the profit from such investments may go to someone else in the future. Many areas of government land (particularly at the peri-urban interface) may be farmed without formal arrangement, and in this situation, farmers are very unlikely to invest in long term methodologies. However, as they are often growing high value vegetable crops, they may be willing to adopt methodologies that give them an immediate benefit in the short term, even if this means extra labour and capital investment (Olivia, *pers. comm.*).

Where land is rented, the issue of security of tenure and longevity of tenure is no less important. For many farmers, the adoption of long-term, and even short-term, methodologies may be impossible if the land is rented. Farmers are often too poor to rent land for the extended periods of time required for the methodologies to function. Owners may also not wish to see certain techniques used on the land, and may for example, prohibit the planting of trees. Rented land is therefore heavily exploited, and long term investment by the tenant or the owner is often minimal, as neither may perceive any benefit to themselves through such investments.

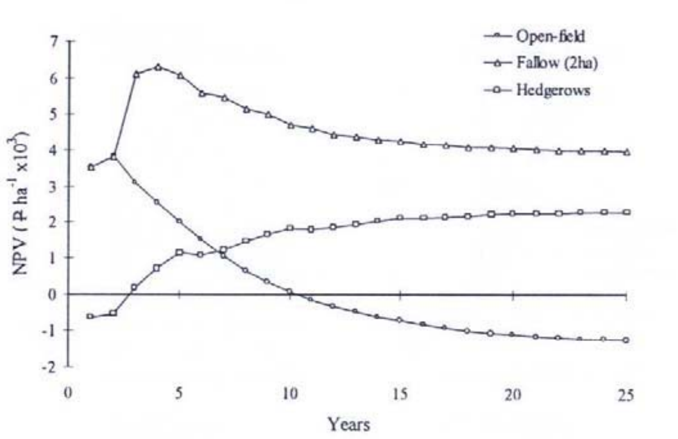
2.3.2 Share-cropping

Under share cropping, a farmer exchanges a proportion of farm output in exchange for the right to crop an areas of land (Ellis, 1988). Perceptions of share cropping have considered it to be economically inefficient, dominated as they are by the Marshallian perspective (Todaro, 1994). In this, share croppers are thought to only input labour at a level that maximises their own perceived share of farm production. This labour is less than what they would be prepared to give if they receive the total production from the farm. In this case, it is suggested that they would be willing to work more and total production and profit would rise (Ellis, 1988), making the farm enterprise more economically efficient. However, some analysis suggests that share-cropped farms are not necessarily inherently less efficient than owner-managed farms (Reid, 1976). Also, share-cropping may at least give very poor farmers the opportunity to farm, and some evidence suggests that it is the poorest and most unskilled who stand to benefit from share cropping (Reid, 1976), especially where the landlord also wishes to maximise the productivity of the farm. Share-cropping may in fact achieve an important compromise between the needs of the farmer and the needs of the landlord, in situations where production is uncertain and risky for both partners (Todaro, 1994).

However, in Ghana, share cropping is often perceived to be problematic in terms of investment in land and the use of long-term techniques, like agroforestry (Cobinnah; Owosu-Bennoah, *pers.comm.*). In the Philippines, Nelson *et al*. (1998), using the APSIM model in an economic analysis of upland agriculture, suggested that share-cropping would reduce the economic attractiveness of alley cropping techniques, compared with alternative techniques (Figure 2.3). This was because it was assumed that under the share-cropping arrangement, landlords would not contribute to the establishment costs of the hedgerows, while a portion of the main crop would be given to them as part of the tenancy agreement. The net present value of three alternatives is shown at a 25% discount rate (Figure 2.3a). The APSIM analysis showed that the net present value (NPV) of alley-cropping was reduced under share-cropping and the time at which the alley-cropping technique could be expected to yield greater benefits than alternative practices also increased (Figure 2.3b).

Additionally, the NPV was shown to be negative for the first three years, a situation which could be problematic for resource-poor farmers (Nelson *et al*., 1998).

(a)



(b)

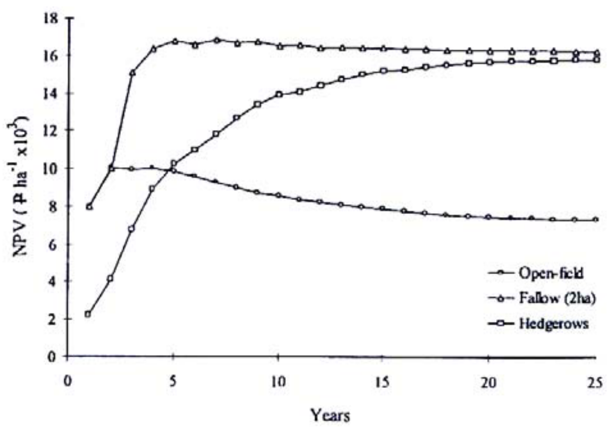


Figure 2.3. (a) The impact of sharecropping on the net present value of open field, fallow and hedgerow intercropping in upland Philippine agriculture at a discount rate of 25%. (b) The net present value without the impact of sharecropping is also shown for all three systems at a discount rate of 25%. (Source: Nelson et al., 1998).

2.3.3 Land fragmentation

Fragmentation of land may also work against the adoption of certain methodologies. Fragmented landholdings may result in a single farmer having to transport inputs to several isolated plots of land in several different locations. This difficulty is particularly great with the use of biomass transfer techniques, where several tonnes of biomass per hectare may be required. In the mountainous terrain found in Nepal or Bolivia, transporting heavy loads to small isolated plots of land is extremely arduous. In Ghana, where animal traction is not available, and where motorised transport is too expensive for most farmers, biomass generally has to be transported manually. This is an extremely labour-intensive process if the farmer has to do it alone, or expensive if he/she hires labourers (Owosu-Bennoah, *pers. comm.*). Additionally, land fragmentation may result in decreasing field sizes, which makes the implementation of certain techniques impractical. Trees used for green manure or fodder, for example, may shade out the crop if planted on the borders of small fields. Clearly, many poor farmers may not own enough consolidated land to make some potentially improved techniques viable.

2.4 Markets

2.4.1 Market access

Evidence suggests that markets help to provide both incentives and inputs for the farmer. Lack of easy access to markets is a problem for many poor farmers at the FAI. The availability of easy market access and a steady demand for produce are usually critical factors determining whether a farmer feels it is worth investing in improved techniques or not. Evidence suggests that in areas with good access to markets, farmers invest time and effort in new techniques, particularly in conjunction with high value products such as vegetables or milk (Gamrakear; Pudisni; Shrestha; Pathic, *pers. comm.*). In isolated areas with poor access to markets, there may be little incentive to produce more than what is required for subsistence. In such cases, low yields and low productivity may be acceptable to the farmer, and introducing long-term techniques for increasing fertility may not be perceived as a priority.

2.4.2 Market demand

When markets become available, farmers are usually quick to take advantage of them. In Nepal, for example, a growing demand in Kathmandu for dairy and meat products has stimulated the growth of cattle herds in areas with good access to the city. This has been aided by the systematic development of infrastructure for the processing of meat and dairy products. The market in meat and dairy products has, in turn, stimulated the use of bursine (white clover) for cut-and-carry fodder, as well as for pasture use (Pradhan, *pers. comm.*). In Ghana, the importance of the fish smoking industry in the coastal areas has meant that the farmers are very willing to invest time, money and energy in wood-lots using fast-growing timber trees (Poku, *pers. comm.*). Cobbinah (1996) has also noted that the demand for wood by the tobacco industry has encouraged farmers with the available resources to develop agroforestry and wood-lot systems, although it must be said that this process has been greatly encouraged by the tobacco companies themselves.

2.4.3 Financial incentive

Access to markets and the availability of market demand may not in itself be sufficient to provide farmers with the incentive required to invest in fertility- and productivity-enhancing techniques. The difference that these techniques make to the performance of the farming system, or to the socio-economic situation of the farmer, may not justify the extra effort involved. For example, often when overall production increases in a good year, prices fall, leaving the farmer with little extra benefit from the extra production (Danso; Olivia; Owosu-Bennoah, *pers. comm.*).

Similarly, as most crops are seasonal, there are many farmers supplying the same produce to the market at the same time, so that buyers can generally dictate prices. Farmers are not usually in a position to influence prices, as buyers can simply find a farmer who is willing to accept the proffered terms. Nor are farmers in a position to delay selling produce until terms of trade improve. They may often be in need of cash and many of their products may be perishable. Delaying a sale may mean forfeiting income altogether. There is little that can be done to remedy this, unless methods are found to produce out-of-season products that can reduce seasonal gluts in the market (Wedgewood, *pers. comm.*).

Possible solutions to this problem may be to create co-operatives, which are able to trade on better terms with consumers (Ahmed, *pers. comm.*). Alternatively, low-cost local food processing may also provide farmers with the incentive to adopt new techniques, as they may be able to capture some of the value added to their products by processing them for themselves (Owosu-Bennoah; Gamrakear, *pers. comm.*).

2.5 Farmer culture

2.5.1 Poverty and social marginalisation

The assumption that people are poor because they are indifferent farmers, with farms operating below their capacity, is rarely true. Very often, people living at the FAI are already the most marginalised members of society. Shifting cultivators, for example, may often be tribal groups with little political power, marginalised by their own national organisations and by other groups in society. Pioneer farmers may migrate to areas because they have no other options. It may prove to be difficult for farmers at the FAI to adopt technologies in this situation. Poverty has the tendency to perpetuate itself and insecure land tenure agreements, lack of access to credit on reasonable terms, lack of access to farming inputs, remote markets, low prices for crops and poor infrastructure contribute to the difficulties that tie those living at the FAI to their poverty. Even an effectively functioning farm may not be sufficient to lift resource-poor farmers and their families out of their poverty. The yield differences that may arise from introducing a new technique to poor and socially marginalised people on small fragmented areas of low quality land are probably insignificant.

2.5.2 Perceptions, status and fashion

Although perceptions of the potential users of new techniques may limit their uptake, researchers and developers of the techniques do not usually take these into account. Some of these perceptions are related to peoples' religious beliefs, status, peer-pressure, fashion, and general ideas of what is appropriate. These may appear trivial to outsiders, but have an overriding influence on the recipients of technology, determining whether such techniques are used or not. Although people may come to accept 'culturally unsuitable' techniques in time, this can be a slow process.

For example, in Nepal, the consumption of white rice is associated with status. Farmers have been reluctant, therefore, to adopt techniques that don't conform to their perceptions of what is associated with status. A cold-tolerant rice variety was rejected because of its colour, despite its ability to grow in the mid-hills. Breeding out the red colour gene made it acceptable to the farmers and increased its uptake (Tripathi, *pers. comm.*). Similar reasons underlie the wide acceptance in Nepal of a light coloured maize variety, because its colour is associated with status. On the other hand, there was much resistance to the introduction of the Pakribas black pig, a tougher and sunburn- resistant strain, although this gradually disappeared and black pigs are now as culturally acceptable as pink pigs (Bhurtel, *pers. comm.*).

For many Ghanaian farmers, the use of animal manure is seen to be regressive, and many feel their status will suffer. Kiff *et al*. (1999) suggest that peer pressure is often the obstacle to the use of manure, with many farmers concerned at how they will be perceived by others if they start to use manure on their fields Clearly, this limits the possibility of using cattle manure as a way to improve soil organic matter in the south, although it should be noted that the presence of other animals, such as goats, is steadily gaining acceptance. This appears to be particularly because of the influx of migrants from the north, who are more at ease with animals.

Cattle diseases may limit the expansion of cattle in south Ghana (Olivia, *pers. comm.*). In addition there is a whole cultural understanding of how to manage and use cattle that is also lacking in the south (Owosu-Bennoah, *pers. comm.*). However, the importance of cattle is noted in the National Soil Fertility Management Action Plan for Ghana (MoFA, 1998), where it is suggested that bottlenecks in production arising from both lack of soil fertility and traction might be reduced with greater use of cattle. Certainly, the present quantities of manure available are unlikely to raise or sustain the yield of crops in southern Ghanaian farming systems.

2.5.3 Tree ownership

In Ghana, the issue of tree ownership has been a stumbling block for the successful use of agroforestry techniques. Until recently, all trees planted belonged to the government. The main reason for this was the prevalence of the *taungya* system, an agroforestry system that allowed farmers to crop the land between trees that had been planted by, and therefore owned by, the government. Farmers, particularly older ones, were reluctant to invest in long-term techniques such as agroforestry, due to their continuing perception that any tree planted belongs to the government (Boakye-Boating, *pers. comm.*).

2.5.4 Inertia, caution and risk-averse behaviour

Many farmers are reluctant to adopt a new technique until they are absolutely sure that it will improve their way of farming. There are many good reasons why farmers are pre-cautionary by nature. They often work with limited resources in difficult conditions, with fickle markets. Adopting a new technique without overwhelming evidence that it is better could mean the difference between survival and starvation. In this climate of uncertainty, farmers may continue to use techniques that are familiar to them. This may be true even when evidence shows that a new technique increases yields (Ellis, 1988). The associated risks of a familiar technique are already known - the farmer knows where to get inputs for it, and what to do if things go wrong. Clearly, there often is a certain amount of inertia to change.

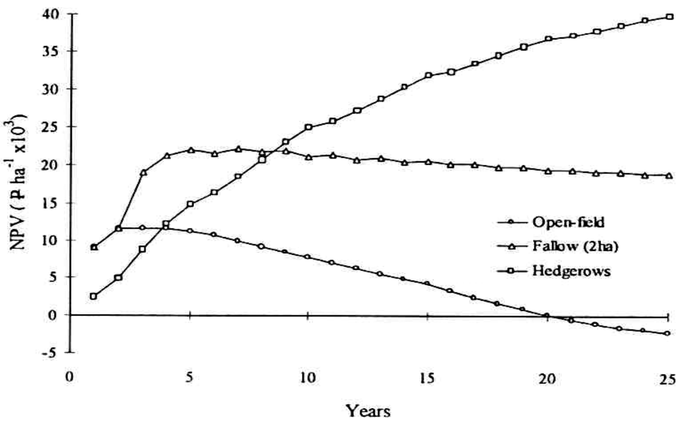
Given the constraints and the vulnerability of farmers, and the natural inertia of farming systems in a resource-poor context, it may be necessary to make stronger efforts to demonstrate to farmers that a new technique offers a better alternative to their existing practice. It is also important to remember that the rationale behind household decision-making is not always to maximise profit or income; for many households, reducing risk is often a greater concern. As Wolf (1996, cited in Ellis, 1988) points out, a subsistence farmer ‘runs a household, not a business concern’.

2.5.5 Short-term benefits

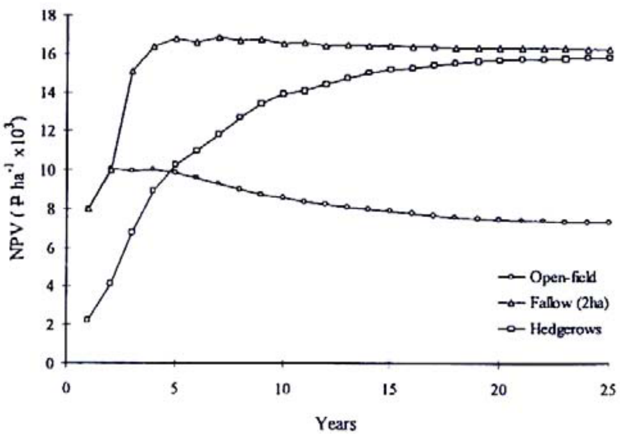
Farmers are keen observers of their farming systems. It may therefore be important to provide immediately perceivable benefits, perhaps in terms of reduced labour or increased yields. However, many of the techniques are not capable of delivering results within a period of time that is perceived to be useful by the farmer, and any technique that does not appear to give an immediate benefit may be discarded as unsuitable or as ineffective. For example, alley cropping trials with *Leucaena* in Ghana, amongst other failings, failed to deliver rapid enough results, and consequently farmers lost interest in the technique (Cobbina, Danso, *pers. comm.*).

Literary evidence suggests that farmers may discount the value of future benefits from the introduction of new techniques at high levels (Nelson *et al.*, 1998). This may be partly related to the difficulty or ease with which they may access credit, but may also be influenced by various other factors, for example insecure tenure (Nelson *et al.*, 1998), or lack of access to assets, reflecting their own inability to consider long-term benefits in such circumstances. This reduces both the 'action time horizon' and the 'planning time horizon' (Vosti & Witcover, 1996), making short-term benefits more significant, than long term benefits. Agroforestry techniques are particularly affected by such considerations, especially as there is often a significant cost to establishing perennial technologies and a relatively long time lag for benefits of such technologies to accrue (Snapp *et al.*, 1998). On the whole, it is poorer farmers who will require techniques that can provide benefits in the short term.

Nelson *et al.* (1998) used APSIM to model the NPV of alley cropping with two different alternatives, open field and fallow rotation at two different discount rates, 10% (Figure 2.4a) and 25% (Figure 2.4b). The 10% discount rate, reflected the supposed cost of borrowing credit under state supported schemes (Nelson *et al.*, 1998). At this discount rate, cost benefits analysis showed that the estimated benefits derived from reduced erosion and improved sustainability from the alley-cropping system would eventually cause its NPV to exceed the NPV of the two alternatives, making it more attractive in the long run (Nelson *et al.*, 1998). But farmers would have to wait at least four years for alley-cropping to become a viable alternative to the open-field system. Additionally, farmers would require at least a twenty-year planning horizon before the prospect of negative NPV from the open field system discouraged its use.



(a)



(b)

Figure 2.4. The effect of (a) a 10% discount rate, and (b) a 25% discount rate on the NPV of open field, fallow and hedgerow intercropping systems. Where farmers have to borrow credit to make use of new technologies, such considerations may influence their future perceptions and planning horizons. Insecurity may also make them discount the value of new technologies at relatively high levels, diminishing the future benefits of those technologies (Source: Nelson et al., 1998).

However, farmers may discount future benefits at relatively high rates, especially if credit is only available at high rates, as might be the case if they are paying the cost of borrowing credit from private traders, or if they perceive high risks to future returns for other reasons. A 25% discount rate therefore more accurately reflected the 'real' discount rate, in that it considered the current cost of borrowing credit, from sources available to the farmer (Nelson *et al*., 1998). The NPV for all three systems was greatly reduced at 25% (Figure 2.4b). Furthermore, the future long-term benefits that could be derived from the alley-cropping system through reduced erosion and increased productivity and sustainability could no longer compete with the fallow system, although alley cropping still outperformed the open field system after about four years (Nelson *et al*., 1998).

It is worth noting at this point that although we have used the example above to illustrate how the perceived value of future benefits might affect farmers' present decisions, it may be difficult to account for the more varied constraints and multiple goals of farmers by using such financial appraisal techniques (Fawcett & Smith, 1999). The danger of this is that better options defined by cost-benefit analysis may be pursued, ignoring the obvious incompatibilities that might occur within the existing socio-economic context. Multiple objectives and farmer limitations may be better accounted for with systems models, reducing the possibility of travelling down the unsuitable routes that might be taken, as a result of acting only on the outcome of cost-benefit analysis (Fawcett & Smith, 1999).

2.5.6 Multiple benefits

In risky production environments, farmers often have multiple objectives and indigenous technologies may be developed in response to these needs (Fawcett &

Smith, 1999). For example, Fawcett & Smith (1999) note that the literature on indigenously developed mixed cropping systems is regrettably low, although it has often been shown that mixed cropping can be more efficient in its use of both biophysical and socio-economic resources. Techniques that are introduced as sole crop packages may therefore be of limited use and where they are adopted, may result in a decline of nutritional level, particularly in a context, as in Ghana, where most people are farming first and foremost to satisfy subsistence needs (Fawcett & Smith, 1999).

Multiple benefits may increase the likelihood that farmers adopt a technique. For example, the use of a grain legume such as pigeonpea (*Cajanus cajan*), which can supply food and fuel-wood in the short-term, may increase the likelihood that farmers will use it to also enhance soil fertility through N fixation in the longer-term. Similarly, the evidence suggests that where alley-cropping has been adopted, it has generally been modified by farmers to provide a variety of other benefits, including the need for fuelwood, fibre, fruit, light construction material or medicine (Field *et al*., 1992; Cenas *et al*., 1996). Techniques, especially agroforestry techniques, may need to be 'flexible' (Fawcett & Smith, 1999) and 'agile' (Vosti *et al*., 1998), ensuring that farmers can use them to satisfy their own perceived needs in response to their own constraints.

2.5.7 Competing demands for resources

The use of certain techniques may be limited because there are competing demands for the use of a resource that are more important to resource-poor farmers than the maintenance of soil fertility. In both Nepal and Ghana, for example, manure may be used as a fuel, and its importance in that respect limits its use as a soil fertility enhancing technology (Bhurtel, Owosu-Bennoah, *pers. comm.*). There may also be competing demands for resources such as land. The incorporation of *Tithonia diversifolia* into hedges bordering fields for example may be restricted because the same hedge has to provide space for plants that provide other services (Jama *et al*., 2000).

2.6 Researcher culture

The gap between creating a workable technique on a research station and reproducing the results on farmers' fields appears to be considerable. Despite the large number of promising methodologies developed by researchers, adoption by farmers of these has been low. Snapp *et al*. (1998), working in Zimbabwe and Malawi, note that 'one of the biggest challenges in the tropics is to develop organic matter technologies which are adopted by farmers'. Although extension departments and NGOs have been promoting such techniques for over 70 years in southern Africa (Blackshaw, 1921; Rattray & Ellis, 1952), their adoption has been nearly nil (Snapp *et al*., 1998).

2.6.1 Over-researching

Research programmes and research institutions are often difficult to steer. It may be difficult for them to discard technologies that fail to show promise, or to redirect the research focus to other areas when an appropriate amount of research on a particular technology has been carried out. In short, there is often too much 'research for research's sake' (Pudnisi, *pers. comm.*). Organisations often act to ensure their own survival by attempting to provide continuing employment for staff. There is also a cost in stopping or downsizing a certain area of research. and judging at which point to stop research on a particular technology is also difficult. Research is typically a slow and arduous process if it is to be done properly, with many blind alleys that have to be explored thoroughly.

2.6.2 The need for a new knowledge base

Farmers may resist a new technique often because it necessitates developing a new knowledge base. In Ghana, the National Soil Conservation Plan foresees the use of cattle in the south for both traction and fertility enhancement (MoFA, 1998). However, this requires farmers in this region to acquire knowledge to look after cattle effectively, something they do not have a tradition of doing (Owosu-Bennoah, *pers. comm.*). The lack of familiarity with new techniques may lead to problems. For example, Kiff *et al*. (1999) found in on-farm trials in Ghana that farmers had scorched some of their tomato plants with the animal manure they were applying. Lack of knowledge in issues relating to seed storage and viability also created problems as farmers were uncertain of how to ensure these for next years use.

2.6.3 The need for a new infrastructure

The introduction of a new technique may require the development of new infrastructure in order to make it sustainable. For example, the suggested introduction of cattle in the south of Ghana would necessitate the development of a veterinary service in the region with the associated physical infrastructure to support it.

2.6.4 Lack of appropriate focus

Scientists have frequently been accused of being oblivious to the fact that it is people who are going to use any new techniques. Instead, their focus has been on perfecting the biophysical performance of agricultural systems through work on research stations, without taking into account the socio-economic context in which the system operates. For example, initial work on alley-cropping concentrated on refining the agronomic management of the system rather than considering that significantly more labour was required from farmers for it to be able to perform as planned. Techniques are more likely to be successful if they fit around the requirements of people.

Technologies may also be donor driven, following trends that are internationally popular. Development projects in Nepal, for example, may often be 'donor driven' (Pudisni; Mathema, *pers. comm.*). While this can sometimes result in a refreshing change of perspective and direction, especially in the face of bureaucratic stonewalling and incompetence, it may also cripple local scientific creativity, result in the loss of locally conceived ideas, and lead to the inappropriate use of new techniques. The tendency to evaluate new techniques under relatively high input conditions using the sole criterion of biomass production or yield, as has been the case many times in the past, does not necessarily produce results that correspond to the needs of farmers. These might be the need to increase productivity per unit labour rather than per unit land; or the need for techniques to survive in a severe environment with minimal farm management input (Thomas & Sumberg, 1995).

The pressure for scientists and research institutions to produce results that can be published can also hamper the development of appropriate technologies in 'recipient' countries. The introduction of alley-cropping in Ghana, for example, was hampered by inappropriate focus. Rather than being introduced as a flexible system that could be adjusted to local conditions and requirements, initial research was geared towards validating existing models for alley cropping. Optimum agronomic management of the system was specified based on work in other countries, and there was little opportunity to develop it for Ghanaian conditions. It was, therefore, never given the chance to be modified and many farmers, having been unimpressed with the results, discarded the technique altogether. However, experimenting with familiar locally-adapted trees rather than *Leucaena*, and altering the spacing of the rows to meet farmer requirements, might possibly have resulted in a more appropriate form of alley cropping for Ghanaian conditions (Quashie-Sam, Cobbinah, *pers. comm.*). Clearly, the difference between conducting validation experiments and introducing a technique to farmers has to be firmly established. Combining the two may prove to be unsatisfactory. As a result of these experiences, farmers may be suspicious of any initiatives to introduce alley-cropping techniques in the future (Quashie-Sam, Cobbinah, *pers. comm.*).

The narrow definition of the role played by scientists may often limit their understanding of the context in which their technologies will operate. Clearly, it is important for all researchers involved in technology development to understand in some depth the limitations that face poor farmers. Presently, understanding the context may be seen as the task of social scientists, and biophysical researchers may be reluctant to get involved in promoting and disseminating technologies themselves, as this is perceived to be the role of extension workers. However, some involvement in dissemination may help scientists to develop a proper understanding of the context of the technique (Mathema, *pers. comm.*).

2.7 Project culture issues

The lack of uptake of new techniques may in part be related to the difficulties that are manifestly part of the project format. Bentley (1998) suggested in the case of projects R6382 and R6008 in Bolivia that farmers and local communities may not have really been 'on-board'. Whilst project leaders and members now see this as a major problem, rapid expansion of the project preventing effective preliminary groundwork was forced by the 'rapid expansion of the project by GTZ and others'. Additionally, DFID's attempt to link up with other bilateral programmes may have forced extra focus on agroforestry techniques, although evidence suggested that farmers were not really interested in agroforestry (Bentley, 1998). On the whole, it appears that sufficient time may not have been available to fulfil the additional demands made upon the project. It is worth noting that evaluating projects in terms of goalposts that have shifted, may also give an inaccurate impression of the success or otherwise of a project. For example, it appears that the original aim of many FAI projects was research, whereas they may often be evaluated afterwards in terms of adoption and dissemination.

Pound *et al*. (1999) have also noted that projects working with limited budgets, and with discrete time-spans can only expect to have limited impacts. Clustering projects, and extending time horizons, or ensuring continuity, might go some way towards disseminating the lessons produced from research. Continuity is particularly important in experimentation with perennial systems, and would help to establish farmers as co-researchers. Pound *et al*. (1999) also note that important working relationships can be established between farmers and project researchers during on-farm research, but that these are destroyed when the project is terminated and may leave farmers feeling let down and exploited. There is a dimension of ‘ethical hypocrisy’ to projects that function in this way, and it may be necessary for all involved to understand how things will work from the beginning.

3 Organic matter management

3.1 Soil organic matter

The primary source of soil organic matter (SOM) is plants, although animals, through waste products and the decomposition of their bodies' provide a secondary source. In plants, dry matter (or biomass) makes up about 25% of the fresh weight of the plant, with the remaining 75% being water. The elemental composition of biomass is about 44% carbon, 40% oxygen, 8% hydrogen, and 8% ash, which includes compounds of mineral nutrients such as nitrogen, phosphorus, potassium and the micronutrients. Most of this is used as the building blocks for carbohydrates (60%), lignins (25%), proteins (10%), fats, waxes and tannins (5%). Sugars, starches and simple proteins decompose rapidly, whilst fats, waxes and lignins do so very slowly. The decomposition of carbon and hydrogen-containing compounds releases CO_2 and H_2O, whilst the decomposition of proteins eventually releases NH_4^+, NO_3^- and SO_4^{2-}, which are important soil nutrients (Brady, 1990).

Humus, which is created through a process of synthesis as well as of breakdown, is also an important product of organic matter decomposition. As well as producing a certain quantity of nutrients that are taken up by higher plants, humus is important for a number of other reasons. The surface area of colloidal humus particles (micelles) is high, which contributes to the soil's cation exchange capacity (CEC), commonly accounting for as much as one third of the total CEC of surface soils. Humus also influences the water holding capacity (WHC) of the soil, and is important in aggregate formation and stability (Brady, 1990). In tropical soils that have low clay fractions, soil organic matter plays a particularly important role in enhancing the CEC and WHC of the soil (Greenland *et al*., 1992).

There are two major groupings in humus, the humic group (60-80% of SOM) and the non-humic group (20-30% of SOM). The humic group is further subdivided into the fulvic acid group, the humic acid group, and the humin group. Compounds in the humin group may take hundreds of years to decompose, and even compounds in the fulvic acid group may take between 15 and 50 years to decompose. However, the humic acids can attack minerals and increase the availability of cations (Brady, 1990). The non-humic group consists of compounds such as polysaccharides and polyuronides.

Cations may also be attracted from the minerals in which they occur to form organo-mineral complexes with compounds in the humus. This may allow them to become available to higher plants (Brady, 1990). Nitrogen may also be held as proteins and other N compounds with humic acids, polysaccharides, and clay-humus combinations. This increases the longevity of N in the soil by protecting it from microbial decomposition and mineralisation to NH_4^+ and NO_3^+, which are often rapidly volatilised or leached from the soil.

The CEC of micelles may be 2-30 times higher than for mineral colloids, and this may account for as much as 20-90% of the adsorption of cations by mineral soils. SOM may help to provide easily replaceable cations on humus colloids, and increase the availability of N, phosphorus (P), sulphur, and micro-nutrients held in organic forms. Acid humus may also help to release elements from mineral soils (Brady, 1990).

Greenland *et al*. (1992) have suggested that the difficulty of sustaining arable productivity in tropical soils is due to the higher rate of turnover of organic matter, generally due to the effects of higher temperature. This has led to the belief that humus in tropical soils is somehow of lower quality than in temperate zones. However, considerable research has shown that there is no difference in the *quality* of organic matter in comparable soils in temperate and tropical zones (Greenland *et al*., 1992). However, the *quantity* of organic matter in tropical soils does vary enormously. The amount of organic matter in the soil at any one time reflects the balance between the quantity of inputs and the rate of decomposition. For example, the equilibrium rate of organic matter in tropical soils under forest cover is high. This high equilibrium occurs despite the high decomposition rates under tropical conditions because the rate of organic matter input to the soil is also high. The amount of organic matter in the soil falls significantly when such areas are brought into cultivation, because the rate of organic matter inputs is greatly decreased while the rate of decomposition may increase (Greenland *et al*., 1992). Generally a new and much lower equilibrium is reached. In the West Bahia region of Brazil, for example, over half the SOM was lost in the three years following the conversion of native Cerrado forest to soybean (Boddey *et al*., 1997). Maintaining levels of SOM in agricultural land at a similar level to those levels found under natural conditions is extremely difficult and may become uneconomical, as the effort required to increase that level, rises dramatically with marginal increases in SOM levels.

In the simulation shown in Figure 3.1a, the equilibrium level of SOM under a tropical forest in a high rainfall area is relatively high due to conditions that favour high biomass production. An input of 11 t C ha^{-1} y^{-1} allows the equilibrium level to be maintained. However, this falls dramatically with the onset of cultivation under which there is an expected input of only 2 t C ha^{-1} y^{-1}, largely due to the removal of biomass in the form of crop yields. In a seasonally arid savannah zone (Figure 3.1b), the natural equilibrium level of SOM is much lower, with the natural rate of input to the soil also much lower at 3 t C ha^{-1} y^{-1}. Again, with the onset of cultivation, the input level declines, resulting in a lower equilibrium level of SOM.

In both cases, it is clearly impossible to maintain the same equilibrium level of SOM found under natural conditions, largely because cultivation changes the land cover and therefore the micro-environment, but also because organic matter inputs are lower and removal is higher under cultivation than under natural conditions. Problems arise when the new equilibrium level is so low that there are insufficient quantities of SOM to carry out important physical functions in the soil. Such a situation may result in increased erosion, due to reduced porosity, increased bulk density, with farmers often noting that their soils are harder to work (Maskey, *pers. comm.*). Many areas of land which are continuously cultivated should ideally be left fallow to allow them to build up SOM for soil physical improvement (Brady, 1990).

Relatively little quantitative information exists on the ideal level of organic matter in the soil. Brady (1990), however, suggests that it should be around 5%. Soil organic carbon percentage (OC%) is often used as a proxy measure of SOM. Using a conversion factor of 1.72 g OM $(g\ C)^{-1}$, the ideal levels of C in the soil would, therefore, be about 3%. In sandy southern African soils, 1-1.5% organic C was recommended as the long term agroecologically viable minimum (Araki, 1993a).

Similarly, research from western African countries suggests that when organic C levels fall below 1%, severe physical soil degradation can be expected to take place(Pieri, 1995). Thus, there appears to be some uncertainty as to an 'ideal' level, but somewhere between 1-3% would seem to be what many researchers consider necessary.

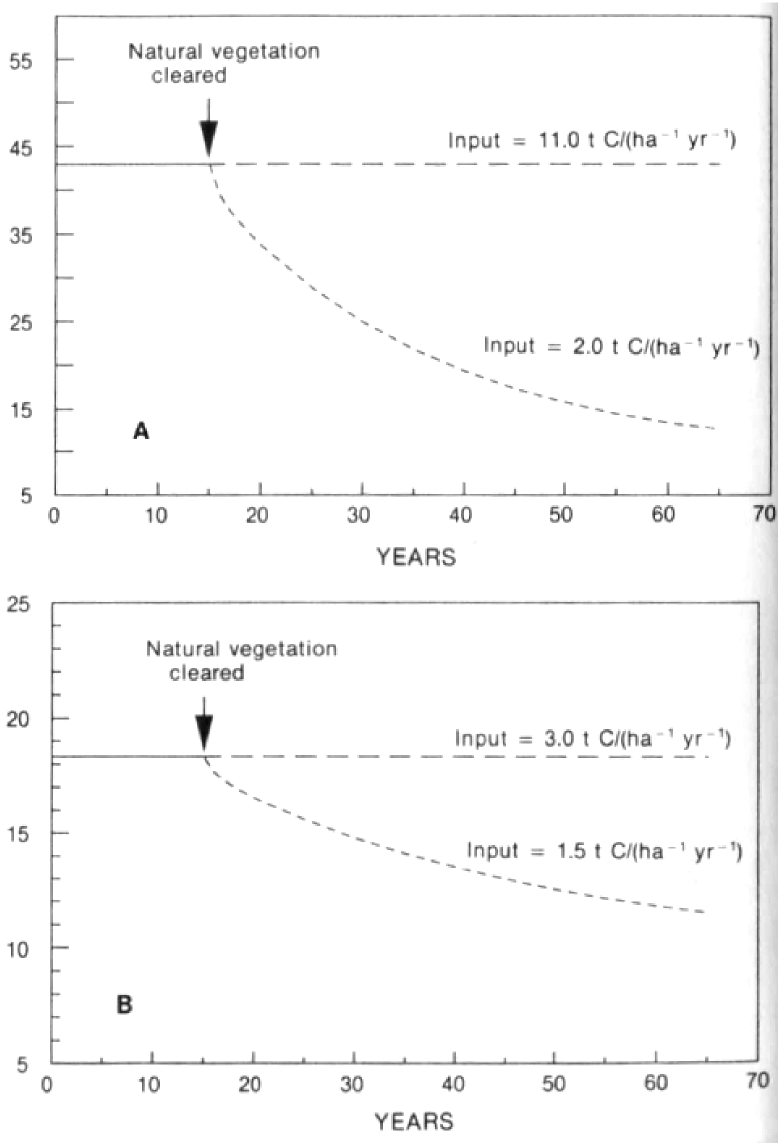


Figure 3.1 Simulation of the impact on soil carbon (t ha^{-1}) of bringing natural land into cultivation for (A) a wet tropical forest area and (B) a seasonally arid savannah area (Source: Greenland et al., 1992).

The maintenance and enhancement of SOM levels in the soil is thus important at the FAI, especially for resource-poor farmers who cannot afford external inputs.

3.2 Organic matter techniques

Most of the techniques being evaluated for use at the FAI are, by their nature, organic matter techniques, and will contribute to SOM. The focus however, is more often on the supply of nutrients, particularly N and P. The impact on SOM in the FAI project reports is rarely quantified, although it is often mentioned. In this chapter, we consider techniques such as agroforestry, green manures, animal manures, crop residue incorporation, (ley cropping or fallow) cover cropping, and intercropping, all of which have an influence on SOM. Nitrogen and phosphorus are not the only nutrients to be supplied by organic matter techniques and SOM is also important in the supply of potassium, the other macro-nutrient, as well as in the supply of various secondary nutrients such as magnesium, calcium, and sulphur as well as some trace elements (Euroconsult, 1989). However, organic manures are generally low grade sources of nutrients, since they contain only a low percentage of nutrients, and it is usually necessary to apply inorganic fertilisers to obtain maximum crop yields (Euroconsult, 1989).

3.2.1 Plant biomass

The role of manures and plant residues in supplying nutrients is well documented (Brady, 1990). However, the quantities required to meet crop requirements can be large, and may often be beyond the capacities of small farmers to produce (Snapp *et al*., 1998; Jama *et al*., 2000). By definition all organic matter techniques provide plant OM to the soil, both from the above-ground and below-ground components. Below-ground biomass is difficult to quantify, although estimates suggest that it is about 40% of above-ground biomass. This is, of course, important for the improvement of soil physical characteristics. However, in the discussions that follow, it is additions of above-ground biomass (net primary productivity) that is considered.

Plant biomass production varies greatly according to climatic conditions. It has been estimated that the production of above ground dry matter for natural vegetation in the humid tropics is about 20 t DM $ha^{-1}y^{-1}$, whilst in the sub-humid tropics it may vary by about 5-10 t DM $ha^{-1}y^{-1}$ depending on conditions. In semi-arid zones, the above ground production is estimated to be about 2.5 t DM ha^{-1} y^{-1} for natural vegetation (Young, 1989).

Although these levels might reasonably be expected from the later stages of a forest or bush fallow, above ground plant biomass productivity can be expected to vary depending on the techniques used as well as on the climatic zones. In particular, net primary productivity will depend on the type of plant used in the technique, the spacing and arrangement of that plant as well as on biophysical conditions such as solar radiation, rainfall and temperature. Even within similar climatic zones the above ground biomass production can vary quite considerably. Brewbaker (1987) found that pure stands of *Leucaena leucocephala* in Hawaii (humid climate) produced between 40 and 80 t DM $ha^{-1}y^{-1}$. Clearly, this figure will be reduced where *Leucaena* is used as an alley-crop, due to differences in per hectare density and possibly because of different growth patterns in an intercrop situation. For example, in sub-humid climates in Nigeria, above ground biomass production of *Leucaena leucocephala* varied from 6.8-16 t DM $ha^{-1}y^{-1}$ (Bahiru Duguma *et al*., 1988).

Cover crops may also potentially provide large quantities of OM, particularly if grown in rotation or in sequence where conditions allow. In Ghana and Bolivia, for example, various cover crops were found to produce between 11-34 t FW $ha^{-1}y^{-1}$. Jackson *et al*. (1999) found that farmers often ranked the use of *Canavalia ensiformis* and *Mucuna pruriens* higher than the controls, which included no fertiliser as well as various levels of inorganic fertilisers. However, for the use of herbaceous cover crops, growth conditions have to be relatively good, and any prolonged dry periods greatly reduce their above ground biomass production. Similarly, in an intercrop, biomass production will be greatly reduced and strong competitive effects with the main crop may be problematic.

Other organic matter techniques include the use of crop residues and compost. Crop residues are traditionally left after harvest and incorporated back into the soil. However, there are generic issues relating to the quantity and quality (see below) of crop residues that can be returned to the soil. Ali (1999) suggests that a typical rice crop might, for example, produce a straw yield of about 3 t DM ha^{-1} y^{-1} (N content about 18 kg), although this will vary depending on local practice and conditions. The economic value of straw for many farmers however lies not necessarily in its use as an organic matter (or source of nutrients), but as a source of fodder and fuel (Ali, 1999). Thus, the use of the straw as a source of organic matter (or source of nutrients) may be irrational.

Compost may be seen as another major source of organic material in resource-poor farming systems. Once again there are issues relating to the quantity of biomass and the quality of the biomass that is produced in the composting process. However, management and incorporation of compost in farming systems can be problematic, particularly concerning labour requirements for its collection, management and incorporation in sufficient quantities to make an impact on soil physical properties (Pandy, *pers. comm.*). Young (1989) suggests that composting may be more relevant in temperate conditions to avoid nitrogen immobilisation caused by the high C/N ratio of fresh plant material, which does not seem to be such a problem under the faster decomposition conditions of the tropics.

3.2.2 Animal manures

Animal manure is an invaluable asset in many LDCs. As an organic matter source, it may improve soil structure and stability and is an important source of nutrients. In remote areas, with poor access to market centres, animal manure may be the only source of soil organic matter and fertiliser for resource-poor farmers, especially as the majority of the plant biomass available, either as crop residues or on-farm and off-farm biomass may be fed to cattle, (Bhurtel, *pers. comm.*).

In on-farm trials investigating the influence of various organic manures on vegetable production in Ghana, farmers ranked animal manure higher than the controls, which included no application of fertiliser as well as the application of various levels of inorganic fertilisers (Jackson *et al*., 1999). However, animal manures tended to be ranked lower than green manure. Tomatoes were also judged to taste better and to have a longer shelf life, although these qualities appeared to be of secondary importance to purchasers of the tomatoes, who preferred the large tomatoes derived with the use of chemical fertilisers.

Manure recommendations appear to be made generally with respect to soil N and P levels rather than with respect to its impact on soil physical properties. Evidence suggests, however, that farmers place a high premium on the impact that it has on the soil physical structure. In the Kenyan highlands, for example, Lekasi *et al*. (1998) noted that the price of livestock-derived manures was approximately five times the price of artificial fertiliser calculated from the content of nutrients alone, indicating the value farmers place on the physical benefits to soil quality derived from using manure

Lekasi *et al*. (1998) found that the OC% of manure from various animals was between 22-42%. This compares with many plant species in the Organic Resources Database (Gachengo *et al*., 1998), as local practice was to mix bedding and inedible crop residues in with the manure. In general, cattle manure examined in the Organic Resource Database appears to have a much lower carbon content, suggesting that the amount of pure manure required to increase soil organic matter levels might be higher than where plant biomass is applied.

As an organic material, manure is subject to the same biophysical limitations that affect other organic matter techniques. It may be difficult to produce sufficient quantities of animal manure for effective fertility maintenance, or it may have undesirable effects if the quality of the manure is low.

The collection and application of animal manure is very labour demanding, and supplying adequate quantities of labour to improve soil fertility in this way can become a limitation to the use of the technique. However, the advantage of using cattle in the decomposition of plant biomass is that as long as the animal is healthy, the breakdown of organic matter is relatively independent of outside temperatures and moisture levels. This may be of great importance to farmers in difficult conditions, particularly in terms of nutrient supply, although where SOM increase is required for improvement of soil physical characteristics, direct application of plant biomass may be better.

3.3 Biophysical constraints

3.3.1 Biomass quantity

Young (1989) attempted to provide indicative quantities of plant biomass requirements for maintenance of good soil physical conditions. After considering approximate oxidation and erosion losses of soil C, required above ground plant biomass inputs were estimated to required at about 8.4 t DM ha^{-1} y^{-1} for humid regions, 4.2 t DM ha^{-1} y^{-1} for sub-humid regions and about 2.1 t DM ha^{-1} y^{-1} for semi-arid areas (Table 3.1). Evidence indicates that such quantities of plant biomass may be difficult to supply. In an alley-cropping system in Costa Rica (humid), the net primary production of *Calliandra calothyrus* was about 4.4 t DM ha^{-1} y^{-1}. Of this, about 2.8 t DM ha^{-1} y^{-1} was estimated to be leaf production (Baggio & Heuveldorp, 1988) and of possible use as a green manure.

Considerable quantities of organic material are required to maintain suitable levels of soil organic matter in agricultural soils. The exact amount will vary greatly under differing conditions, although, as an example, in soils in southern Africa, annual applications of about 10 t DM ha^{-1} y^{-1} of high quality plant biomass (see below for discussion on biomass quality), or 7 t DM ha^{-1} y^{-1} of low quality residue, was found to be necessary to maintain a minimum level of 1% organic C in a sandy loam soil in the sub-humid tropics (Snapp *et al*., 1998), assuming a decomposition rate of 0.05 y^{-1} (Janssen, 1993). Thus, the ‘ideal’ level of 3% organic C mentioned previously may require as much as 30 t DM ha^{-1} y^{-1} in similar conditions, assuming a linear relationship between organic C levels and biomass inputs. This may not be the case, but the data suggests that on the whole, large amounts of organic matter are required, to maintain the physical condition of the soil at a level that could support continuous and sustained crop production.

Table 3.1: Estimated inputs of plant biomass required for the maintenance of soil organic matter in various climatic zones.

Climatic zone	Initial topsoil carbon (%)	Oxidation loss (kg C ha^{-1} yr^{-1})	Erosion loss (kg C ha^{-1} yr^{-1})	Required addition to soil humus (kg C ha^{-1} yr^{-1})	Required plant residues added to soil (kg DM ha^{-1} yr^{-1})	
					Above ground	Roots
Humid	2.0%	1200	400	1600	8400	5800
Sub-humid	1.0%	600	200	800	4200	2900
Semi-arid	0.5%	300	100	400	2100	1400

(From Young, 1989).

3.3.1.1 Plant biomass

If these levels of biomass are required to have an appreciable effect on soil organic matter, the question arises as to how easily these quantities could be produced. In recent years, a number of studies have appeared in the literature reporting the biomass productivity of several plant species, which can help to answer this question.

In Ghana, Kiff *et al*. (1997) examined the effect of introducing cover crops and animal manure to use with high-value dry season vegetables. Both on-farm and research station experiments were established to establish how cover-crops and animal manure might be integrated into the farming system, to help maintain fertility, conserve soil moisture, and reduce weed and pest problems. On-station trials (dry or fresh weight not specified) showed that *Crotalaria* spp. produced high biomass yields (19-23 t ha^{-1} y^{-1}), whilst being at the same time easy to incorporate into the soil (Jackson *et al*., 1999). *Mucuna pruriens* (19-23 t ha^{-1} y^{-1}) and *Canavalia ensiformis* (11.5 t ha^{-1} y^{-1}) were less suitable as they were harder to incorporate into the soil, with more rubbery and woody plant parts. Pigeon pea (*Cajanus cajan*) failed to perform well (6.3 t ha^{-1} y^{-1}). Similar experiments on cover-crops (dry or fresh weight not specified) in the Ichilo and Sara region of Bolivia showed that *Canavalia ensiformis, Mucuna pruriens* and *Cajanus cajan* all gave good biomass yields at 34 t ha^{-1} y^{-1}, 16 t ha^{-1} y^{-1} and 15 t ha^{-1} y^{-1}, respectively (Pound *et al*., 1999).

In Nepal, a number of potential green manure species were evaluated in Pokhara in 1988 (Pande, 1997). *Cajanus cajan* was able to produce about 3-4 t DM ha^{-1} y^{-1}, *Centrosema pubescens* about 5 t DM ha^{-1} y^{-1}, and *Calopogonium mucunoides* about 4 t DM ha^{-1} y^{-1}. *Canavalia ensiformis* appeared to grow, although data on its production was not presented. *Crotalaria anogyroides* failed to establish altogether.

In Malawi, Saka *et al*. (1995) showed that the leaf biomass production of three hedgerow species (*Gliricidia sepium*, *Leuceana leucocephala* and *Senna spectabilis*) varied between 0.5-2 t DM ha^{-1} y^{-1}, and did not affect the level of organic C in the soil over a one year period. In Malawi, Kanyama-Phiri *et al*. (1997) found that *Sesbania sesban* produced about 2-3 t DM ha^{-1} y^{-1} of high quality leaf biomass. This was in addition to the fuel-wood produced during the ten months of growth between January and October.

In the studies where alley cropping has been shown to benefit crop yields, tree biomass production has been in the order of 6-8 t ha^{-1} y^{-1}, using *Leucaena leucocephala* (Kang *et al*., 1985). For *Flemingia congesta*, Budelman (1988) recorded an annual dry matter production of 12.4 t ha^{-1} y^{-1} in the Ivory Coast, while Yamoah *et al*. (1986) measured 16.9 t DM ha^{-1} y^{-1} for *Flemingia congesta* in Nigeria. In Zambia, however, although *Flemingia congesta* produced a maximum of 3 t DM ha^{-1} y^{-1} in one trial (Table 3.2), the mean production of all the species was only 1.3 t DM ha^{-1} y^{-1}. These results depend on the planting density of the trees, which in the Zambia case were planted at a spacing of 3.8 × 0.25 m (21,000 trees ha^{-1}). Although these trials were not in a forest/agriculture interface production system, the results are probably analogous, especially in the case of the *chitemene*, in which woody biomass from *miombo* woodland is collected from a wider area and burnt in a smaller area. Even where there a sufficient nutrients from the ash in the first year, the soil fertility is lost in the succeeding 1-2 years before the trees have time to establish and begin to act as a nutrient ‘safety net’, which is also likely to occur in a true temporal FAI system.

Table 3.2: Mean annual biomass production (t ha^{-1} y^{-1}) of different tree species in agroforestry trials at Kasama, Northern Province, Zambia.

Trial no.	Species	1987	1988	1989	1990
D11	*Flemingia congesta*		1.40	2.45	2.91
D21	*Flemingia congesta*		0.28	2.22	1.09
D22	*Flemingia congesta*		1.06	1.89	1.41
	Tephrosia vogelii		2.19	0.33	
	Cassia spectabilis				0.56
	Calliandra calothyrsus			0.64	1.51
D31	*Leucaena leucocephala*	2.46	2.23	2.47	1.48
	Albizzia falcataria	0.67			
	Flemingia congesta		0.44	1.09	0.73
	Gliricidia sepium	0.94	0.79	1.08	0.47
D32	*Flemingia congesta*	0.83	0.74	0.51	0.60
	Cassia spectabilis	0.54	1.31	0.84	1.12
	Sesbania sesban	0.72	0.44	0.07	
D33	*Flemingia congesta*	1.05	1.13	1.36	0.82
	Cassia spectabilis	0.56	2.14	1.40	0.97
	Sesbania sesban	0.86	0.66	0.81	

(Developed from Matthews *et al*., 1992a; Matthews *et al*., 1992b)

Although it has been suggested that above-ground primary production of some alley cropping species may be sufficient to build up SOM even with the removal of crops (e.g. Young, 1989), the data shown above would indicate that this is not likely. Cover crop species are likely to produce even less biomass annually due to their shorter duration of growth compared to woody perennials. Increasing soil organic matter to ‘ideal’ levels, therefore, will, in most cases, necessitate the importation of additional amounts of organic matter.

The question is, therefore, where is this biomass to come from? If the farmer is to grow it, can it be produced in sufficient quantities to have an appreciable effect on soil organic matter levels? Assuming an annual biomass production of 2 t DM ha^{-1} y^{-1}, 3 ha of land would be required to supply 1 ha of cropped area with enough biomass to maintain the soil organic carbon level at just 1%. Significantly more would be required to raise it to the 3% level suggested earlier. In the initial years of hedgerow intercrop systems, when farmers are most likely to reject or accept a new technique, the biomass production is likely to be well below 2 t ha^{-1} (e.g. Matthews *et al.*, 1992a). This is clearly insufficient to maintain the OC% at the 1% level suggested above.

From the farmer's perspective, if this biomass is to be grown on-farm, the growth of sufficient supplies of organic material will detract greatly from the area available for food crop production. If it is to be supplied from outside the farm, the transport of such large quantities of organic matter from off-farm locations requires considerable physical effort (Quashie Sam, *pers. comm.*). In addition, in either case considerable labour will be required for incorporation of the biomass into the soil, which resource-poor farmers may find difficult to supply. In many situations, therefore, it may simply not be possible to increase soil organic matter within farmer constraints.

3.3.1.2 Animal manure

The problem of supplying adequate amounts of SOM through animal manure may be equally great. In general, the smaller the animal, the higher the nutrient concentration in its manure, but the lower the quantity of manure produced. A greater number of animals will, therefore, be required to supply a given quantity of organic matter. Most literature appears to examine quantities of manure in relation to the soil chemical, rather than the soil physical, characteristics. However, we assume that the dry matter quantities required for soil physical improvement are similar to the amounts required when using other organic matter sources, such as plant biomass (Euroconsult, 1989). The actual dry matter requirements of animal manure for maintaining the soil physical properties will therefore depend on local conditions, but the data presented by Young (1989) gives a broad indication of the amount of animal manure that might be needed in different climatic conditions (Table 3.1).

The evidence suggests that the quantities required for the effective management of other soil nutrients can also be large. For example, in Ghana (dry or fresh weight not specified), Jackson *et al*. (1999) found that to correct zinc deficiencies of soils near Wenchi, about 20 t ha^{-1} of poultry manure was required. The amount of sheep or cattle manure required was estimated to be between 40-60 t ha^{-1}. However, in surveys in a number of villages in the region, Kiff *et al*., (1997), noted that farmers knew that manure could be used, but generally found its use unattractive due to its supply being unreliable, too much effort involved in its collection, and a perception that manuring techniques were regressive and old-fashioned. The presence of cattle in the main FAI areas of Ghana is limited (Owosu-Bennoah, *pers. comm.*), partly because tsetse fly, which causes the disease trypanosomiasis (sleeping sickness) in cattle (and humans), makes livestock rearing in the FAI areas impractical. Other problems would include the provision of fodder, which might have to be imported or produced with fodder crops and would require new demands of the farmer, in terms of land, labour and capital. There is also the cultural problem of persuading farmers who have no knowledge or interest in cattle to keep them on their farms (Dickson & Benneh, 1995).

In Nepal, where many people own their own livestock, supplying adequate quantities of manure may be less acute, though still great. Animals are multifunctional in Nepalese agricultural systems, and provide meat, milk, *ghee*, curd, and draught power, as well as manure. Many families may own more than a single species of animal, with the most common combination (60% of those owning animals) being cattle, goats, chickens and buffaloes (Gatenby *et al*., 1990). Often there are competing demands for manure produced by livestock, particularly for use as fuel, which may make its availability as a nutrient source scarce. Pilbeam *et al*. (1999), in deriving an N balance for a hypothetical household with one hectare of agricultural land suggests that feed for animals is derived from a variety of sources, including dry and green crop residues, tree fodder and grasses. Total feed requirement for buffalo assuming a live-weight of 450 kg was estimated to be about 2.6 t DM y^{-1}. For cattle, assuming a live-weight of 250 kg, feed requirements were estimated to be 1.8 t DM y^{-1}. Fodder yields in Nepal vary greatly depending on location and species.

Assuming that typical fodder yields are about 3-4 t DM ha^{-1} y^{-1} (for native grass species Pande, 1997), and that nearly 100% of the biomass passes through the livestock, producing sufficient feed to satisfy oxidation losses of OC (as noted by Young for humid areas, Table 3.1) will require fodder production from approximately 2-3 ha of land. The yields of certain introduced fodder species can be as high as 13 t DM ha^{-1} y^{-1} (Pande, 1997), although this level of production will require the appropriate inputs and conditions and may be difficult to sustain, where the biomass is exported in cut and carry systems. The analysis by Pilbeam *et al*. (1999) suggests that about 2.5 t of animal feed might come from dry and green crop residues, presumably from on farm sources. However, this still leaves a requirement for about 6 t ha^{-1} if SOM levels are to be maintained through the use of animal manure alone.

In the Kenyan highlands in the Enbu District application rates of 5-8 t fresh manure ha^{-1}, are recommended to farmers (Lekasi *et al*., 1998). With a DM% of 40%, this represents about 2-3 t DM ha^{-1}. However, average rates of fresh manure applied by farmers is often much higher (11 t ha^{-1} = 4.4 t DM ha^{-1}), and can exceed 17 t fresh manure ha^{-1}. (=7 t DM ha^{-1}). Despite these relatively high levels of manure applications, farmers often felt that lack of adequate quantities of manure was the major constraint to manure use.

These biomass requirements are very rough guides, and relate more to nutrient management, rather than to soil organic matter improvement. However, they serve to show that the quantity of animal manure required to effectively promote soil physical characteristics are substantial. This amount appears to be less than the amount required to supply N or P, but still large enough to necessitate the application of several tons per hectare of fresh manure. It is debatable whether resource-poor farmers at the FAI would have access to sufficient quantities of manure to supply the total organic matter requirements of their cropped land, particularly as there are competing demands for its use. Reliable access to off-farm land for fodder collection may also be a major requirement for the use of animal manure.

The use of animal manure is already a widely-used technique in many tropical countries, and farmers are well aware of its importance (Webster & Wilson, 1980). As a limited resource, animal manure is, however, likely to have applications in niche areas of the farming complex, and there may be scope in trying to improve the way in which it is managed and applied, if this is possible within local constraints. In most cases, however, any strategy involving the use of animal manure to maintain soil fertility may have to consider it as a partial solution to the problem.

In areas where animal manure is not already used, for example in the major FAI areas of Ghana, it is worth noting that the labour requirements involved in using animal manure are likely to be a major concern (as are the requirements for new knowledge and resources). Providing fodder is a labour-demanding undertaking, if the animals are stall-fed. Much labour may also be required for transporting the manure from the animals to the fields, often located in different places, and also for incorporating it into the soil. These issues are discussed in more detail later in this report.

3.3.2 Biomass quality

The 'quality' of biomass is a function of its nutrient content and its resistance to breakdown. Biomass quality has two opposing effects, in that lower quality organic matter is likely to have a larger impact on soil organic matter levels than high quality material, which mineralises more rapidly. On the other hand, higher quality organic material contributes more to the nutrient status of the soil (N, P, K and micronutrients), and is important for maintaining soil microbial activity and the soil buffering capacity. Successful organic matter management depends on finding the correct balance between these two effects. This applies to plant organic matter, whether green manure or crop residues, as well as to animal manure. Crop residues and other low quality organic residues, particularly if added in large quantities, may temporarily induce N or P deficiencies in the soil due to microbial immobilisation, thereby reducing crop yields. Palm *et al*. (1997b), for example, have shown that addition of organic matter containing less than about 0.25% P to the soil is in danger of causing net immobilisation of P. Such deficiencies may have to be overcome through the use of inorganic fertilisers (Muriwara & Kirchmann, 1993).

The ratio of carbon to nitrogen (C/N ratio) in organic material has been used as a measure of its quality for some time. The CERES family of crop models, for example, account for biomass quality by using the C/N ratio to calculate a multiplier to adjust the potential decomposition rate of the fresh organic matter in different pools (Figure 3.2). More recently, the concentrations of lignin and polyphenols have also been found to be important; Mafongoya *et al*. (1997b), for example, have shown that when the lignin content and polyphenol content of the residues incorporated into the soil were over 15% and 3% respectively, immobilisation of N occurred.

The nutrient content of animal manure depends on the diet of the animal, and on how the manure is collected and stored. Diet is particularly important in relation to the partitioning of N between the faeces and the urine (Snapp *et al*., 1998). High quality diets (low in lignin and polyphenols) result in more N being excreted in the urine than in the faeces (Somda *et al*., 1995). N that is excreted in the urine is much more quickly volatilised, and urine is also more difficult to collect. Animals fed with a tannin-rich diet tend to excrete more of the N in their faeces. However, recent results suggest that this kind of N is very resistant to mineralisation (Mafongoya *et al*., 1997a).

In India, Goyal *et al*. (1992) found that a combination of wheat straw (low quality organic matter) and urea actually reduced yields, while a combination of *Sesbania* green manure (high quality organic matter) and urea increased yields compared with the application of urea alone. In Kenya, Nandwa (1995) found that maize stover (low quality organic matter) used as an organic matter source reduced maize grain yield by between 3-30%. Maize stover has also been shown to reduce crop yields in Zimbabwe (Rodell *et al*., 1980; Muriwara & Kirchmann, 1993).

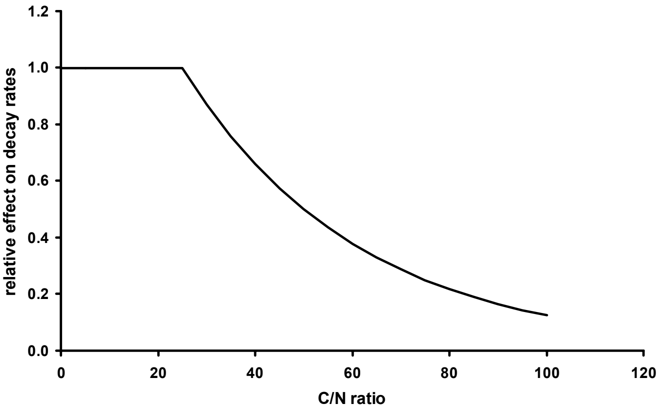


Figure 3.2: Multiplier function used in the CERES crop models to adjust the potential decay rates of the fresh organic matter pools in response to the pool C/N ratio.

The beneficial effects of N released from manure appear to be directly after application. This is in the form of ammonium (NH_4^+) and nitrate (NO_3^-). However, poor quality manure has been found to result in prolonged periods of N immobilisation, and under these conditions N availability has been increased with inorganic sources (Muriwara & Kirchmann, 1993). Typical quantities for nutrients in domesticated animals are shown, indicating that although P supply is above the threshold that may be required to prevent P immobilisation, N content is often below the critical limit that may be required to prevent N immobilisation (Table 1.1).

Table 3.3. Mean content N, P, K, and C in manure from various domestic animals in Murang and Kiambu Districts, Kenya. (From Lekasi et al., 1998).

Manure type	N (%)	P (%)	K (%)	C (%)	C:N ratio
Cattle	1.4	0.60	0.59	35	26
Cattle & compost	1.3	0.44	0.36	25	21
Goat	1.5	0.40	0.53	32	22
Pig	2.0	1.19	0.49	40	21
Poultry (broilers)	2.4	1.60	0.41	41	17
Poultry (local)	1.2	0.91	0.26	22	19
Rabbit	1.6	0.40	0.50	33	20
Sheep	1.5	0.33	0.44	33	22

These issues are important in the context of adding organic matter to the soil, whether it be to improve soil physical or soil chemical characteristics. The Organic Resources Database (Gachengo *et al*., 1998) developed by Wye College and the Tropical Soils Biology and Fertility Programme (TSBF), Nairobi, Kenya, includes a decision making tree which classifies the quality of both animal and plant organic matter according to quantities of N, lignin and polyphenols. Based on this information, we have developed some guidelines on the use of various plants and technologies in relation to organic management, shown in Table 3.4.

Table 3.4: Possible technical options for organic matter of varying quality. The table indicates critical levels of N, P, lignin and polyphenols required for good quality biomass. See text for details. (Developed from the Organic Resources Database (Mafongoya et al., 1997b; Gachengo et al., 1998).

N > 2.5%	P > 0.25%	Lignin < 15%	Polyphenol < 4%	Comment
✓	✓	✓	✓	**Green manure** High quality organic matter could be used as a green manure.
✗ ✓ ✗	✓ ✗ ✗	✓ ✓ ✓	✓ ✓ ✓	**Integrated nutrient management** Low levels of N, P or N and P may cause net immobilisation of N, P or both N and P. If incorporated immediately, use with N, P or both N and P fertiliser. Alternatively mix with very high grade organic matter to compensate for low N, P or N and P levels.
✓ ✓	✓ ✓	✓ ✗	✗ ✓	**Compost/soil physical improvement** High levels of lignin and polyphenol may encourage immobilisation of N and P or reduce the rate of mineralisation despite high levels of N and P in the organic matter. This organic matter may be composted to start the breakdown
✗	✗	✗	✗	**Surface mulch or erosion control** Low levels of N and P and high levels of Lignin and Polyphenol make this organic matter unsuitable for use as a fertiliser technology. It may be used however as a surface mulch to protect against evaporative losses or to control surface water flow.

This table could be used to indicate possible technique options given variable biomass quality in different plants. For example, where the plant biomass is of high quality, the plant could be used as a green manure for immediate incorporation into the soil. With moderate biomass quality and in order to prevent immobilisation of N and P, it might be necessary to use inorganic fertilisers as well, and/or to compost the biomass prior to use on the fields. Where plant biomass is of very low quality, and there is a strong possibility of immobilising N and P, it could be used instead to physically control soil and water movement.

Clearly, the issue of organic matter quality is important for farmers and we believe technique requirements may need to vary depending on the quality of biomass available to the farmer as shown previously. Where an improvement to soil physical characteristics is important, the requirement will be for moderate- to low-quality organic matter. However, as has been shown, this may result in N and P immobilisation, particularly without supplementary use of inorganic fertilisers, and crop yields may therefore be reduced. This is the paradox inherent in the use of organic matter technologies; the development of soil physical characteristics is better served by low-quality organic matter which does not best serve to improve soil chemical characteristics, at least at a rate that is practically useful to the farmer. Where land is not limiting, the best option for soil physical improvement is probably to return it to long fallow. Where land is limiting, the situation is more complex and the quality requirements of organic matter are likely to be dictated by the need for rapid crop yield benefits. This may mean the use of techniques producing high quality organic matter, or moderate quality organic matter with supplementary use of mineral fertilisers.

3.3.3 Soil temperature

One of the major environmental factors influencing the development and decomposition of soil organic matter is temperature. According to Van't Hoff's Law, the rate of any chemical reaction, including those carried out micro-organisms, approximately doubles for every 10K rise in temperature, provided all other factors are held constant (Greenland *et al*., 1992). Figure 3.3 shows the rate-modifying factor for temperature in the decomposition of SOM used by the ROTHC-26.3 model (Coleman & Jenkinson, 1999). Clearly, decomposition is low at low temperatures, but tends to rise with higher temperatures. Thus, SOM will tend to accumulate more in colder areas (Brady, 1990). However, this also depends on the level of input of organic material into the soil, so that under natural conditions in the tropics, due to higher plant growth rates, the rate of SOM accumulation can be very much higher than in colder areas (Greenland *et al*., 1992).

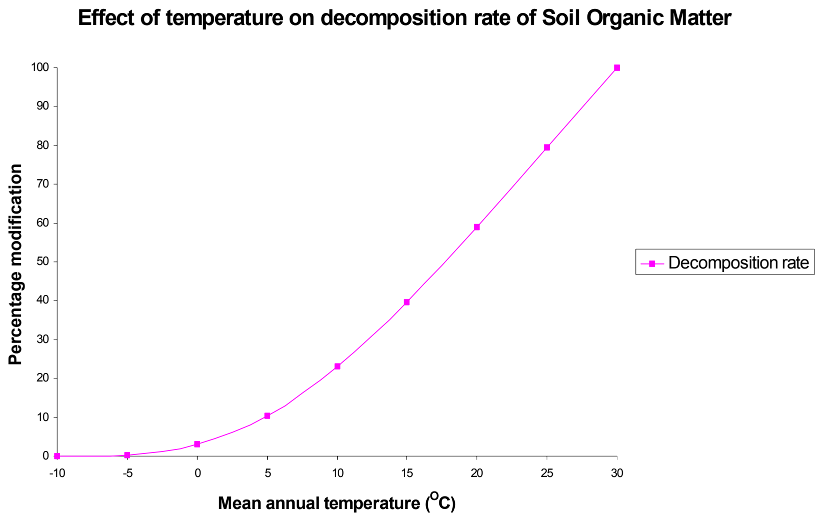


Figure 3.3 Rate modifying factor for temperature (expressed as a percentage of the rate at 30°C) used by the ROTHC-26.3 model for soil organic matter decomposition (Redrawn from Coleman & Jenkinson, 1999).

Figure 3.4 shows the schematic relationship between temperature and the accumulation of SOM, which illustrates the following points. Synthesis and accumulation of biomass by plants (line A) is generally most rapid between about 20-30 °C. Although the accumulation of SOM is favoured by extremely low rates of microbial decomposition below 10 °C, the biomass synthesis by plants, and hence input of carbon to the soil, is also relatively low. Thus, SOM accumulation is low. When temperatures increase, plant growth increases proportionately more than microbial activity so that there is an increase in OM accumulation with a maximum around 15 °C. As temperatures continue to increase, microbial breakdown dominates, and SOM accumulation again declines to near zero. Eventually plant synthesis stops altogether and SOM accumulation is impossible. According to this scheme, therefore, accumulation of SOM will not occur at significant rates above about 25 °C.

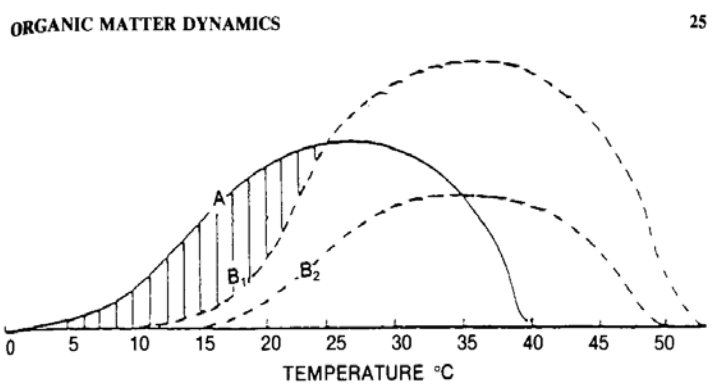


Figure 3.4: Essential features of Mohr's diagram relating to organic matter. Curves represent (A) synthesis by plants, (B1) destruction by aerobic bacteria, (B2) destruction by anaerobic bacteria. The shaded portion indicates temperatures favourable for soil organic matter accumulation. (From Greenland et al., 1992).

The implication from this is that the development of organic matter will be difficult in areas dominated by high temperatures and that one of the many requirements for successful use of organic matter techniques is relatively cool temperatures. Where temperatures are low, for example in hill areas such as Nepal or Bolivia, improvements to soil physical characteristics may be possible through the use of organic matter, and there may be some merit to employing such techniques to build up SOM. Such a strategy might rely on improvements to soil physical qualities and the sustained release of nutrients from humus decomposition. This may not, of course, entirely substitute for the need for high quality biomass or inorganic fertiliser for more rapid supply of nutrients to the crops, which where necessary, should still be part of the family of techniques used with organic matter technologies.

Where temperatures are high, rapid mineralisation of organic matter makes soil physical improvements more difficult to achieve through increases in SOM. Where the availability of land is not limiting, long fallow rotations will probably provide the best means of improving SOM. Where land is scarce, technologies that allow rapid release of nutrients to the soil will be able to make some contribution. This is not to say that there is no merit to attempting to improve soil physical characteristics in high temperature areas, as farmers often value improvements to soil physical conditions in terms of 'softness', 'looseness' or 'coolness' (Kiff *et al*., 1999; Pound *et al*., 1999). We merely wish to point out that in such conditions, SOM development may be more difficult.

3.3.4 Soil moisture

Along with temperature, soil moisture content also has a major influence on the rate of organic matter decomposition (Greenland *et al*., 1992). The relationship between the soil moisture content and the relative response of decomposition rate of organic matter used in the nutrient sub-model of the CERES crop models is shown in Figure 3.5. As the soil moisture content increases above the drained lower limit (roughly equivalent to the permanent wilting point) there is a steady increase in decomposition rate until the drained upper limit (equivalent to field capacity) is reached, after which there is a decline in decomposition rate. All other factors being equal, therefore, the build-up of SOM would be fastest when the decomposition rate is the slowest, i.e. in very dry soils, or in very wet soils. In practice, however, inputs of plant biomass are unlikely to be high in dry soils due to low biomass production. At the other end of the scale, SOM build-up is high in such systems as peat bogs, where biomass production is relatively high, and decomposition is slow because of the anaerobic conditions brought about by extended periods of submergence.

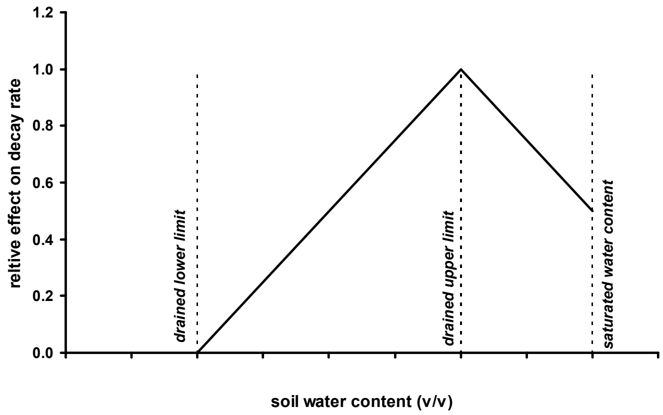


Figure 3.5: Multiplier function used in the CERES models to adjust the potential decay rates of the fresh organic matter pools in response to soil moisture.

Certainly on a macro scale, rainfall and temperature are considered to be the major determinants of SOM status. In general, the higher the rainfall, the greater the SOM level. This is partly due to increased biomass production in such areas, but also is due to reduced activity of the aerobic bacteria responsible for the decomposition of SOM. The effect of soil moisture status on the SOM level is shown for two different kinds of US soils in Figure 3.6. Where the soils are poorly drained, the percentage SOM is clearly higher in both Mollisols and Alfisols (Brady, 1990).

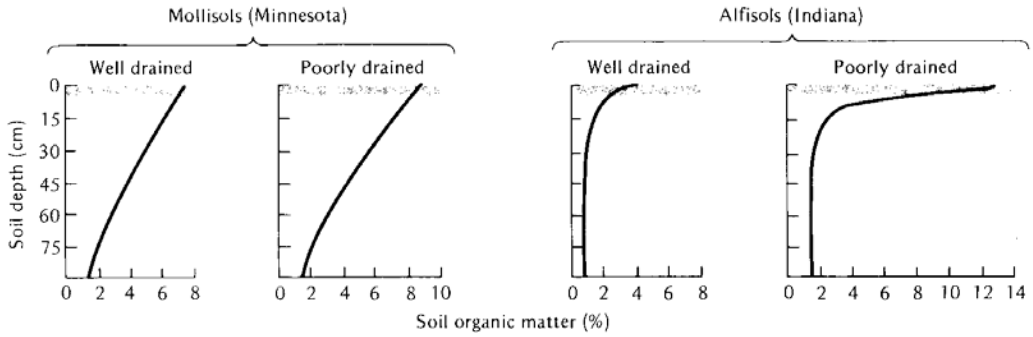


Figure 3.6 The effect of soil moisture on organic matter content in Mollisols and Alfisols. (Source: Brady, 1990).

At a practical level, for the successful use of organic matter technologies for SOM development, sufficient levels of moisture to at least ensure good biomass production are required. Although reduced rates of decomposition occur in very dry or very wet conditions, these are generally not ideal for maximum plant growth. A more reasonable requirement would be to suggest that moisture levels in the soil and rainfall should at least be capable of good plant growth, without leading to prolonged waterlogged conditions that would reduce decomposition. Thus a rough requirement might be to suggest a minimum rainfall of about 1000-1500 mm y^{-1}, preferably with no more than about four dry months per year. These are typical conditions for moist sub-humid to humid areas (Young, 1989). At low rainfall levels, technologies such as intercropping may result in increased competition with the main crop for soil moisture, leading to a decline in yields (Snapp *et al.*, 1998).

3.3.5 Soil texture

Evidence indicates that the accumulation of SOM is also influenced by soil texture (Brady, 1990). In general, soils with high clay and silt contents also have higher organic matter levels compared to coarse textured soils (Figure 3.7), mainly due to lower SOM decomposition. This is a consequence of complexes being formed between the organic matter and the clay minerals, which help to protect organic N from mineralisation. As there is insufficient N available for the growth of micro-organisms, overall organic matter decomposition rates are also reduced (Brady, 1990).

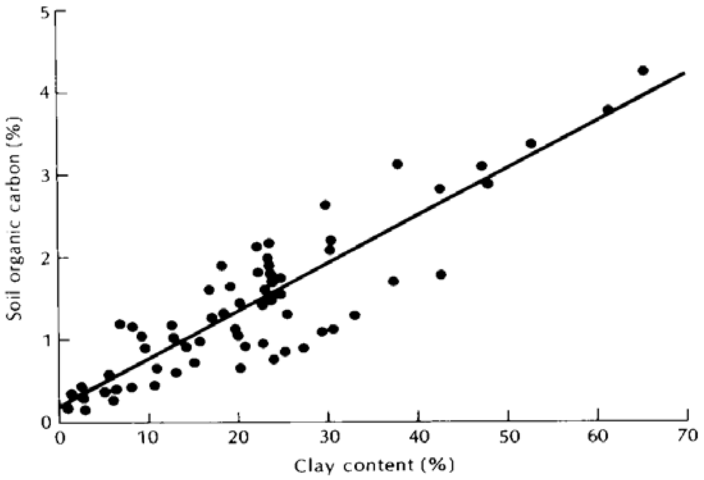


Figure 3.7 The effect of clay content on soil organic carbon (Source: Brady, 1990).

The threshold level of organic matter required to prevent severe physical degradation of a soil is also related to the soil's texture. For soils with a low sand content, an organic C content of 0.9% may be adequate, but for sandy soils, the organic C content may have to be as high as 1.5% (Araki, 1993b).

Clearly, the extent to which SOM techniques may be used to build up the level of fertility in the soil is partially dependent on the texture of the soil, and this needs to be considered when a new technique is introduced to an area. Techniques aimed at improving SOM levels may meet with more success when they are used on loamy or clayey soils. On the other hand, attempting to build up the SOM status of sandy soils, especially in the long term, may be highly impractical for farmers in terms of the quantity of OM required for the task. In these conditions, it may, therefore, be necessary to use techniques that can provide more rapid release of nutrients to crops, so that crops can make immediate use of the nutrients, rather than trying to build up soil physical properties with organic matter.

3.3.6 Soil pH

Acid soils account for about 63% of the land in the humid tropics (Sanchez, 1987). Soil pH influences several important ecological processes, including the solubility and exchangeable reactions of plant nutrients, soil biological activity, and weathering of soil minerals(Binkley & Richter, 1987). Greenland *et al*. (1992) have cited evidence to suggest that on the whole, organic matter levels rise as pH decreases. However, as acid pH is generally unsuitable for main crop growth, it is clearly impractical to draw any conclusion from this finding, other than to say that it is preferable from an overall perspective that pH should not be too acidic or too alkaline, but ideally about neutral. These other factors are examined in the N and P sections of the report.

3.3.7 Nutrient mining in biomass transfer systems

Biomass transfer systems, such as cut-and-carry grasses or fodder banks, may function effectively for a certain period of time and relieve pressure on other sources of biomass, in particular, forest biomass and on-farm sources of biomass (Gamrakear, *pers. comm.*). However, it is unlikely that such systems can exist long without additional inputs, as nutrients are 'mined' from the soil in which the biomass is being produced. This may be especially true where the collection of biomass occurs on-farm in a small area. In Nepal, the introduction of *Sylosanthes* and *Monasses* as cut-and-carry grasses for animals was effective for a short while, but it soon became apparent that the productivity of the grass banks was declining due to the continuous removal of biomass and hence of nutrients from the soil (Gamrakear, *pers. comm.*). Evidence from Kenya, where fodder banks have also been developed, suggest the same problem (Wandera *et al*., 1993).

3.3.8 Sustainability of organic matter techniques

It is important that the growth and development of the species providing the biomass in organic matter techniques are compatible with the agricultural system they are to be part of. Where annual crop species are used, such as for green manure or as cover crops, self-sufficiency in seed production is vital if farmers are to adopt such techniques in the long term, particularly in remote areas. Keatinge *et al*. (1998), for example, suggest that if the phenology of a leguminous cover crop species does not match the target environment, seed set will be poor, which may lead to inappropriate recommendations to farmers. Similarly, Kiff *et al*. (1999) suggest that in difficult environmental conditions, green manure may produce low quantities of (or even totally unviable) seeds for future use. In such cases, if farmers have to depend on distant sources for seeds, which may need to be purchased, and then transported to the farm in order to produce plant biomass, they are unlikely to adopt the technique.

3.3.9 Do organic matter techniques 'work'?

From the analysis above, it would seem that the use of organic matter techniques is unlikely to have a major effect on the organic matter content of the soil, due to both the relatively low quantities of biomass that can be produced by the resources available to FAI farmers, and the relatively high rates of organic matter decomposition in the warmer temperatures of the tropics.

However, an important effect of the addition of organic matter to the soil, and one that may be immediately appreciated by farmers, is an improvement in the workability of the soil, so that farming operations, particularly ploughing or hand hoeing, are eased. This is likely to be particularly important where continuous cultivation of land is already practiced. Evidence suggests that such soil physical improvements are much appreciated by farmers, although they may refer to these improvements differently. Farmers in Ghana and Bolivia often mentioned the 'softness', 'looseness' or 'coolness' of soils, as benefits after the use of plant biomass incorporation from cover crops and animal manure incorporation in on farm trials (Kiff *et al*., 1999; Pound *et al*., 1999). To what extent this is a result of the incorporation of the organic matter in the soil or the growth of cover crops is not specified. However, it is significant in that it may be one of the few ways in which soil physical improvements and SOM increases may impact in the short- rather than in the long-term. Additionally, farmers' interest in such improvements should be noted and efforts perhaps directed at presenting organic matter techniques in this context, rather than in the context of yield-enhancing techniques.

3.4 Socio-economic constraints

The requirements for land, labour and capital as factors of production can vary substantially, depending on the techniques that are used for improving soil organic matter levels. These issues tend to be fairly generic in nature and we have already discussed them in Chapter 2. What can be mentioned here is that technologies are rarely neutral. Their introduction demands changes in resource use that farmers are not always capable or willing to make. Supplying large amounts of biomass to increase SOM to levels that are considered by researchers to be 'ideal', requires large amounts of labour for collection, transport and incorporation into the soil. In addition, it requires provision of land for the production of biomass. Ultimately, where labour or land are not available, SOM techniques may require the use of capital, which resource-poor farmers may not have access to.

3.5 Summary

Greenland *et al*. (1992) have shown that decreases in SOM with land clearance of forest or secondary vegetation for agriculture are more or less inevitable. In continuous agricultural systems, the difficulty of maintaining adequate equilibrium levels of SOM in the soil increases both with time, due to oxidation losses and removal of organic matter in the crop harvest. Moreover, the critical SOM level for prevention of physical damage to the soils also increases with duration of cultivation. Eventually, it may become too difficult and too uneconomical for farmers to provide adequate organic matter inputs for SOM maintenance, and the best solution for improving the soil physical conditions may be to put the land to long fallow if this option is possible (Brady, 1990).

Very large amounts of biomass are required to counter losses that take place as a result of oxidation, erosion, and removal of biomass in the harvestable portion of the crop. This requirement can easily be several tons per hectare and SOM techniques are, therefore, most likely to succeed where biomass production is naturally high, as, for example, in the humid tropics or the moist sub-humid tropics (Young, 1989). Although augmentation of SOM is best served with low quality biomass, this conflicts with the need to supply nutrients to the crop, so a further major requirement may be to produce SOM of high quality, to prevent N and P immobilisation. Where only moderate quality biomass is used, it may be important to supplement the biomass with inorganic fertiliser, or to compost it to advance the decomposition process. Low temperatures tend to reduce the decomposition of organic matter and therefore increase SOM in the soil. However, it is clear that this particular biophysical requirement cannot be greatly modified. Although mulches, cover crops and vegetation in general can be used to reduce micro-climatic temperatures to some extent, SOM development in cooler areas generally occurs more rapidly. However, as noted previously, the value of SOM development in warmer areas should not be underestimated as farmers appreciate the improved workability of land that has been treated with organic matter and cover crops (Jackson *et al*., 1999; Pound *et al*., 1999). Soil pH and texture may also be important. However, as ideal pH and textural conditions for SOM development are generally not ideal for crop growth, it is clear that SOM development must therefore occur in less than 'ideal' conditions. The overall fertility of the soil is important for adequate plant growth, although here we hit upon a problem, in that it is poor soil physical and chemical conditions that we are interested in rectifying with organic matter techniques in the first place. Finally, from the biophysical side, a further requirement is that a plant introduced with a technique should be capable of growing and seeding within local conditions; farmers may be reluctant to buy new seed every year, or may live too far away to feel that it is worth the trip.

Of no lesser importance are socio-economic considerations. Clearly, there is a requirement for large areas of land to produce sufficient biomass. Where land is very abundant however, SOM development with long fallow rotations may continue to be the best option available to farmers. Where land is scarce, biomass transfer techniques are likely to be the best option available, particularly from off-farm to on-farm sources. It is unlikely that on farm biomass banks will be able to supply sufficient quantities of biomass needed for SOM development to minimum levels for continuous and sustained cropping, unless the majority of the land is devoted to that purpose.

Abundant labour is required for the harvesting, transport and incorporation of organic matter, particularly in land scarce areas. Where land is abundant, farmers will probably prefer to return the land to long fallow and SOM development will occur as a matter of course, provided the fallow period is sufficient. The requirement for very large inputs of labour, often clashing with other important farming operations, may often be a limitation to the use of organic matter techniques and ultimately to the development of SOM. Where farmers do not have access to sufficient land or labour the only available option is to buy in the organic matter. In many situations, the evidence suggests that SOM development to minimum levels with organic matter techniques may only be possible where capital is used to substitute either for land or labour. However, capital may often not be available for this purpose and other more important competing demands for capital may take preference.

The time taken for benefits to accrue is important. Farmers may discount the value of new techniques very highly, so that what is of long-term future benefit, may not be considered to be particularly important, whilst what is of almost immediate benefit may be much more highly valued. Thus, a further requirement is for SOM techniques to have immediate benefits within the criteria that are important to farmers, perhaps in terms of 'softening' the soil, or in making it 'cooler'.

4 Nitrogen management

4.1 Introduction

Adequate levels of N are essential for proper plant growth, as it is a major component of amino acids and proteins used for building plant tissues and cell organelles. In many tropical agricultural systems, the importance of N is second only to water (Webster & Wilson, 1998). The N content of most surface mineral soils is about 0.02-0.5%. However, most of the soil N is in organic form associated with humus and silicate clays, and only about 2-3% of this is mineralised each year (Brady, 1990). Thus, the amount of readily available N in the form of nitrate and available ammonium compounds is generally only about 1-2% of the total soil N in the soil, except where large amounts of fertiliser have been added.

In many developing countries, there is an increasing deficit of N. Giller *et al.* (1995a) estimated that between 20-70 kg N ha^{-1} y^{-1} may be exported every year from developing countries in sub-Saharan Africa, Asia and Latin America. Nitrogen is also lost by volatilisation, leaching, denitrification, and to the atmosphere through burning. Clearly, such losses must be replaced if agricultural productivity is to be maintained.

There are two major routes to improving the N budget in agricultural systems with the use of low-input techniques. These may involve using approaches to biologically fix N from atmospheric sources with the use of leguminous plants and their associated *rhizobia*, or those involving the transferral of N from one area to another with the use of plant biomass technologies or animal manure. Biological nitrogen fixation (BNF) represents the only means by which net N may be increased *in situ*. Transferring N in plant biomass or animal manure may increase net N on the farm, but mines nutrients from other areas.

4.2 Nitrogen techniques

4.2.1 Biological nitrogen fixing techniques

Nitrogen is so important to plants that after photosynthesis, BNF is probably the second most important biological process on earth . In general, BNF technologies use the symbiotic relationship between higher plants and certain bacteria to fix atmospheric N. There are several associations involved in this process. Symbiotic fixation may occur in association with legumes. In this case the bacteria involved are *Rhizobium* species. These invade the root hairs and the cortical cells, causing the formation of root nodules. The nodules provide a home for the *rhizobia* which use the plant as a source of carbohydrate for energy. The bacteria in turn supply the plant with fixed N compounds. The potential quantity of N fixed by legumes is generally related to the growth of the legume plant. Where conditions favour plant growth, the potential for N fixation is greater, but where conditions do not favour plant growth (except if N is limiting), the potential for N fixation is lower.

Biological nitrogen fixation by legume/*rhizobium* associations is one of the major routes of N fixation in tropical soils (Webster & Wilson, 1998). The amount of N fixed is often difficult to quantify, as it is difficult to distinguish how much is taken up from the atmosphere and how much is taken from the soil and subsequently returned to it again. Other sources of confusion may also stem from the addition of N to the soil through rainfall and the mineralisation of organic matter in the soil. Additionally, the amount fixed by different crops of the same species can vary dramatically owing to differences in annual growing conditions. Nevertheless, a review of studies in Africa (Dakora & Keya, 1997) showed that the rate of N fixation by a variety of legumes ranged from 15-581 kg N ha^{-1} (Table 4.1).

Table 4.1: BNF estimates for a various countries in Africa. (Source: Dakora & Keya, 1997).

Legume species	**Country**	**BNF (kg N ha^{-1})**	**Reference**
Food legumes			
Soybean	Nigeria	15 - 125	Eaglesham (1982)
Cowpea	Kenya	24 - 39	Ssali & Keya (1984)
	Ghana	201	Dakora *et al*., (1987)
	Nigeria	122	Ealesham *et al*., (1981)
Groundnut	Ghana	32 - 134	Dakora (1985a)
Common bean	Kenya	17 - 57	Ssali & Keya (1986)
Bambara groundnut	Ghana	40 - 62	Dakora (1985a)
Tree and Shrub Legumes			
Leucaena	Tanzania	110	Hogberg & Kvarnstrom (1982)
	Nigeria	448 - 548	Sanginga *et al*., (1985)
	Nigeria	304	Danso *et al*.,
Sesbania rostrata	Senegal	505 - 581	Ndoye & Dreyfus (1988)
Sesbania sesban	Senegal	43 - 102	Ndoye & Dreyfus (1988)
Gliricidia sepium	Nigeria	108	Danso *et al*., (1992)
Albizia lebbeck	Nigeria	94	Danso *et al*., (1992)
Acacia holosericia	Senegal	36 - 108	Peoples & Herridge (1990)

Symbiotic fixation may also occur in association with non-legumes. In this case, it is *Actinomycetes* of the *Frankia* genus that are responsible for invading the root hairs and forming nodules. The rate of N fixed per hectare in this way tends to be relatively low, although as a total global quantity, such fixation is estimated to compare with the total fixed by *rhizobia* (Brady, 1990). Occasionally, the site of fixation may be on the stems of higher plants. Some blue green algae of the genus *Nostoc* are capable of making this association with *Gunnera*, an angiosperm (Brady, 1990). Non-leguminous symbiotic fixation may also occur without the formation of root nodules. The organism responsible for this is the blue green algae *Anabaena* that lives on the floating fern *Azolla*. This association is important in rice paddies and rates of N fixed are equivalent to the amount fixed by leguminous species. *Azospirillum* and *Azobacter* bacteria are responsible for the fixation of N that occurs in the *rhizosphere* of certain non-legumes, particularly grasses. The amount fixed in this way is thought to be relatively low.

There are also non-symbiotic micro-organisms that have no association with plants. There are several free-living bacteria and blue-green algae that are involved in this process. For example, the bacteria *Clostridium* can fix N anaerobically, while *Beijerinckia* is a heterotrophic aerobic bacteria that fixes N in upland tropical soils (Brady, 1990). However, such non-symbiotic associations are thought to have relatively low N-fixing capabilities, generally in the order of about 3-15 kg N ha^{-1} y^{-1}.

The use of BNF may be the only viable option for N supply to plants available to poor farmers in less developed countries, especially due to the cost of importing N fertilisers and the generally deteriorating terms of trade (Dobereiner, 1997; Hungria & Vargas, 2000). Vance *et al*. (1995) estimate that 65% of N input in global agriculture comes from BNF, and Dakora *et al*. (1997) suggest that BNF is probably the cheapest and most effective tool for maintaining sustainable yields in African agriculture.

Clearly, LDC farmers are not strangers to the use of BNF technology. In Brazil, for example, there is great importance attached to the use of BNF technologies and great savings have been made to the Brazilian economy as a result of economising on N fertiliser. Dobereiner (1997) estimated that for soybean, the country's largest export product, which is generally grown without N, the amount saved nationally was in the order of $3.2 billion in 1997. Similarly, it has been estimated that about 150 kg N ha^{-1} is fixed annually by sugar cane, which is non-leguminous (Dobereiner, 1997). Much of the sugar cane in Brazil is used to produce ethanol for powering cars; indeed, the energy surplus derived from the ethanol has been shown to be more than five times greater than that required to produce it (Boddy, 1993, cited in Dobereiner, 1997).

In Malawi, Kanyama-Phiri *et al*. (1997) showed that *Sesbania sesban* was capable of fixing 30-60 kg N ha^{-1} after one year as a green manure relay intercrop. In Zimbabwe, Rattray & Ellis (cited in Webster & Wilson, 1998) showed that maize, which has relatively high N requirements, could be grown for over 20 years without dramatic declines in maize yield if grown in alternate years following a green manure crop such as velvet bean (*Mucuna utilis*) or sunn hemp (*Crotalaria juncea*). This was in contrast to the yields from continuous cropping, which declined dramatically. Many legumes are commonly grown by farmers for direct consumption, as their seeds, pods or green leaves are an important source of dietary protein.

In general, the removal of N from the soil can vary from about 50 kg N ha^{-1} (e.g. jute and tobacco) to about 200 kg ha^{-1} (e.g. corn) ((ILACOBV, 1985), p531). If this removal is to be met from BNF, the annual addition of N in this way probably needs to be much greater than these figures, as recovery rates of N can vary from anywhere between 0 to 50%, depending on how much is added to the soil, and whether biophysical factors, such as the level of other plant nutrients, also limit uptake by the main crop. Much research has been done in the tropics on legume/*rhizobium* associations and some of this suggests that some legumes could theoretically supply sufficient N to maintain a healthy N balance (Table 4.1). However, Sprent (1995) suggests that nodulation in woody legumes can be very variable and should not be assumed.

In the following sections, we describe some of the particular forms that BNF technologies assume.

4.2.1.1 Green manures

Early attempts to introduce planted fallows were dominated by the planting of herbaceous legumes for green manure (Webster & Wilson, 1980). Many species, such as *Pueraria phaseoloides*, *Centrosema pubescens*, *Calopogonium muconoides* and *Calopogonium caeleruleum*, are widely used in this context in humid regions in the tropics (Pushparajah, 1982 cited in Nair, 1993). In Malawi, for example, Kanyama-Phiri *et al*. (1997) evaluated *Sesbania sesban* and *Tephrosia vogelii* as green manures in a relay intercrop in on-farm experiments, and found that *Sesbania* was capable of producing about 2-3 t DM ha^{-1} of high quality leaf biomass in addition to the fuel-wood produced during the ten months of growth between January and October.

In Ghana, Jackson *et al*. (1999) found that the reduced capital cost of green-manure was a consideration for many farmers, as chemical fertilisers are expensive. In on-farm trials, small-scale farmers ranked green-manure treatments higher than the controls (no fertiliser and inorganic fertiliser treatments), often mentioning improved soil physical properties, such as looseness and wetness and improved weed control contributing to their high ranking. For some farmers in the area, lack of fertiliser inputs of any kind was often the norm, and clearly green-manuring would increase yields in this situation. However, some farmers found that it was necessary to hire labour to incorporate the green manure, contributing to the capital costs involved in using the technology.

In Malawi and Zimbabwe, green manure legumes such as *Crotalaria, Mucuna*, pigeon pea (*Cajunus cajan*), and *Dolichos* have also been grown as relay intercrops or in rotation with maize in on-farm trials (e.g. Shumba *et al*., 1990; Muza, 1995; Kumwenda *et al*., 1997b).

Legumes grown as cover crops can also be an important source of nitrogen in the soil. They may also play an important role in reducing erosion, increasing soil moisture availability, and suppressing weeds. Incorporating the whole of a cover crop can have a beneficial effect on the yield of following crops (Webster & Wilson, 1980; Brady, 1990). To what extent this is due to the input of nutrients in the soil and to what extent this is due to the improvement of the soil physical conditions is often hard to determine. Rattray & Ellis(1952) showed that maize, which has relatively high in N requirements, could be grown for over 20 years in Zimbabwe without a dramatic decline in yields when rotated with cover crops such as velvet bean (*Mucuna utilis*) or sunn hemp (*Crotalaria juncea*) in alternate years.

However, the use of herbaceous legumes (and green manuring with herbaceous legumes) is not suitable in many tropical areas, especially in areas with long dry periods preceding the main planting season (Wilson *et al*., 1986). Such conditions may reduce the quality of the biomass, or the plants may simply be incapable of surviving such extreme conditions (Milsum & Bunting, 1928 cited in Nair, 1993). On the other hand, woody legume species, such as *Cajanus cajan* and *Crotalaria* spp., are often able to survive extended dry seasons and provide abundant biomass and leaf litter for green manure at the beginning of the rains.

4.2.1.2 Grain legumes

Grain legumes may be used either in rotation with another main crop (usually a cereal), where the main crop and legume are grown in the same field alternatively at different times, or as an intercrop, where the main crop and legume are growth together in the same field at the same time.

Snapp *et al*. (1998) noted that legume rotations are already an important practice in many countries for farmers with large enough holdings (above 1 ha), and the use of grain legumes in rotation with maize is widely practised in southern Africa as a fertility sustaining measure. In their review, Dakora *et al*. (1997) reported that grain legumes fix between 15-210 kg N ha^{-1} and that crop rotations involving legume and cereal monocultures are more sustainable than intercropping, the most dominant cultural practice in Africa. Snapp *et al*. (1998) cited unpublished data from Zimbabwe showing that the contribution of a groundnut crop to soil N on smallholder farms where inorganic fertilisers were already being used was equivalent to about 86 kg N ha^{-1} of inorganic N fertiliser. There is much evidence showing that maize yields can be increased substantially in the year following a grain legume, compared with the continuous cropping of maize (Mukurumbira, 1985; Hulugalle & Lal, 1986; MacColl, 1989).

The multi-purpose nature of grain legumes has added to their popularity (grain and leaves can be used for food). Snapp *et al*. (1998) consider self-nodulating promiscuous types of indeterminate soybean (*Glycine max*), pigeon pea (*Cajanus cajan*), groundnuts (*Arachis hypogaea*), dolichos bean (*Dolichos lablab*), and cowpea to be amongst the most promising in southern Africa for the twin roles of food provision and fertility enhancement. Using farm survey data collected in S. India and the central *terai* of Nepal (not typical FAI areas), Ali (1999) found that a cereal/grain legume/cereal sequence produced higher cereal yields than a cereal/cereal sequence rotation and additionally produced 500 kg ha^{-1} y^{-1} of grain from the legume . Problems noted by farmers using grain legumes in the above survey included the delay caused in planting rice due to long-duration grain legumes, the susceptibility of the grain legumes to diseases, and the conflict in labour demand between the need to harvest the grain legume and transplant the rice (Ali, 1999).

Because grain legumes produce a harvestable product which removes N from the field, in many cases the addition of N to the soil through BNF may be minimal, particularly where there is a high harvest index. Other problems that have been noted in the use of grain legumes include the reliability of legume establishment and growth during the fallow period, particularly in adverse weather conditions (Snapp *et al*., 1998), and deficiencies of other nutrients (in particular P) restricting the growth of the legume (Boddey *et al*., 1997). The latter is particularly problematic for legumes grown in rotation, as a farmer may be unwilling to invest money in fertiliser for a crop of secondary importance, although often there maybe some carry over of P from the main crop if it was fertilised. Finally, farmers are often unwilling to use a grain legume in rotation with a main crop, as the total production of the main crop is usually still higher under continuous cropping, despite poor annual yields.

Using grain legumes as intercrops may be one way of overcoming the need to keep land out of production for a year or to sacrifice whole areas of land to a secondary, and as far as the farmer is concerned, less important crop. Grain legumes could be used either as sequential, relay, or full intercrops. Intercrop technologies could be particularly valuable where main crop yields are increased as a result of reduced competition or facilitation, despite the presence of the grain legume (Vandermeer, 1989). Additionally, it is thought that some fixed N may be transferred directly to the main crop, at least in relay and full intercropping. Leaf litter may also provide N for the main crop - the leaf abscission during the growth of a pigeonpea intercrop, for example, has been estimated to be equivalent to between 10-40 kg N ha^{-1} (Kumara Rao *et al*., 1981). The deep root system of pigeonpea may also be important in recycling N from deeper layers, and in certain areas, some authors have noted the build-up of sub-surface nitrates at about 1-3 m (Farrell *et al*., 1996; Hartemink *et al*., 1996). Morris *et al*. (1990) observed N transfer from arrow-leaf clover to rye grass, and suggested that in mixed stands of legumes and non-legumes direct transfer of N during the growing season is possible (e.g. via vesicular arbuscular mycorrhizal hyphae), although the extent to which it occurs is small and most likely in the range of 10% or less of the total N fixed. A further N benefit of intercropping may be in the rate at which N is fixed from the atmosphere. As growing a non-legume with a legume reduces mineral N in the soil due to increased plant uptake, legumes respond by fixing more N than they might do in a pure stand, so long as the legumes dominate the mixture (Marschner, 1995).

However, the limitations facing BNF technologies should be noted, and in particular the issues concerning the quantities of N fixed (i.e. is this sufficient for continuous agricultural production, especially where the legume covers only a portion of the land as in relay or full intercropping?) and the quality of the biomass produced (is this sufficient to prevent immobilisation of N or P, which in turn reduces crop yield?). The efficacy of grain legume intercrops is also often hampered by deficiencies of other soil nutrients, particularly P. This may less of a problem with full and relay intercropping as the legume can benefit from some of the fertiliser applied to the main crop. In sequential intercropping, however, the situation may be quite different and the farmer may be reluctant to provide fertilisers to reduce P deficiency in the soil.

Additionally there are issues relating to main crop competition between the legume intercrop and the main crop. Depending on the relative competitiveness of the plants selected, the main crop may either reduce the growth of the legume intercrop, or *vice versa*. The associated problem of reliability of establishment of both main and intercrop, particularly when environmental conditions are difficult, are of paramount importance to resource-poor farmers. Ironically, it is when conditions are most difficult that the technology may function least effectively.

Relay intercropping may go some way to reducing the effects of competition that can occur in full intercropping. For example, in many circumstances it may be more appropriate to plant a late maturing grain legume intercrop such as pigeonpea, which does not compete with and reduce the yield of the main crop. This allows the grain legume to go on maturing after the main crop has been harvested with the possibility of high biomass yields. The benefits of this have been shown in areas of Africa with rainfall varying between 500-1000 mm (Snapp *et al.*, 1998). However, the N fixed by grain legumes used as relay intercrops has generally not been sufficient to maintain yields in an on-farm situation. As mentioned previously, Dakora & Keya (1997) consider intercropping to be less sustainable than crop rotations for typical African farming situations.

4.2.1.3 Spatial agroforestry systems

The use of perennial legumes used in spatial agroforestry technologies may provide certain advantages over the use of annual legumes. In particular, their deeper rooting systems may allow them to extract nutrients released by rock weathering from soil depths that roots of annual plants are not able to reach (Nye & Greenland, 1960; Jaijebo & Moore, 1964; Lundgren, 1978; Jordan, 1985). This is important where sub-soils are fertile or where nutrients are deposited by leaching. Alternatively, nutrients may be recycled from below an indurate layer that crop roots cannot penetrate. In appropriate conditions, reduced competition and facilitation may allow the main crop to produce more than in a monoculture.

In terms of N fixation, Dakora & Keya (1997) reported that tree legumes in Africa can fix between 40-580 kg N ha^{-1}. Nair (1993), summarising data on N fixation in trees from a variety of sources, concluded that, in general, annual rates of N fixation vary from 20-200 kg N ha^{-1} y^{-1}. Clearly, much variation can be expected depending on local biophysical factors. In general, the closer conditions are to the optimal for plant growth, the greater the potential rate of N-fixation, although this is usually reduced with increasing levels of mineral N in the soil.

Spatial agroforestry technologies are limited by the various generic constraints that affect all BNF technologies. These include such issues as the actual net quantity of N added by fixation where the legume only covers a portion of the land, and immobilisation of nutrients at critical growth stages of the main crop if the quality of the biomass applied to the soil is low (Nair, 1993; Snapp *et al*., 1998). Much of the research that has been undertaken with hedgerow intercropping systems is based on the assumption that the production of large amounts of biomass under a pruning regime is desirable. This inevitably will increase competition with the main crop for resources such as light, water and nutrients, and has been found to be problematic in alley-cropping systems in semi-arid areas where water is limiting (Nair, 1993).

Some spatial agroforestry technologies, such as alley cropping, may also be limited by the availability of labour, especially if the perennial is prone to weediness without intensive management. Land availability may also be of concern in areas where farms are particularly small, as the perennial inevitably removes land that would otherwise be in production. Pests may be increased by the environment offered by the perennials, and termite activity may also increase (Nair, 1993). The use of technologies may also be limited by the farmers' perception of the efficacy of the technology, especially in the short-term, and by cultural perceptions of what constitutes acceptable and normal farming operations. Nair (1993) makes the point that most traditional spatial agroforestry systems in the tropics tend to be mixed, whereas newer technologies developed by researchers, such as alley cropping, tend to be zonal.

4.2.1.4 Improved fallows

Traditional shifting cultivation systems are temporal agroforestry systems in that trees and crops occupy the same area of land but do so at different times. After the cropping period has exhausted the fertility of the soil, the land is returned to fallow, during which natural vegetation regrows and the fertility is slowly restored. In many parts of Africa, fallow periods are decreasing due to population pressure, and in a number of cases, continuous cropping without the use of fallow periods is widespread (Snapp *et al*., 1998). In addition to this, marginal land is increasingly brought into production.

So-called 'improved' fallows, in which fast-growing leguminous trees are deliberately planted, have been suggested as an intervention to help speed up the process of fertility regeneration. The idea has some merit as it is merely a modification of an existing system that farmers are already familiar with, and, in the case of 'enriched' fallows, may also provide an economic product, such as fruit, nuts or spices (Quashie-Sam, *pers. comm.*). Improved fallow systems using fast-growing leguminous trees have been shown to be effective as a means of restoring soil fertility and maize grain yields (Kwesiga & Coe, 1994).

In the Santa Cruz Department of Bolivia, the use of *Canavalia ensiformis*, *Mucuna pruriens*, *Mucuna nivea* and *Dolichos lablab* as a winter fallow in a rice cultivation system was examined by Southgate *et al*. (1999). Results showed that yields increased when the four legumes were used as compared with a weedy winter fallow, the local practice. However, the major reason for these improved yields appeared to be due to the extra protection given by the legume residues to emerging rice seedlings compared to the weedy fallow which produced much less biomass.

Nye (1958) and Webster & Wilson (1980), found that a fallow of shrub and legumes (such as *Cajanus cajan*, already widely used by farmers) could be more efficient than a natural fallow in the regeneration of soil fertility and in the increase of crop yields. However, it has also been noted that main crop yields after an improved fallow may not be significantly greater than yields after a natural fallow. The yield increases observed, particularly after a herbaceous fallow, may be no better than the yield that one might expect after natural fallow provided that the fallow is not burnt annually. Dennison (1959), found that there was no significant difference in a variety of main crop yields after pigeon pea, gamba grass, or natural fallow in the Guinea savannah zone of Nigeria. The large yield differences reported in some experiments may be reported in comparison to a control, which does not reflect the effect of natural fallow in soil fertility regeneration. Also, little consideration may be given to the possibility that farmers may have existing techniques that in the end perform to a level generally comparable to the new techniques being examined, especially when implemented in on-farm situations.

There is also the issue of 'lost time' with improved fallow systems. Lower crop production overall is usually the case with any fallow system as compared with continuous cropping due to the loss of productive land while it is being fallowed. Webster *et al*. (1998) suggest that, although crop yields may increase after a fallow period, this increase is still insufficient to make up for that lost from not cropping continuously. However, they note that this conclusion came from data on experiments which lasted no longer than 15 years and concede that yields from continuous cropping could decline to such a low level over a long period of time, that managed fallow periods might eventually start to produce better overall yields.

On the other hand, Nair (1993) suggests that eventually the level of soil improvement offered by improved fallow technologies will be insufficient to maintain yields, no matter how 'miraculous' the improved fallow species may be. The implication is that eventually permanent agricultural cultivation is inevitable, and that technologies need to be developed for this. *Taungya*, home-gardens, plantation crop systems, alley cropping, and tree incorporation on farm and grazing lands are given as examples of these. Improved fallows may therefore at best prove to be a transitory stage, through which the move to permanent cultivation can be eased.

4.2.2 Nitrogen transfer techniques

Although BNF may represent the only way of increasing net N *in situ*, transfer of N in organic material from one part of the system to another may also be an important source of N for a farmer. This transfer may be 'horizontal' – for example, the growth of a green manure on one part of a farm for use on another, or the purchase of organic material (e.g. compost) from outside the farm for use within it, or the use of animal manure to transfer N from the area of grazing (either on-farm or off-farm) to the cropped area. It can also be 'vertical' - the use of non-leguminous deep rooted perennial trees in agroforestry systems can transfer N and other nutrients from lower in the soil profile, allowing the crop to make use of these nutrients, which would otherwise be below the level of their roots.

Such N transfer technologies provide a means of capturing, recycling, and transferring on-farm nutrients, and may also represent a net addition to the farm if they are imported from outside. However, at the larger scale, they clearly do not increase net N in the system and represent a nutrient drain on those areas from where biomass is being taken.

The use of biomass transfer is not new at the FAI. For generations, farmers in Nepal have transferred nutrients in plant biomass from the forest to their farmlands to improve soil structure and fertility, either through direct collection of plant biomass or indirectly by grazing their animals there. Similarly, Snapp (1998) describes how nutrients are transferred from *miombo* woodland in Zimbabwe to enhance the fertility of neighbouring farmland. However, he suggests that the practice of transferring nutrients from forest to agricultural land may not lead to a sustainable production system in the long run, as not only are the nutrients mined from the forest ecosystem, but also the quantities of nutrients transferred are not high due to the rather low quality of biomass from the *miombo*. Clearly, the extent to which this is true depends on the area of forest land supporting farmland, the rate at which nutrients are being removed and replenished in the forest ecosystem, and the quality of the organic matter that is available.

On farm biomass banks developed for production of high quality organic matter might be developed from both annual and perennial plants, both from off- and on-farm sources where appropriate. In Zimbabwe, Mafongoya *et al*. (1997b) showed that the application of 5 t DM ha^{-1} of high quality residues from three perennial legumes (*Leucaena leucocephala*, *Cajanus cajan* and *Acacia angustissima*) gave a mean maize yield of about 5 t DM ha^{-1}, compared to the yield of 1.1 t DM ha^{-1} obtained for maize when no organic inputs from the three legume species were used. The results also showed that the legume prunings were superior in their nutrient release characteristics to *miombo* litter, the traditional source of nutrients in the area. However, for these to work, they must still fall within the resource possibilities of the farmer, and these may be different or unacceptable to the farmer. The example below using *Tithonia diversifolia* provides an example of the possible issues that need to be faced.

4.2.2.1 Plant biomass banks

Biomass transfer technologies to increase N supplies has been explored, for example, with the use of plants such as *Tithonia diversifolia*, for use as a green manure (ICRAF, 1997; Jama *et al*., 2000). *Tithonia diversifolia* is non-leguminous species, although data from the Organic Resources Database (Gachengo *et al*., 1998) shows that its biomass is of high quality (N>2.5%, P>0.25%, lignin<15%, polyphenol<4%) that may allow it to be applied directly as a green manure. The N content of its biomass is about 3.38%, which is relatively high for a non-leguminous plant, and above the level required to prevent net immobilisation of N (Palm *et al*., 1997b).

Estimates of *Tithonia* biomass production vary widely. King'ara (1998) found that yields of high quality biomass (green tender stems and green leaves) were between 2-3.9 t DM ha^{-1} after eight months when grown from 10 cm cuttings. This is equivalent to a fresh weight production of between 10-20 t ha^{-1} (assuming 80% water content).

Drechel *et al*. (1998) found that *Tithonia* biomass production in hedges was about 1 kg DM m^{-1}, although this could be less where the hedge contains other plants, which is often the case (Jama *et al*., 2000).

Table 4.2: Production of dry biomass (t ha^{-1}) by Tithonia diversifolia *in soft and woody stems in western Kenya (Adapted from Jama et al., 2000).*

Cuttings	First cutting (8 months)	Second cutting 13 months)	Third cutting (18 months)	Total
Soft	2.2	3.4	2.3	7.9
Woody	3.4	4.7	4.5	12.6
SED	0.84	1.21	0.77	1.82

Various techniques have been found to increase *Tithonia* biomass production and therefore the quantity of nutrients extracted from the soil and available for transfer. The use of woody cuttings for propagation instead of soft stem cuttings, for example, was found to increase its biomass production (Table 4.2), as was the application of mineral P fertiliser (Table 4.3).

Table 4.3: Production of dry biomass by Tithonia diversifolia *with and without mineral P application and associated N content of biomass. (Adapted from Jama et al., 2000).*

Treatment	Dry biomass (t ha^{-1}) leaves and litter	Dry biomass (t ha^{-1}) in stems	N content (kg ha^{-1}) in leaves and litter	N content (kg ha^{-1}) in stems
No added P	1.0	7.4	32	55
50 kg P ha^{-1}	1.2	9.3	40	70
SED	0.05	0.95	2.1	15.6

Experimental evidence suggests that addition of N and P through the application of *Tithonia diversifolia* biomass may increase yields more than the use of equivalent quantities of mineral N and P, because of the presence of K, Ca and Mg in the biomass which might ameliorate deficiencies of these nutrients in the soil, and also possibly because of an improvement to soil physical characteristics (Jama *et al*., 2000).

4.2.2.2 Animal manure

In many LDCs it is common practice to collect and use animal manure, and represents a major means of transferring N within the farm. Grant (1967) reviewed the beneficial effects of animal manure on soil fertility, noting in particular that the beneficial effects on crop response is often as much a result of the addition of P, Ca and Mg, as of the addition of N.

Where extensive off-farm fodder or food concentrates are used, this may also represent a major means of importing N onto the farm. Nitrogen in manure is subject to the same losses that face N in plant biomass. Ammonium-N from manure may be immobilised, adsorbed, volatilised, and leached, making manure management essential. Lekasi *et al*. (1998) found that farmers in the Kenyan highlands placed a high premium on manure, to the extent the price paid for animal manure was well in excess of the cost of the equivalent quantity of nutrients in mineral form.

Lekasi *et al*. (1998) found that cattle density (and ruminant density) per hectare was greater on small farms (<0.5 ha) than on large farms (>2.8 ha), indicating that animal numbers were not constrained by farm size and on-farm fodder supplies (Table 4.4). The manure used to fertilise crops generally contained a mixture of animal faeces and urine, bedding, and crop residue material. A typical maize crop for the area might require about 100 kg N ha^{-1} (Sanchez *et al*., 1997), and analysis of the N and P contents of the manure and the quantity of excreta produced by the animals suggests that sufficient N and P could be supplied to all farms, irrespective of their size. However, this assumed no loss of N or P during storage, and the use of urine as well as faeces for N supply, as most of the N is excreted in the urine rather than in the faeces.

Table 4.4: Estimated faeces production and theoretical quantity of N derived from faeces and urine assuming no loss of N. (Adapted from Lekasi et al., 1998).

Mean size of holding (ha)	**Estimated mean production (t dry biomass ha^{-1})**	**Theoretical N application rates (kg $^{ha-1}$)**		
		Faeces	**Urine**	**Total**
Small (0.45)	8.2	114	289	403
Medium (1.08)	3.6	50	121	171
Large (2.82))	2.2	30	78	108

Clearly, the quantity of N produced in manure varies greatly from area to area and the different management practices employed. The collection of manure from free-grazing animals may be impractical and certainly the collection of urine, where over half the N may be excreted, will be impossible. Conservation of soil nutrients in such free-grazing systems will only be practical where animals are grazed in rotation with crops. It is possible that some of the N excreted in the manure, and to a far lesser extent the urine, may be recycled by the pasture. Boddey *et al*. (1995) suggest that cattle living on a *Bracharia* pasture capable of supporting 3 animals ha^{-1} might be expected to produce about 40 kg N ha^{-1} y^{-1} in their dung and about the same amount in their urine, the latter of which is too difficult to collect and volatilises quickly. However, there is usually little benefit to be had in terms of N improvement under pasture, except where the pasture is leguminous or fodder is imported from elsewhere into the system.

In both Bolivia and Brazil, farming systems at the FAI move from pure forest to shifting cultivation to arable agriculture and finally to pasture (Muchagata, 1997). For various socio-economic reasons, cattle remain the favoured option rather than arable agriculture

4.3 Biophysical constraints

There are various biophysical factors constraining the use of N management techniques at the FAI. These may be limitations of a general nature that affect N transfer and BNF techniques alike. For example, once organic matter is in the soil, various factors may act to limit the rate of mineralisation, or increase volatilisation, leaching and denitrification. Similarly, biophysical factors can limit the production of plant biomass in both N transfer and BNF techniques. There may also be limitations imposed on the process of N fixation itself; for example, the development of *rhizobia* populations in the soil can be limited by particular biophysical conditions. As we have suggested before, examining these limitations gives us a good idea of the requirements needed for these techniques to function effectively.

4.3.1 General biophysical limitations

4.3.1.1 <u>Quantity of biomass</u>

As we have seen before with the use of organic matter technologies for soil physical improvement, one of the major requirements for effective functioning of N management techniques in general will be the requirement for large quantities of biomass. As before, we need to ask ourselves where the farmer is going to obtain this biomass. The use of plant biomass and animal manure may require several tons of biomass per hectare, in order to supply adequate quantities of N. This implies that large areas of land are needed to grow the biomass, and that considerable labour is required to shift it to its new location. For example, the amounts of dry and fresh weights of *Tithonia diversifolia* and animal manure required for a range of crop N requirements are shown in Table 4.5.

The transfer and supply of N through large quantities of plant biomass and animal manure at levels required to sustain most crops at an attractive levels may be problematic. In the context of continuous agriculture, the labour requirements for the harvesting, preparation, transfer, and incorporation of the biomass at adequate levels may be beyond the means of many resource-poor farmers at the FAI, especially where the full N requirements of the crop are to be supplied entirely through organic matter. This might help to explain why long fallow rotations may continue to remain attractive to many farmers at the FAI, especially where labour is a limiting resource.

Table 4.5: The required dry weight and fresh weight amounts of Tithonia diversifolia *(3.5% N dry matter content) and animal manure (1.5% N dry matter content), assuming a 25% recovery rate of N by the first crops (Giller & Cadisch, 1995b), 80% water content of fresh* Tithonia *biomass, and 60% water content of fresh manure. Adapted from Jama* et al. *(2000) and Lekasi (1998).*

Crop N removal (kg ha^{-1})	N application requirement	Dry biomass requirement (t ha^{-1})	Estimate fresh biomass requirement (t ha^{-1})
Tithonia diversifolia			
25	100	3	15
50	200	6	30
75	300	9	45
100	400	12	60
Animal manure			
25	100	7	17
50	200	13	33
75	300	20	50
100	400	27	67

4.3.1.2 Quality of biomass

One of the major requirements for the effective use of low-input techniques in supplying N to main crops is that they produce high quality biomass, that mineralises in time to supply main crop yields, without immobilising N during critical periods of crop growth and development. Where such high quality organic matter cannot be supplied for direct use as a green manure, further requirements may be to supplement nutrients in the organic matter with mineral fertilisers, or to start the decomposition process by producing compost. As shown previously, the quality of biomass is related to its content of N, lignin and polyphenols, and to the C/N, lignin/N, polyphenol/N and (lignin+polyphenol)/N ratios (Snapp *et al*., 1998). High quality organic inputs are low in lignin and polyphenol and high in N (Palm *et al*., 1996). Evidence suggests that to prevent immobilisation of N in the soil, the minimum N content of any added organic matter should, in general, be more than about 2.5%. The addition of low quality organic matter may increase the organic matter in the soil, but may not necessarily increase the yields of the main crop, particularly if the C/N ratio is high, or the N% is low. The C/N ratio is particularly important in the mineralisation of N, and the use of low quality organic matter may result in a reduction in nutrient cycling efficiency and availability.

Mafongoya (1997b) showed that immobilisation of N occurred when the lignin and polyphenol contents of the residues incorporated into the soil were over 15% and 3% respectively. However, at values less than these figures, and where the N content was above 2%, the N mineralisation proceeded rapidly. Interestingly, N immobilisation resulting from high polyphenolic levels seems to last much longer than that resulting from low C/N ratios (Palm *et al*., 1996).

Evidence suggests that the release of C and N from high quality organic matter (green manures and legume tree prunings) results in the provision of more soluble C and N, which encourages soil microbial activity without immobilisation. High quality residues decompose more quickly and release between 70-95% of their N within a season under tropical conditions (Giller & Cadisch, 1995b). In the absence of inherently fertile soils and inorganic fertilisers, high maize grain yields have been found to be associated only with high quality organic matter. Low or even medium quality residues have generally been unsatisfactory (Snapp *et al.*, 1998).

4.3.1.3 Immobilisation

Nitrogen immobilisation is a major problem, particularly if it coincides with critical growth stages of the main crop. As mentioned above, the composition of organic matter is important in determining its quality and the mineralisation rates of both N and P. The quality of organic matter produced by a plant is not constant, but may vary with age and depends on whether a plant is leguminous or non-leguminous. In general, young plant material has C/N ratios that are conducive to rapid decomposition, ensuring that its nutrients will be released quickly when it is incorporated into the soil (Figure 4.1). Organic matter from older plants (or plant organs) of the same species generally has higher C:N ratios, possibly resulting in a net immobilisation of N and depression of soil nitrate levels that inhibits the growth of the main crop for a period of time following organic matter incorporation.

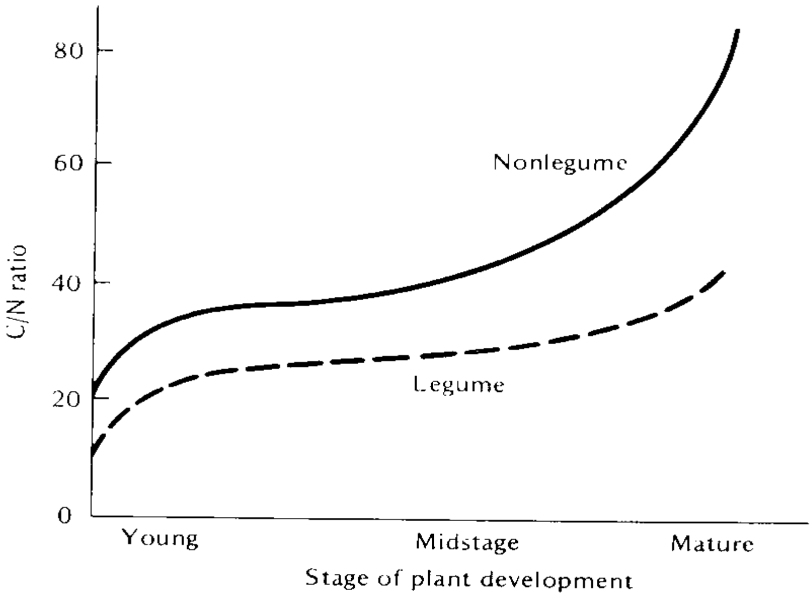


Figure 4.1. The relationship between the stage of plant development and the C/N ratio. (Source: Brady, 1990).

Evidence suggests that when the N content of plant biomass and animal manure falls below a critical N level of about 1.8-2%, the N can also be temporarily immobilised in soil micro-organisms (Brady, 1990). Palm *et al.* (1997b) suggest that this critical level may be slightly higher at between 2.0-2.5%. Clearly, the N immobilised in the bodies of micro-organisms is unavailable to the main crop until the micro-organisms die and decompose (Figure 4.2). The duration of nitrate depression seems to be positively correlated with the C/N ratio.

The N content of the organic matter from various species can be found in the Organic Resources Database (Gachengo *et al.*, 1998) and the survey by Lekasi *et al.*

(1998). Based on these data, Table 4.2 shows the N contents of various types of organic material that could possibly be used in FAI technologies. Cover crop species, the leguminous tree species, and *Tithonia diversifolia* all contain N levels above the critical 2.5% level below which net immobilisation may occur.

The animal manures, on the other hand, tend to have mean N levels that might lead to net immobilisation of N in the soil. This seems to be particularly problematic in the case of cattle. Data from Lekasi *et al*. (1998) also suggest the pig and poultry manure is marginal in terms of N levels, although the data from the Organic Resources Database shows more favourable levels of mean N in animal manure. The low levels of N in most residues from cereal crops also suggest that there may be negative yield effects on crops to which they are added, due to nitrate depression and net immobilisation.

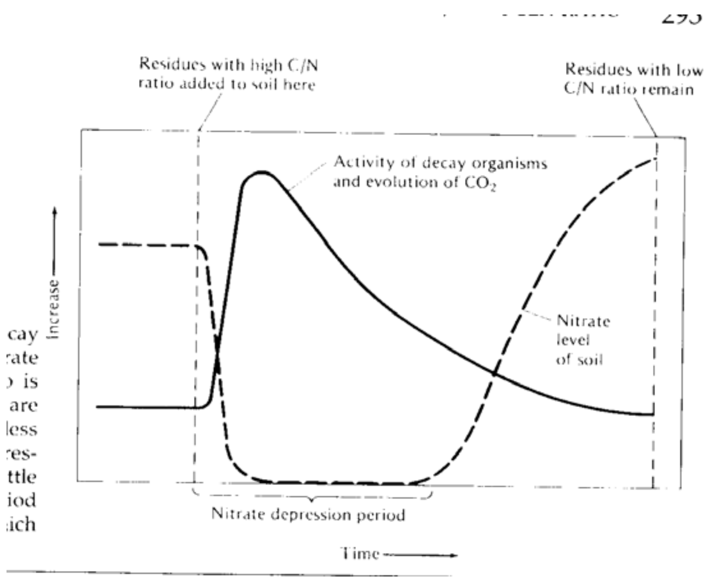


Figure 4.2 The impact of immobilisation of nitrate availability after the addition of organic matter to the soil with a high C:N ratio. (Source: Brady, 1990).

It is important to realise that a beneficial impact of biomass on N supply to main crops cannot be taken for granted. Nearly all the organic matter sources are capable of producing biomass that contains less N than the critical level of about 2.5%. Where farmers at the FAI apply biomass deficient in N, they may find that at best, little difference is evident, or at worst, that main crop yields may be reduced.

Table 4.6. Mean, maximum and minimum N percentages for various techniques. Compiled from the Organic Resources Database and Lekasi et al. *(1998).*

Organic matter source		Mean	Max	Min
Non-legume	*Tithonia diversifolia*	3.38	4.59	1.10
Legumes (cover crops)	*Crotalaria juncea*	3.47	6.30	0.80
	Canavalia ensiformis	2.89	4.74	0.23
	Mucuna pruriens	3.23	6.05	0.83
Legumes (trees)	*Leuceana leucocephala*	3.68	6.32	1.04
	Gliricidia sepium	3.38	5.33	1.33
	Sesbania sesban	3.54	4.81	1.39
Animal manure	Cattle	1.04	4.15	0.30
	Cattle (Lekasi *et al.*, 1998)	1.40	2.00	0.50
	Pigs	3.79	4.25	3.08
	Pigs (Lekasi *et al.*, 1998)	2.00	2.20	1.50
	Poultry	4.02	6.73	1.85
	Poultry (Lekasi *et al.*, 1998)	2.40	2.60	2.30
Crop residues	Maize	1.01	3.07	0.25
	Sorghum	0.63	0.63	0.63

4.3.1.4 Low recovery of N by crops

The amount of N recovered by crops can vary substantially depending on biophysical conditions, but is generally thought to be low for organic inputs. Giller *et al*. (1995a) suggest a value of 20% for most organic inputs. In western Kenya, Gachengo *et al*. (1999) found that the recovery of N in *Tithonia* prunings was about 25% by a first maize crop. Other evidence suggests that N recovery by the first crop after organic matter incorporation is generally between 9-28% of the N supplied in the organic matter, but may be as low as 2-10% in a second crop (Snapp *et al*., 1998).

However, it appears that the rate of recovery may be improved with the addition of limiting nutrients to ensure that the growth of the main crop is not limited by other factors. For example, the recovery fraction of organic matter N was increased from about 25% to 46% in the first year when 25 kg P ha^{-1} was applied to correct the P deficiency at the site (Snapp *et al*., 1998). One of the major ‘requirements’ for low-input N technology may be to improve the recovery rate of N by main crops, perhaps by improving techniques and practices. As certain natural processes cannot necessarily be avoided, increasing recovery rates may have to rely on improved management of N if this is at all possible within the constraints of the farmer. Several of the processes below, whereby N is lost to main crops are responsible for low N recovery by the main crops.

4.3.1.5 Adsorbtion

Most of the N held in the soil is in organic form, and much of this (up to 80%) may be held in organic combination with the humus complex and silicate clays (Brady, 1990). As such, it is protected from leaching, volatilisation and denitrification, and generally only 2-3% of it is mineralised each year. This can, however, be of significance to crop growth, depending on the initial quantity held in the soil, and local biophysical conditions. In humid, temperate areas this release has been found to be up to 60 kg N $ha^{-1}y^{-1}$. In arid areas this tends to be much lower, except where irrigation and large amounts of biomass are added to the soil (Brady, 1990).

Once the N has been mineralised from organic into inorganic form by micro-organisms that hydrolyse the organic N compounds, the N becomes available to plants as ammonium (NH_4^+) ions. About 5-20% of the total N in the soil may be found as NH_4^+ (Brady, 1990). Most higher plants are able to make use of N in this form, although nitrate (NO_3^-) is usually preferred due to difficulties in maintaining the internal *pH* balance with NH_4^+. Some plants, like lowland rice, may actually grow better when N is in its NH_4^+ form (Brady, 1990). However, NH_4^+ can be adsorbed by organic matter and clay minerals (particularly those with a 2:1 type structure), reducing the overall amount available to plants. Vermiculite is most effective, followed by fine-grained micas and smectites (Brady, 1990). Although the N is protected from loss in this form, it may be released at a rate that is insignificant for the needs of higher plants. Organic matter may also adsorb anhydrous ammonia (NH_3) by combining with it to form organic compounds that resist decomposition. In normal mineral soils this would tend not to be a serious problem, although in organic soils this could result in a serious loss of N to the plant (Brady, 1990).

4.3.1.6 Nitrogen mobility

As mentioned above, the vast majority of N in the soil is immobile and tied up in organic compounds with humus. However, the management of available soil N, particularly that in the NO_3^-form, can also be difficult due to its mobility. Nitrogen management can be especially difficult when using organic nutrient sources, as the time taken for N mineralisation, and possible N immobilisation and nitrate depression need to be considered in relation to the N demand of growing crops, along with issues of volatilisation, leaching and denitrification. There is a requirement here to understand the dynamics of N in the different biophysical conditions found at the FAI, possibly to influence the techniques and research products that are recommended for use with low-input N management technology. Good N management depends on coping with these dynamics to best possible effect (Weber, *pers. comm.*).

4.3.1.7 Volatilisation

The ammonium ions (NH_4^+) produced from animal manure and plant biomass not adsorbed by clay or organic matter may be volatilised. The loss of ammonia (NH_3) in this way is usually highest in sandy soils, alkaline soils, and calcareous soils. Volatilisation is also compounded when organic material, such as animal manure and plant biomass, are left on the surface of the soil and subjected to high temperatures. Ammonia volatilisation increases with increasing biomass temperature, and it has been found that the incorporation of organic manure into the topsoil can reduce the amount of NH_3 volatilisation by between 25-75% (Brady, 1990).

4.3.1.8 Nitrification

Nitrification, the process whereby NH_4^+ is broken down into NO_3^-, is of great significance, as NO_3^- is the form in which most higher plants obtain their N supply. Thus good conditions for nitrification are an important requirement for the successful use of N technologies. Nitrification is essentially a process of enzymatic oxidation by micro-organisms occurring in two stages. Firstly, NH_4^+ is oxidised into nitrite by *Nitrosomonas*. Secondly, nitrites are oxidised into NO_3^- by *Nitrobacter*. The rapid oxidation of nitrites to NO_3^- is important as nitrites are though to be poisonous to higher plants (Brady, 1990). The overall rate of nitrification is influenced by a number of environmental factors, which may be significant in determining the effectiveness of FAI technologies dependent on the process.

Increasing temperature, for example, increases the rate of nitrification, with an optimum between 25-35 °C. At higher temperatures, rates decline again, and cease altogether at around 50 °C. Nitrification is also reduced by very low or very high soil moisture contents. The optimum soil moisture content for nitrification is similar to the optimum conditions for higher plants, although significant nitrification may occur when the soil moisture is at, or even below, the permanent wilting point (~1.5 MPa) (Brady, 1990).

As NH_4^+ is the substrate for nitrification, its rate is dependent on the NH_4^+ content of the soil. If NH_4^+ levels are too low, nitrification rate and hence the supply of nitrates to the plant will be reduced. Excessive NH_4^+ levels, however, can result in toxic levels of nitrite building up in the soil, due to a suppression of the *Nitrobacter* population which convert nitrites to nitrates. This may therefore reduce the growth of crops, but appears only to be a problem where excessive anhydrous NH_3 or urea is used as fertiliser in alkaline soils (Brady, 1990). It probably is of little concern to the majority of resource-poor farmers, who may find it difficult to supply inorganic fertilisers at all. The quality of the organic matter residue also needs to be high. A high C/N ratio in the organic matter residue could prevent the release of NH_4^+ and therefore reduce the rate of nitrification (Brady, 1990). The N may also be immobilised as the bacteria multiply in the presence of OM with high levels of C.

The degree of soil aeration can also influence the rate of nitrification - good soil aeration (and therefore good drainage) is required to supply oxygen for the oxidation process. Ploughing and modest cultivation can help to aerate the soil whereas minimum tillage practices may reduce nitrification due to lack of soil aeration and reduction in drainage (Brady, 1990).

Soil nutrient status is also important. Nitrification increases when there is an abundance of exchangeable base-forming cations (Brady, 1990). The lack of exchangeable bases in acid mineral soils may account in some measure for reduced nitrification, and is reflected in slow plant development. However, in certain organic soils, such as peat soils, exchangeable bases may be present in sufficient quantities to allow for the accumulation of NO_3^- in the soil, even at a *pH* as low as 5 (Brady, 1990). Nitrifying bacteria appear to perform best in conditions that are also optimal for plants. If soils are low in P or K, the application of these can increase the rate of nitrification. However, the application of large quantities of ammonium-based fertilisers to strongly alkaline soils should be avoided to prevent loss of NH_3 gas and to alleviate the negative effects of NH_3 on *Nitrobacter*.

The application of recommended levels of pesticide in the soil appears not to harm nitrifying bacteria, although there is evidence that they are sensitive to excessive applications, which may at best slow down nitrification significantly, or at worst, inhibit nitrification altogether (Brady, 1990).

4.3.1.9 Denitrification

Denitrification is the biochemical reduction of nitrate N to elemental N through the intermediary of enzymatic reduction by anaerobic micro-organisms. The process occurs in five stages and N can escape as gas from the soil as nitric oxide (NO), nitrous oxide (N_2O), or dinitrogen gas (N_2) (Brady, 1990). As the process is anaerobic, its rate depends particularly on the level of soil drainage. In well-drained humid areas the loss of N from the soil is usually between 5-15 kg N ha^{-1} y^{-1}. However, where drainage is poor and denitrification is not restricted by lack of nitrate N, the loss can rise to between 30-60 kg N ha^{-1} y^{-1}. Denitrification, therefore, is a serious problem where farming systems rely on practices that flood soils to produce crops, for example, in rice cultivation, where the loss of N by denitrification can be as high as 60-70% of the N added to the soil as fertiliser (Brady, 1990).

4.3.1.10 Leaching

Leaching is often a significant problem where rainfall or irrigation is high. Conservation tillage measures can also increase leaching, by causing more water to drain through the soil profile than would otherwise occur. In unirrigated dry areas, the problem is less important. Nitrate ions, which are negatively charged, are not adsorbed by the negatively-charged colloids that dominate most soils (Brady, 1990). This leaves nitrates vulnerable to leaching by water.

4.3.2 Limitations of biological nitrogen fixation techniques

4.3.2.1 Rates of biological nitrogen fixation

As the metabolic activity of *rhizobia* is dependent on a supply of energy from the host plant in the form of photosynthate, environmental conditions conducive to vigorous plant growth will also favour N-fixation. Photosynthesis of the host plant is a major factor in the symbiotic relationship between *rhizobia* and leguminous plants. Thus, legume breeding for improved growth and yield should also increase N fixation (Giller & Wilson, 1991). In general, legume technologies are most likely to be successful in optimal plant growth conditions.

The quantity of N fixed by legumes is difficult to quantify and may vary from place to place. Webster (1998) noted that estimates of the amount of N fixed by groundnuts and grain legumes range from about 25-200 kg N ha^{-1} during growing seasons of 60-120 days. Bouldin *et al*. (1979) found that some legumes seemed to fix N at relatively high rates - for example, values up to 535 kg N ha^{-1} have been recorded for *Crotalaria* spp., and values of 400 kg N ha^{-1} for other pure legume green manure crops. Moore (1962) found that *Centrosema pubescens* (star grass) fixed N at the rate of 280 kg ha^{-1} y^{-1}. Most documentation suggests that the normal rates of N fixation can vary from about 20-250 kg N $ha^{-1}y^{-1}$.

However, although high rates of fixation have been reported in some cases, evidence suggests that generally the quantities of N fixed are not sufficient to sustain a main crop either as an intercrop or in an annual rotation (Table 4.7), even without taking into account the amount of N lost through immobilisation, adsorption, volatilisation, leaching and denitrification.

Where high yields are required or where main crops are N demanding, sustaining the supply of N with biological N fixation techniques may be even more difficult. For example, a typical 5 t ha^{-1} maize crop removes about 100 kg N ha^{-1}. As a rule, the recovery of N from organic sources appears to be about 25% of the N applied in the biomass (although this can be improved if other nutrients are limiting the growth of the crop). The equivalent of about 400 kg N ha^{-1} would therefore have to be added to the system to balance the amount of N required by the maize crop. Clearly, none of the annual quantities of N fixed by the legume crops shown in Table 4.7 could sustain N levels in soils growing maize in annual rotations. Thus, although BNF is an important source of N in the soil, it may not be sufficient to maintain main crop yields at the required level (Brady, 1990).

Table 4.7: Typical rates of nitrogen fixation for various systems (Source: Brady, 1990).

Plant	Associated organism	Typical level of N fixation (kg N ha^{-1} yr^{-1})
Symbiotic		
Legumes (nodulated)		
Alfalfa	Bacteria (*Rhizobium*)	150 - 250
Clover		100 - 150
Soybean		50 - 150
Cowpea		50 - 100
Lupine		50 - 100
Vetch		50 - 125
Bean		30 - 50
Non-legumes (nodulated)		
Alder	Actinomycetes (*Frankia*)	50 - 150
Gunnera spp.	Blue-green algae (*Nostoc*)	10 - 20
Non-legumes (non-nodulated)		
Pangola grass	Bacteria (*Azospirillum*)	5 - 30
Bahia grass	Bacteria (*Azobacter*)	5 - 30
Azolla	Blue-green algae (*Anbaena*)	150 - 300
Non-symbiotic		
	Bacteria (*Azobacter*, *Clostrium*)	5 - 20
	Blue-green algae (various)	10 - 50

Although the rotation of legumes may supply some of the N requirements of a main crop, much evidence from southern African countries suggests that there is very little N benefit to be had, from grain legume rotations on smallholder farms, particularly in adverse weather conditions. Where climatic conditions are periodically or inherently difficult, grain and biomass yields (and therefore BNF) are low, and any beneficial impact of the grain legume on the following maize crop is very small (Mukurumnira, unpublished, cited in Snapp *et al.*, 1998). Ironically, it is during these adverse periods that the farmer would most need the best results from the technology.

The role of BNF may be even more limited under adverse conditions in intercropping systems. Although grain legume intercrops can help to increase the resource use efficiency and stabilise yields of the main crop under optimal plant growing conditions, in semi-arid areas or in dry years, the yields of the main crop can be greatly reduced (Snapp *et al.*, 1998). Assuming that the amount of N fixation is roughly proportional to the land under the legume in a monocrop situation (this is not always the case, as reduced mineral N availability due to main crop competition can encourage greater N fixation by the legume than in a monocrop (Marschner, 1995), it is clear that intercropping techniques are unlikely to be able to sustain the N requirements of main crops on a long-term basis, unless low yields are acceptable to the farmer. Intercropping greatly reduces the quantity of N fixed per unit area due to the low population density of the legume (Snapp *et al.*, 1998).

In southern Malawi, Kumara Rao *et al*. (1981) showed that both relay and consecutive intercrop systems produced insufficient quantities of biologically fixed N to maintain a maize biomass yield of 4 t ha^{-1} on infertile land. The estimated contribution of *Sesbania sesban* when relay intercropped in low fertility areas was 28 kg N ha^{-1}, while the N contribution from a pigeonpea/groundnut intercrop was about 20 kg N ha^{-1}. However, the quantity of N required to sustain maize yields was estimated to be about 100 kg N ha^{-1}.

Nevertheless, Snapp *et al*. (1998) suggest that farmers may contemplate the use of intercropping systems, providing that excessive quantities of land are not lost to the legume. The aggregate effect of this may be of some importance and the technique may provide a partial component within the farmer's N supply strategy.

It should be noted that BNF generally occurs most effectively where soil N levels are low (Figure 4.3) - the rate of N-fixation generally decreases as the availability of mineral N in the soil increases, either from addition of fertiliser or due to the inherent fertility of the soil. Clearly, the benefits of using BNF techniques may become increasingly marginal as soil N availability increases (Brady, 1990).

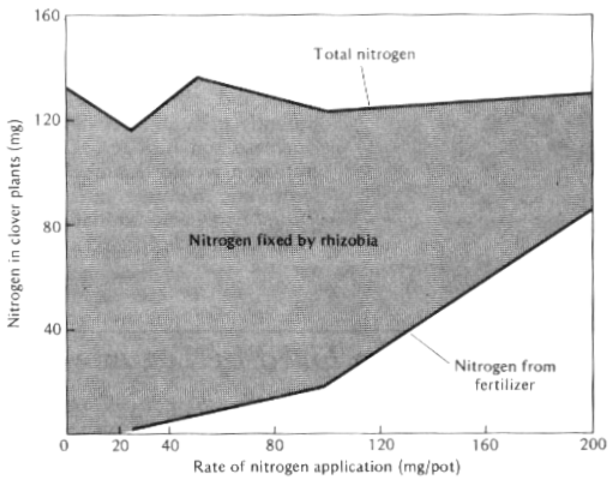


Figure 4.3: The relationship between increasing nitrogen application as fertiliser and the level of nitrogen fixed. (Source: Brady, 1990).

In addition to the modest amounts of N that can potentially be fixed in BNF techniques, the problem is compounded by low crop recovery rates of N. It would appear, therefore, that these techniques are unlikely to provide more than a small fraction of the N requirements of main crops, unless low yields are acceptable to the farmer, or unless he/she has access to sources of very large quantities of leguminous plant biomass. Certainly, the use of these techniques exclusively would require more land under the legume than the main crop to be viable, which will deprive the farmer of land that might otherwise be productively used. The use of intercropping may enhance competitive effects between the main crop and the legume, particularly in difficult biophysical conditions, where legume growth is limited for example by lack of P, or where lack of rainfall exacerbates competition for water.

4.3.2.2 Soil temperature

There appear to be optimum temperature ranges for nodulation and N fixation, although these can vary between host species (Webster & Wilson, 1998). For example, the optimum temperature for root-nodule symbiosis in the common bean is between 25-33 °C (Barrios *et al*., 1963; Pankhurst & Sprent, 1976; Graham & Halliday, 1977), although a decline in N fixation appears to occur above 28 °C (Hungria & Vargas, 2000). In general, the upper limit for N fixation in tropical legumes ranges from between 27-40 °C(Gibson, 1971; Dart, 1974; Gibson, 1975). *Rhizobium* growth is generally inhibited at temperatures between 32 °C and 47 °C (Pankhurst & Sprent, 1973; Gibson, 1975; Dart *et al*., 1976; Eaglesham & Ayanaba, 1984; Karanja & Wood, 1988), while most activity ceases altogether at temperatures above 47 °C. These optimum temperature ranges for N fixation may be greatly reduced when plants are starved of mineral N (Hungria & Vargas, 2000). In addition to this direct effect on the rate of N fixation, high temperatures also have an indirect effect on the metabolism of the host plant (Jones & Tisdale, 1921). Thus, where soil temperatures are high, such as in the semi-arid tropics where soil surface temperatures may be in excess of 50 °C (Hungria & Vargas, 2000), there is a strong likelihood that the rates of BNF will be severely restricted.

There are various explanations for the effect of high soil temperatures on the reduced rate of N fixation. High soil temperatures not only result in a reduced population of *rhizobia* in the soil; but the remaining *rhizobia* may be in a poor physiological state, possibly undergoing genetic modification and plasmid loss (Hungria & Vargas, 2000). High temperatures also reduce the exchange of molecular signals between the host plant and the *rhizobia* - the activity of *nod*-gene inducers, for example, is severely reduced at temperatures above 39 °C. The formation of root hairs may also be restricted by high temperatures, reducing the number of sites available for nodule formation (Jones & Tisdale, 1921).

Even where nodules are formed, high temperatures reduce the efficient functioning of the nodules. This can be due to reductions in the rates of leghaemoglobin synthesis (Bergesen *et al*., 1973), nitrogenase activity (Pankhurst & Sprent, 1976; Hernadez-Armenta *et al*., 1989), and allocation of electrons to N_2 reduction (Rainbird *et al*., 1983). Decreased activities of glutamine synthetase and glutamate synthase, and lowered synthesis of ureides can also occur (Hungria & Vargas, 2000). Nodule senescence is also accelerated by high temperature (Pankhurst & Sprent, 1973; Sutton, 1983), and respiration rates can increase, reducing the carbohydrate available in the nodules for their metabolism.

The adverse influence of high temperatures on *rhizobia* survival and establishment in tropical soils means that the benefit of BNF technologies may be severely restricted unless high rates of inoculation of legumes or repeated inoculations are carried out (Hungria & Vargas, 2000). Clearly it is important that strains used for the inoculation of legumes should be resistant to high temperatures in the tropics. Interestingly, *rhizobia* tolerance to high temperatures does not appear to be related to the original geographical habitat of the *rhizobia* strain or host species (Hungria & Vargas, 2000).

In vitro selection of strain tolerance to temperature has not always been successful, due to lack of correlation between *in vitro* and *in vivo* performance (Karanja & Wood, 1988). Nevertheless, in Brazil, selection for high temperature tolerance has resulted in the development of the strain PRF 81, which has been shown to compete effectively with normal bean *rhizobia* and increase yields by up to 900 kg ha^{-1} (Hungria & Vargas, 2000). Its success is demonstrated by its increased use by farmers since 1998, when it first became commercially available (Hungria & Vargas, 2000). In the Sudan, Habish (1970), found that certain native *Acacia* species were capable of fixing significant amounts of N at fairly high soil temperatures.

4.3.2.3 Soil moisture

Biological nitrogen fixation is influenced by the availability of moisture in the soil, which in turn depends on the texture of the soil, the management practices of the farmer, and the type of vegetation growing in the soil (Hungria & Vargas, 2000). The rate of N fixation is reduced in most agricultural legumes at matric potentials between -0.5 and 1.5 MPa (Dakora & Keya, 1997), due to both a reduction in the overall population of *rhizobia* in the soil from nodulation failure and a decrease in nodule longevity, and also a reduction in the growth rates of the survivors. The latter is due to a reduction in nodule cortical permeability restricting oxygen transport to the *rhizobia*, which reduces their respiration and the activity of nitrogenase (Hungria & Vargas, 2000), and also a reduction in the synthesis of leghaemoglobin. Very severe water deficits can lead to the cessation of N fixation altogether (Sprent, 1971; Vincent, 1980; Walker & Miller, 1986; Guerin *et al*., 1991), although there is variation between species. Sall *et al*. (1991), for example, reported some soybean cultivars being able to fix N under water stress, and Dakora *et al*. (1997) have observed that indigenous legumes such as bambara groundnut and Kersting's bean are able to grow and fix N in drought-stricken environments in Africa where no other crops can survive.

The interactions between host plant and *rhizobia* can also be affected by water stress. The transport of nitrogenous compounds from the nodules to the plant, for example, can be reduced, leading to the accumulation of NH_4^+ and other end products of fixation which can cause the cessation of N fixation in the nodule (Hungria & Vargas, 2000). Similarly, some studies have shown that the amount of photosynthate available to the nodules is also important under high soil water deficits. For example, Serraj *et al*. (1998) demonstrated that N-fixation under drought conditions was less sensitive under elevated CO_2 levels, although other studies have failed to show this. Durand *et al*. (1987) and Fellows *et al*. (1987), for example, found that nodule carbohydrate levels were not affected by drought stress, although nitrogenase activity had virtually ceased. Additionally, a lag time of several days was found for N fixation when water was applied to the crop again, indicating that nodule energy-charge was not the cause of low nitrogenase activity (Patterson *et al*., 1979). Acacias (which are legumes) in the desert and savannah areas of Namibia use more water per unit of carbon assimilated than non-legumes implying that there is a 'water cost' to the process of N fixation (Schultz *et al*., 1991). Danso *et al*. (1992) have suggested that this may represent the cost of supplying extra carbohydrate for N fixation.

In general, therefore, it is likely that there is a complex interplay of mechanisms (oxygen permeability changes, ureid feedback changes, carbon shortages, and transport problems), determining the actual rate of BNF under water stress. The evidence suggests that the process of BNF requires extra quantities of water, and that low levels of soil moisture reduce N fixation. Deep-rooted leguminous species should, therefore, be used for BNF where such conditions are prevalent (Webster & Wilson, 1998).

4.3.2.4 Soil *pH*

The correct soil *pH* is an important requirement for effective N fixation and therefore for leguminous technologies in general, especially as acidity is considered to be a growing problem in tropical soils (Hungria & Vargas, 2000). In general, the optimal *pH* for effective *rhizobia* growth has been suggested to be fairly neutral at about 6-7 (Jordan, 1984), and some sources suggest that the ability of *rhizobia* to tolerate external acid *pH* depends on their maintaining intracellular *pH* at around 7.2-7.5 (O'Hara *et al*., 1989; Graham *et al*., 1994). Most *rhizobia* do not appear to grow well where soil pH falls below about 5 (Graham *et al*., 1994), although there are some exceptions. These include some strains of *Rhizobium tropici*, *Mesorhizobium loti*, *Bradyryzobium* spp., and *Sinorhizobium melilotti* (Brockwell *et al*., 1995).

Hungria (2000) suggested that acid *pH* might affect the early stages of the *rhizobia* infection process by influencing the exchange of molecular signals between symbiotic partners and attachment to the roots. Additionally, in common bean roots and soybean, *nod*-gene inducers were found to be released less at *pH* 4.5 than at *pH* 5.8 (Hungria & Stacey, 1997), whilst some were found to be 'switched off' as the *pH* became more acid (Richardson *et al*., 1988). Other stages of nodule establishment and function are also affected by acidity (Graham, 1981; Munns, 1986). Low soil *pH* often occurs concurrently with increased Al and Mn toxicity, reduced calcium (Ca), P and molybdenum supply, all of which can affect the growth of *rhizobia* (Hungria & Vargas, 2000).

Selection of acid-tolerant strains of *rhizobia* from acid soils can prove to be useful, although this does not necessarily guarantee success. In Brazil, some success has been had in the selection of *rhizobia* and legume cultivars for acid tolerance, and liming the soil to neutral *p*H (the only practical way of decreasing acidity at present) is not always necessary. Thus, in common bean and soybean, good nodulation and N fixation can occur at about *pH* 5.2, although acidity below this level is problematic (Hungria & Vargas, 2000). In some cases, flavonoid *nod*-gene inducers can be used to encourage nodulation in acid soil conditions, although liming to reach a *p*H of about 5.2 as to ensure the presence of calcium and molybdenum may still be a minimum requirement. Chemical mutagenesis has been found to be able to increase the acid tolerance of *rhizobia*, but no agronomically useful strains have yet been obtained (Hungria & Vargas, 2000).

4.3.2.5 Soil fertility

As *rhizobia* activity is closely related to the growth of the host plant, low soil nutrient status can restrict the rate of biological N fixation (with the obvious exception for legumes of limiting soil N). The lack of success to *rhizobium* inoculation in many cases may be largely a result of soil nutrient deficiencies (Dakora & Keya, 1997).

Phosphorus deficiency, for example, can severely limit nodulation and BNF by legumes, as a result of reduced plant growth. The benefits of grain legume intercrops and rotations have been greatly reduced by a deficiency of P in the soil. The problem may be particularly important in a sole crop leguminous fallow, because farmers are reluctant to spend money on fertiliser for a fallow crop. Limited use of P on legume/maize intercrops may, however, be acceptable to farmers, and this can result in very large yield benefits of both the legume and the maize in on-farm conditions (Snapp *et al*., 1998).

Other nutrients are also required in appropriate quantities for effective N fixation. The trace element molybdenum is important as it is a constituent part of the enzyme nitrogenase and nitrate reductase. However, the addition of excessive quantities of N to the soil can reduce nodulation and BNF due to the build up of nitrates in the soil. In Ghana, the application of 'complete fertiliser' (excepting N) to ten groundnut cultivars increased nodulation and plant growth by 612% and 453% over control plots in the savannah zone. Kernel yield was increased by 60% and N fixation by 65% over the control (Dakora, 1985). Other results from West and East Africa are consistent with these results (Dakora & Keya, 1997). In South Africa, boron deficiencies were also responsible for reducing BNF in bambara groundnut (Dakora & Keya, 1997).

4.3.2.6 <u>Competition</u>

Although grain legume intercrops in some cases can help stabilise yields and may increase main crop productivity through better resource capture and use, in semi-arid areas or in dry years, the yields of the main crop can be greatly reduced due to competition for scarce resources such as water, nutrients and light (Snapp *et al*., 1998). This competition, especially for light, has been shown to be particularly acute with perennial legumes as they are generally larger than the main crop (Ong, 1994). Danso (*pers. comm*.) believes that for many leguminous plants, at least some of the N requirement may still come from the soil. This may therefore result in strong competition for soil N, especially if the legume is particularly vigorous, and particularly when adverse environmental conditions limit the ability of the legume to fix N.

Growing green manure crops as an intercrop or even a relay crop with competitive main crops such as maize can also be problematic. *Crotalaria juncea, Mucuna* spp., *Cajanus cajan* and *Dolichos lablab* appear to have problems establishing themselves, particularly in drought prone areas, or in areas with difficult growing conditions. Where environmental resources are limiting, strong competition from the main crop can be expected, ultimately reducing the quantity of BNF (Shumba *et al*., 1990; Muza, 1995; Kumwenda *et al*., 1997b). Reduced light intensity as a result of interception from a dominant main crop has also been found to reduce nodulation (Webster & Wilson, 1998).

Where grain legumes have been used as intercrops in a maize/grain-legume system, it has often been found difficult to obtain a significant biomass yield from the legume because maize is highly competitive. For example, Kumuwenda *et al*. (1993) found that low growing legumes in southern Africa were shaded out by taller cereal crops, leading to poor emergence and growth of the legume. Clearly, this will restrict the level of N inputs to the system through BNF. In smallholder farms in southern Africa, for example, little benefit was gained from growing grain legumes, particularly in adverse weather conditions (Mukurumbira, cited in Snapp *et al*., 1998). Grain and biomass yields (and therefore N fixation) were very low, and the impact of the grain legume on the following maize crop was very small. Similar work in the region with hedgerow intercrop systems has shown that maize yields were not increased in years with below average rainfall, indicating that competition by trees predominate over any benefits to soil fertility (Snapp *et al*., 1998). Other evidence suggests limited benefits from perennial intercrop systems, except on highly eroded and steep land

(Ehui *et al*., 1990; Versteeg & Koudokpon, 1993). Competition for light can be managed with the timely pruning of the perennial species, and some authors have also suggested that competition for water and nutrients can also be managed with pruning, although the effectiveness of this is still debated (Snapp *et al*., 1998). Nair (1993) has pointed out that controlling the below-ground competition of roots is far more difficult than controlling the above ground competition of canopies for light.

Competition for resources between a legume and a main crop has also been found to increase the variability of yields in some cases. Reviewing experimental data from India, Indonesia, and the Philippines, Ali (1999) found that although green manure could help to increase the yield of rice, it also increased the variability of this yield. The conclusion was that long-term green manuring could not increase the productive capacity of the soil more than mineral fertiliser.

Many green manure crops have been selected on the assumption that maximum biomass quantity is desirable, and much of the screening for such crops has been undertaken in research stations under relatively good environmental conditions. While quantity of biomass may be one part of the equation, the reliability of the technique under adverse conditions is probably more important to many farmers than productivity under good conditions. Ironically, it is usually under adverse conditions that competition for resources between main crop and legume crop is the most intense, and when the farmer can least afford a reduction in yields of the main crop.

4.3.2.7 High harvest index

In any BNF technique, the amount of N returned to the system is dependent on whether the legume is harvested for seed, forage, or incorporated into the soil as a green manure. Where the legume produces a useable product, farmers will most likely harvest and use that product. In the case of edible grain legume crops grown either as intercrops or in rotation, the removal of the grain can result in lower than expected residual N effects on the following crop, particularly if the grain legume has a high harvest index. It appears that farmers are generally unwilling to use a potential source of food as a soil improvement technique - where farmers can make use of the grain, it is unlikely that they will be willing to harvest lower quantities of it in the interest of long term fertility (Boddey *et al*., 1997).

In Brazil, the BNF benefits derived from using soybean as a leguminous green manure have been greatly reduced as much of the N was harvested and removed in the grain (Boddey *et al*., 1997). Clearly, farmers are likely to leave the grain for incorporation as a green manure only where they cannot market or consume it themselves. Boddey *et al*. (1997) suggest that in the case of soybean (and the same principal may be applied to other grain legumes), the solution may be to use or to develop varieties of soybean which produce more biomass whilst not producing less yield. This reduces the harvest index and would allow more N to be incorporated into the soil with the plant biomass. Grain legumes with a naturally low harvest index, such as pigeonpea or groundnut, might also be used. Alternatively leguminous plants with no commercial or edible value could be used (Boddey *et al*., 1997). However, the success of such options are culturally dependent. Clearly, farmers may not be prepared to shift from soybean (high harvest index) to pigeonpea (low harvest index) if they have a preference for the former. Additionally, due to the opportunity cost of foregoing productive land, farmers may not be willing to grow legumes with no direct subsistence or market value, particularly if they are already using a leguminous plant which does have a subsistence or market value.

4.3.2.8 Undesirable breakdown products

The decomposition of green manure can reduce the yield of the following crop if undesirable decomposition products are released. For example, the release of organic acids and/or other compounds with the incorporation and decomposition of legume residues may affect germination and seedling growth of the following crop (Boddey *et al*., 1997), reducing its yield, and deterring the farmer from using the technology again.

4.3.2.9 The time dimension of N dynamics

The management and timing of application of organic matter used for N supply is crucial, as the quantity of available N in the soil is dynamic and changes rapidly over time as soil N changes states due to immobilisation, volatilisation, adsorption, leaching and denitrification. If OM is applied too early, many of the inorganic forms of N may be adsorbed, volatilised, denitrified or leached away. If the OM is applied too late, sufficient N may be unavailable during important growth stages of the crop. The optimum time for organic matter supply depends on the quality of the organic matter, but also on the prevailing environmental conditions of the area. An understanding of the dynamics of nutrient release and nutrient demand by the crops is crucial if techniques are to have a beneficial impact on farming systems (Weber, *pers. comm.*).

4.3.2.10 *Rhizobium* strains incompatibility

The native *rhizobium* strains in soils may be incompatible with the host legume resulting in sterile nodules (Webster & Wilson, 1998). This is not a major limitation for most legumes, apart from soybean. The implication is that the seed of such legumes with specific *rhizobium* requirements should be inoculated with the appropriate strain. However, although much experimental evidence shows positive results with inoculation, there are few examples of it being used by small farmers (Webster & Wilson, 1998).

4.3.2.11 Inconsistent nodulation and nodule effectiveness

The nodulation of legumes is not always a foregone conclusion and may not be consistent even within the same genus in different parts of the world. There are about 650 genera and about 18,000 species in the *Leguminosae*. Polhill (1981) subdivides the *Leguminosae* into *Caesalpinoideae*, *Mimosoideae* and *Papilionoideae*. In the *Caesalpinoideae* only about 23% of the species examined actually have the potential to nodulate. In the *Mimosoideae* sub-family, nodulation appears to be far more common at around 90% of the species examined, and in the *Papilionoideae* sub-family, 97% of those species examined were capable of nodulating (Sprent, 1995).

In a review of N fixation by woody legumes, Sprent (1995) found that nodulation in the genus *Parkia* of the *Mimosoideae* family varied - nodules were found in some Philippine and Hawaiian species, but evidence of nodulation in African or Brazilian species could not be found. The same variability has been found amongst the 1200 species of the *Acacia* genus - *Acacia greggii* from America, for example, does not form nodules, neither does *Acacia brevispica* from Africa. Other non-nodulating sub-groups of species in the sub-genus *Aculeiferum* were reported by Allen & Allen (1981).

The effectiveness of nodules has also been found to vary. This may relate to environmental effects on the growth rate of the *rhizobia*. For example, the growth rates of *rhizobia* isolated from species of *Acacia* varied widely, with the fastest growing isolates being also the most desiccation and salt-tolerant (Zhang *et al*., 1991).

The soil has an important influence on the nature and composition of *rhizobia* populations, and may sometimes influence them to the detriment of the host plant. From the point of view of the *rhizobia* themselves, under stressed conditions survival is probably more important than the ability to nodulate host plants (Sprent, 1994). For example, it is thought that they produce extra-cellular polysaccharides (EPS) to aid their survival in difficult conditions, but it is known that these can also lead to alterations in the host range, and, in *Acacia cyanophylla*, to major reductions in the proportion of cells in the central zone of nodules which are infected (Lopez-Lara *et al*., 1993).

4.3.2.12 Tillage practices

Tillage practices may influence the number and diversity of *rhizobia* found in soils. Conventional tillage methods often reduce the size of *rhizobia* populations, probably due to reductions in SOM and increases in erosion, compared with no-till land management, in which reduced soil temperatures and soil moisture deficits protect them from adverse conditions. For example, Hungria *et al*. (2000) found that common bean *rhizobia* increased 160-fold from 2.5×10^3 cells g^{-1} in land under conventional tillage to 39×10^3 cells g^{-1} under no-till practices. Increases were also noticed in the *nod*-gene inducing activity of the soil solution, nodulation, crop yield, and in the diversity of the *rhizobia* strains. With soybean, no-till also increased the number of nodules and the depth to which they were found in the soil, the soybean *bradyrhizobia* population, the diversity of strains, all of which helped to increase soybean yields at little extra cost.

4.3.2.13 Phenology and reproductive viability

The importance of crop phenology on the sustained use of legume techniques is important for two reasons. Firstly, legumes should be able to produce edible grain within the available growing season should they be capable of doing so, and secondly, they should be capable of producing viable seeds to ensure their sustained use of the technique.

Self-sufficiency in seed production will be particularly relevant in isolated areas such as the mountain regions of Nepal (Keatinge *et al*., 1998). According to Bunch (1993) and Fischer (1997), the acceptability of new techniques to small scale farmers is often related to their retention of seed at the end of the season. A technique is more likely to be accepted if the farmer does not have to spend time and effort looking for and carrying seeds from external suppliers. In Ghana, Jackson *et al*. (1999) considered that the ability of farmers to have long-term access to green manure seeds was key to the sustainability of the technique for dry season vegetable production systems there.

Even if seeds are successfully produced, their subsequent viability is also essential. At the Wenchi Agricultural Station in Ghana, Kiff *et al*. (1999) found that germination was very poor in *Tephrosia vogellei* and *Indigofera hirsuata*, and pod-set and seed-set were also poor. *Indigofera hirsuata* seeds were also very difficult to extract. Similar problems were encountered for *Mucuna pruriens*, *Crotalaria spp*., and *Canavalia ensiformis* at the Sunyani site, primarily because of localised flooding and soil differences. Although the multiplication rates for these seeds were expected to be higher on better sites with less extreme environmental conditions (Kiff *et al*., 1999), it is in just such difficult conditions that many poor farmers operate, and that new technologies may have to prove themselves.

The introduction of N-fixing plants to new areas requires a detailed understanding of the impact of local physiographic factors and environmental variables on the growth and development of the introduced plant (Kassam, 1988). The prevalence of local variation, especially in hill areas, can create a mosaic-like environment, which necessitates the specific adaptation of legumes to those conditions. This can be a complex and time consuming task, given the number of legume species and the mosaic of environments that are found in hillside conditions.

The work of Keatinge *et al*. (1996) indicated that an understanding of the photothermal effects (i.e. temperature and photoperiod) on phenology and the incorporation of this into a model had the potential to match legume cover-crop genotypes to their biophysical context more efficiently. They found that for tropical and subtropical species of legume, the shortest photoperiod (11.5 h day^{-1}) combined with the warmest mean diurnal temperature (27 °C) resulted in the shortest time to flowering and fruit maturity. On the other hand, in the temperate legumes (with the exception of *Lupinis mutabilis* which was photoperiod insensitive), they found that flowering and maturity was most rapid when the warmest mean diurnal temperature (27 °C) was combined with the longest photoperiod (14.5 h day^{-1}). In general, genotypes adapted to temperate areas showed better plant growth and vigour at cooler temperatures, whilst those adapted to the tropics tended to show better plant growth and vigour at warmer temperatures. However, when the latter were grown at the coolest temperature regime, although their initial growth was slow, they recovered to grow well later on. Cool temperatures combined with longer photoperiods also tended to increase fruiting in the temperate legumes, while warm temperatures with shorter photoperiods tended to increase fruiting in the tropically-adapted legumes (Keatinge *et al*., 1998).

The number of days required for the legumes to show the first mature pod after flowering was mainly determined by temperature, and the effect of photoperiod was relatively small. Only *Vicia dasycarpa* was an exception to this rule - for this plant, the mean duration to the first mature pod from first flowering was 48 days at any temperature (Keatinge *et al*., 1998). For this reason, the use of short day species that are grown successfully at low elevations in the tropics may not be appropriate for use in high altitudes there. *Pueraria phaseoloides*, for example, failed to produce seeds at all after 173 days of growth at photoperiods greater than 11.5 h day^{-1}, or at temperatures less than 27 °C (Keatinge *et al*., 1998). *Canavalia ensiformis*, *Mucuna pruriens* and *Dolichos lablab* took so long to bear seed that reproduction for them would be impossible at higher altitudes or latitudes within the possible growing period (Keatinge *et al*., 1998). *Mucuna pruriens* (106 days) and *Dolichos lablab* (95 days) reached pod maturity sooner than *Canavalia ensiformis* (170 days). Both

Crotalaria juncea and *Stylosanthes hamata* appeared to be useful in hill conditions as they flowered more quickly than the other short day species. However, *Crotalaria juncea* needed to be pollinated by hand during the experiment, as bees were not to be found at the experimental site, underlining that their presence was essential if the use of *Crotalaria juncea* was to be successful.

Variations in temperature and photoperiod may have less of an impact on the reproductive viability of long day species. *V. faba*, *T. resupinatam* and *V. sativa* all responded in the expected way to changes in temperature and photoperiod. *T. resupinatum*, for example, appeared to be able to survive well in a wide range of photothermal environments. *Vicia dasycarpa* was completely insensitive to the range of photothermal conditions to which it was subjected to in the experiment, explaining its wide geographical distribution. It has been found growing as high as 2300 m at latitude 31 N in Pakistan (Keatinge *et al*., 1991), and as low as 320 m at latitude 31 S in Bolivia (Paterson *et al*., 1984). Clearly, both these species may have potential for hillside environments where tolerance to a wide range of photoperiods and temperatures are required.

L. mutabilis, which is widely grown in the Andes, is completely insensitive to photoperiod (i.e. day neutral), although it is sensitive to temperature and increasingly loses flowers as mean annual temperatures rise (Keatinge *et al*., 1998). This suggests that it could be useful in a wide range of latitudinal zones, provided the mean annual temperatures are not too high.

4.4 Socio-economic constraints

Most of the socio-economic limitations to the use of N transfer and BNF techniques are similar to the more generic socio-economic limitations that have been discussed previously. This section presents a more detailed examination of the socio-economic limitations and requirements, under the generic titles of land, labour and capital. This is done through an analysis of some of the material reviewed so far and a case study undertaken by Ali (1999), on the use of N management techniques, in particular grain legumes and green manure.

4.4.1 Land

4.4.1.1 Plant biomass

As with SOM management technology, in order to be effective, BNF technology requires land that resource poor farmers may not have. The amount of land required by a BNF nutrient bank to provide the full N requirements of a main crop may, in fact, be much greater than the area of the main crop itself.

Taking the mid values for the legumes shown in Brady (1990) and Giller *et al*. (1997), the amount of land required to supply sufficient N to a crop removing 100 kg N $ha^{-1}y^{-1}$ can be estimated (Table 4.8). Generally, the amount of N applied to the crop must be well above the amount extracted and removed by the crop biomass. The recovery rate of applied N in organic matter varies greatly, and has been found to be as little as zero or as much as 50% of added organic matter (Giller *et al*., 1997), influenced by such factors as leaching due to high rainfall, volatilisation, or denitrification. However, a general rule of thumb is to assume that between 20-25%

of N is recovered from most organic inputs by the first main crop (Giller & Cadisch, 1995b). If a crop removes 100 kg N ha^{-1} from the farm, the supply of N in the plant biomass needs to be as much as 400 kg N ha^{-1} to ensure the long term stability of the system. To supply the biomass requirements for this would necessitate more land under the BNF crop than under the main crop. For example, supplying N for a crop removing 100 kg N ha^{-1} with alfalfa biomass would require 2 ha; for *Leuceana leucocephela*, supplying the main crop would require between 1.5-5.3 ha, while for *Gliricidia sepium*, between 2.0-2.4 ha of land would be required. Clearly, in all of these examples, the amount of land required to fix the required amount of N is substantially more than the amount of land under the main crop, although this depends on what the farmer perceives to be an adequate yield. Where the farmer is prepared to accept relatively low yields, the amount of land required for BNF techniques will also be less.

Table 4.8: Estimates of the amount of land required to supply a crop extracting 100 kg N ha^{-1} and assuming a 25% recovery rate of applied N. (Total N application requirement = 400 kg N ha^{-1}).

Plant	N fixation ha^{-1}	Land area (ha) required to supply 100 kg N ha^{-1} to a main crop	Source
Biological Nitrogen Fixation			
Alfalfa	200	2.0	(Brady, 1990)
Clover	125	3.2	″
Soybean	75	5.3	″
Cowpea	75	5.3	″
Lupine	75	5.3	″
Vetch	87.5	4.6	″
Bean	40	10.0	″
Calapogonium mucunoides	64	6.3	(Giller *et al.*, 1997)
	126- 182	3.2 - 2.2	″
Centrosema pubescens	67 - 136	6.0 - 2.9	″
	80 - 280	5.0 - 1.4	″
Gliricidia sepium	170 - 204	2.4 - 2.0	″
Leuaceana leucocephala	76 - 274	5.3 - 1.5	″

With a biomass transfer technique, the possibility of a farmer finding sufficient land on-farm to grow the appropriate quantities of biomass is limited. This may be particularly so in regions where the average farm-size of resource-poor farmers is small, making it physically difficult, if not impossible, to integrate biomass transfer techniques into existing systems. In such cases, off-farm sources of legume biomass may be a more preferable option to devoting land on-farm solely to the production of such biomass.

It is worth noting that the amount of N fixed biologically by the legume/*rhizobia* association is greatly affected by the amount of mineral N in the soil. All other factors being equal, the higher the N content of the soil, the lower the rate of fixation. Land that is low in N is therefore likely to have a higher rate of BNF, although the growth of the legume may then be limited by other nutrients.

In the case of intercropping techniques, the generation of N will be severely restricted, as the amount of land required to maintain the crop will remain unchanged. This may be particularly problematic with perennial techniques such as alley-cropping, as there is only a limited amount of land that can be given over to the legume if the farmer is to continue producing main crops at a viable level. Indeed, the evidence suggests that to maintain a main crop on biologically fixed N would require more land to be put under the perennial legume than under the main crop. The opportunity cost of this is high in the short term. Relay cropping with annual legumes, or perennial legumes like *Cajanus cajan* for a single season, may offer flexibility in terms of the farmer's ability to crop the land and fix some atmospheric N simultaneously. However, it appears that unless N fixation is exceptionally high, BNF over a single season will be insufficient to provide the quantities of N required for the growth of most staple crops.

As discussed in Section 4.2.1.4, improved fallows may offer one possible option for resource-poor farmers. Such techniques may have potential where the use of fallow is already an accepted part of the cropping system. Improved short-term fallows with cover-crops or long-term fallows with leguminous perennials may be used to improve soil N, soil organic matter levels, reduce weeds, and minimise soil erosion. Such techniques may have more relevance where fallowing is already integral to the farming system. However, in a situation where land is limiting and fallow periods are under pressure, improved fallows may require the sacrifice of a main crop which would not be feasible for resource-poor farmers not able to sacrifice a year's food supply or cash income. There are clearly large short-term benefits to be derived from reducing fallow periods, particularly where cropping to fallow period ratios are already relatively low. For example, if a farmer is cropping for one year and fallowing the next, removing a year's fallow doubles the amount of land that can be cropped. Improved fallow systems also require relatively little labour and low capital investment. But where land is scarce, the full benefits of the improved fallow may be unavailable to the resource-poor farmer, because the fallow period required to derive practically significant benefits from the land may be too long.

Farmers may find that improved fallows are relatively unproductive and require more resources in comparison with natural fallows. There is clearly a disincentive in the labour and costs that are incurred as a result of planting of an 'unproductive' grass or leguminous fallow, particularly if no return other than soil fertility is derived. An improved fallow may need to be planted and weeded to ensure that it is not swamped by invading or naturally regenerating plants. A natural fallow, particularly a fallow of several years may provide goods and services that an improved fallow cannot. There may be naturally occurring plants, animals, or residual germination and growth of cultivated crops that provide valuable free products to the farmer. The opportunity cost of forgoing a natural fallow is clearly large due to the variety of services that may be offered by the fallow period. The farmer will need to perceive major benefits from the fallow period, if he/she is to invest resources in it. Some of these benefits may need to include food, fuel and fodder, as well as soil fertility, if the benefit is to outweigh the opportunity cost of forgoing a natural fallow.

It is worth noting that the benefits of improved fallow techniques may decrease as the length of the fallow increases. There is some scientific basis to substantiate this. The fixation of N in the soil and the net increase of N in the soil show diminishing returns to time as an equilibrium level of N in the soil is reached. The greatest benefit to legume fallows may therefore be derived during the early years, whilst the latter years may be of little practical benefit at least in terms of N fixation.

Where non-leguminous plants such as *Tithonia diversifolia* are used in a biomass transfer system, the requirement for land will be equally great. The yield of *Tithonia diversifolia* in pure stands has been found to vary between 2-3.9 t DM ha^{-1} for biomass of sufficient quality to be used as a green manure. Assuming a mean content of 3.5% N, the amount of land required to supply N to a crop removing 100 kg N ha^{-1} may be between 3-6 ha depending on the exact yield of sufficient quality biomass (Table 4.9).

Some researchers suggest that field boundaries could be used as a general source of nutrients from *Tithonia diversifolia*. Whilst this may provide part of the N requirement for a main crop, it clearly cannot meet all of it, as the length of the hedge required to produce sufficient N would be impractical. In Rwanda, the quantity of dry matter produced from a *Tithonia* hedge has been found to be about 1 kg $m^{-1}y^{-1}$ (Drechsel & Reck, 1998). To produce sufficient N to maintain a main crop extracting 100 kg N ha^{-1} with an N recovery rate of 25% (total application requirement of 400 kg N ha^{-1}), for example, would necessitate 12 km of hedge.

Table 4.9: Estimate of the amount of land required to grow sufficient Tithonia diversifolia *assuming a 3.5% N dry matter content and a 25% recovery rate of N and a mean yield of between 2-3.9 t useable DM ha^{-1}.*

Crop N removal ($kg\ ha^{-1}$)	**N application requirement ($kg\ ha^{-1}$)**	**Dry biomass requirement ($t\ ha^{-1}$)**	**Estimated land requirement (ha)**
25	100	3	0.8 - 1.5
50	200	6	1.5 - 3.0
75	300	9	2.3 - 4.5
100	400	12	3.1 - 6.0

(Adapted from Jama *et al*., 2000).

4.4.1.2 Animal manure

The amount of land required to provide sufficient N through animal manure may be far larger than that required to supply N through the use of N in plant biomass. This may be particularly the case where high losses of N occur during storage and in particular as a result of loss in the urine, which is difficult to collect. Data from Boddey *et al*. (1997) suggests that about 50% of the N is excreted in urine. Lekasi *et al*. (1998) suggest that this may be even higher at about 70%. Where all the N in the urine is lost and unavailable to the cropping system, the amount of land required to maintain the N requirement of a particular crop could be approximately twice the amount that is required to maintain the crop with the direct application of plant biomass. Clearly, where animals form an important component of the farming system, it is important to make proper provision for the capture and use of N in the urine (Lekasi *et al*., 1998).

In countries such as Nepal or Kenya, the use of animal manure in certain areas may be successful in maintaining crop yields at relatively high levels. The collection and management of the manure is practical as the animals are stall-fed. However, the problem of transferring sufficient N through animal manure is no less significant than with plant biomass. Although some fodder is produced on-farm in such circumstances, much of the N in the manure, for example in the highlands of Kenya, arrives from off-farm sources in the form of imported fodder and food concentrates (Lekasi *et al*., 1998). The amount of land, therefore, required to maintain the productivity of the cropped on-farm areas is clearly greater than the land owned to the farmer. Animal manure would cease to be effective without the possibility of the large import of nutrients from off-farm sources.

In countries such Bolivia and Brazil, animals are generally free-grazed. Collecting manure from free-grazing animals is usually impractical. Supplying N through manure from free-grazing animals would also require large areas of pasture to support the N requirements of a single hectare of arable crop. In fact, the provision of N through animal manure is probably less efficient as large amounts of N are excreted in the urine which is impossible to collect from free-grazing animals. As noted previously, cattle reared on a *Bracharia* pasture in Bolivia or Brazil capable of supporting 3 animals ha^{-1} might be expected to produce about 40 kg N ha^{-1} y^{-1} in the faeces (Boddey *et al*., 1995). Assuming that there is no loss of the N in the dung during collection and storage, about 10 hectares of pasture and about 30 animals would be required to produce 100 kg N ha^{-1}, assuming a 25% recovery rate of the N supplied in the manure.

4.4.2 Labour

Ali (1999) found that for many farmers, the cost of labour was partly responsible for making nutrient supply through organic matter technology less cost-effective for farmers than mineral fertilisers. In Asia this problem may be increasingly acute as wages are generally increasing rapidly. In India, the requirement for a pair of bullocks and a ploughman was 10.5 days ha^{-1} in a rice/green manure/rice rotation. In Nepal, the number of days needed in a wheat/green manure/wheat system was 11 days ha^{-1}. In both cases, the cost of this was about 40 US$ ha^{-1} and largely accounted for the differences in economic performance between organic matter techniques and mineral fertilisers. This occurred despite the reduced need for weeding and the increased yields obtained. Ali (1999) also analysed the performance of grain legumes and found that these could perform better than the inorganic fertilisers, despite increased labour requirements, because the grain produced a saleable product. However, acceptance was not as high as expected and this was due mostly to other factors such as the delaying of monsoon crops, high labour demand at grain legume harvesting which coincided with planting of the following main crop, and pest and disease susceptibility of the grain legume used.

4.4.3 Capital

Some research has shown that BNF techniques (such as green manure) can improve yields and increase the long-term stability of agricultural systems. However, the small differences usually obtained in experiments do not necessarily translate into benefits of practical significance to the farmer. The financial benefits for the farmer may be minimal, particularly if labour has to be hired or land put out of production for biomass banks.

Ali (1999), in a study on the economic viability of combined fertiliser, green manure and grain legume techniques found that the short-term benefits of green manure were ‘negative or trivial’. This was despite on-farm experiments showing that yields were higher with combined fertiliser and green manure treatments, compared to the use of fertiliser alone. Farmers using grain legumes, on the other hand, increased short-term benefits as well as long term benefits over fertiliser only systems, mainly due to the economic benefit of growing the grain legume. Ali (1999) concluded that recommended techniques need to have short-term economic benefits, or risk being rejected by farmers, despite any long-term advantages they might have.

For many farmers, the adoption of techniques is an economic decision that depends on factor prices, such as land, labour and water, and other resources. In land-abundant farming systems, the opportunity cost of leaving land fallow is virtually zero. As land becomes scarce the opportunity cost of using SOM management techniques increases until it may become uneconomic. This may be particularly so in a situation where governments subsidise fertiliser, where wage rates increase, and where transport networks are effective (Ali, 1999).

As relative factor prices change, the economic viability of differing nutrient sources also changes. Since 1970, in India, Pakistan, Philippines and Indonesia, the price of labour has increased by 74, 113, 72, and 170% respectively (Ali, 1999). Land prices have also risen relative to fertiliser prices in these countries, which may explain why land- and labour-based soil fertility techniques are declining. In Taiwan, for example, green manure crops have decreased from an area of 153,000 ha in 1954 to 11,000 ha in 1991. In India, Nepal and Pakistan, green manure is no longer widely used (Ali, 1999).

Ali (1999) performed an economic analysis of the use of *Sesbania*, *Azolla*, and rice straw as green manures in India, Indonesia and Philippines. For this he assumed that a *Sesbania* green manure crop would provide 70 kg N ha^{-1}, azolla 30 kg N ha^{-1}, and rice straw 18 kg N ha^{-1}. Ignoring the opportunity cost of growing green manure on productive land, and taking current (1999) labour and fertiliser prices in the three countries, he found that the benefit/cost ratio of all three techniques was less than 1.0. This indicated that at these labour/fertiliser price ratios, green manure was not a cost-efficient option in any of the three countries, and that artificial fertiliser was more economical as a source of N than green manure.

Clearly, the cost of mineral fertiliser would have to increase, or labour rates fall, to make the use of nutrients available in green manure more economical than the use of mineral fertiliser. Ali suggested that for green manure to be competitive with fertiliser at a competitive fertiliser price (US$ 0.6 kg^{-1} N) and with zero opportunity cost of land, the ratio of wage (US$ day^{-1}) to fertiliser price (US$ kg^{-1} N) should not exceed 3.0 for *Sesbania* and *Azolla*, and 2.0 for rice straw. As the ratio is higher than this in India, Indonesia and the Philippines, this explains the low use of green manure techniques there. In Myanmar and China, a more favourable ratio explained the greater use of green manure in these countries.

The economic unattractiveness of green manure as land and labour factor prices grow, increases the pressure towards intercropping and grain legumes. In India, farmers growing *Crotalaria juncea* and *Tephrosia purpurea* as green manure after winter rice have shifted over to grain legumes such as *Cajanus cajan* and *Vigna* spp., particularly if irrigation water is available. In Nepal, on the central *terai*, *Crotalaria* *juncea* and *Sesbania rostrata* have given way to grain legumes such as mung-bean, particularly if water is available during the dry season.

Ali (1999) suggests that in many cases, the cost of nutrients from organic matter sources may be too high to be economical, especially as many countries are steadily improving their transport infrastructure. Only dramatic increases in fertiliser prices due to scarcity of fossil fuels may make green manure viable in countries such as India, the *terai* in Nepal, and the Philippines. Grain legumes, on the other hand, have potential if the grain has economic value. However, the large-scale removal of nutrients in the grain may largely undermine their net N-fixing capacity, and sustained cultivation on this basis can only occur with external supplies of nutrients.

4.4.4 Gender considerations

The use of organic material as a supply of N may be constrained by lack of capital or give insignificant financial benefits as discussed above. However, Gladwin *et al*. (1997), in a study on constraints that women face when using organic fertiliser sources, found that there were many factors involved. It should be remembered that women often make up a sizeable proportion of the labour force, perhaps reaching even more than half of the agricultural labour force in some countries. The significance of women's agriculture is that it is very often focused on meeting subsistence needs, generally with lower inputs of both organic and inorganic fertilisers than men's agriculture (Gladwin *et al*., 1997). Lack of capital prevents them from investing in either organic or inorganic fertilisers, lack of land limits their ability to make use of BNF or biomass transfer techniques, while lack of labour limits their ability to undertake the activities that may be required to implement organic matter techniques, particularly as most women are solely responsible for household duties and child care.

In Kenya, alley cropping with *Leucaena leucocephala* and *Calliandra calothyrsus* was tested in on-farm trials by the International Centre for Agroforestry Research, the Kenya Forestry Research Institute, and the Kenya Agricultural Research Institute (Williams, 1997). Both species were found to be suitable either as fodder banks or as nutrient supply banks, but the adoption of these techniques was lower than expected. An ethnographic survey found that, of forty women questioned, only eight would consider using alley-cropping techniques as a part of their farming systems. The various reasons given are shown in Table 4.10.

Table 4.10: Reasons for non-adoption of alley cropping techniques by women in Kenya. (Adapted from Williams, 1997).

Reason for not using alley cropping techniques	No.	Percentage of total survey	Percentage of those who know
Lack of awareness of alley cropping technology	12	30.0	
Lack of access to seedlings	2	5.0	7.0
Lack of knowledge on how to integrate alley cropping	3	7.5	10.5
Negative soil fertility effect	2	5.0	7.0
Insufficient land	5	12.5	18.0
Pruning too labour intensive	4	10.0	14.0
Shade out crops	2	5.0	7.0
Affected by pests	2	5.0	7.0
Use alley cropping technology	8	20.0	28.5

The major reason for non-adoption of the technique appeared to be lack of awareness of alley cropping as a possible option, with 30% having never heard of it. However, of those who had, 18% felt that they lacked the land, and 14% felt they lacked the labour to prune the trees. Other women felt that shading of the crop (7%) and attack by pests (7%) reduced the utility of the technique. A sizeable proportion of the women surveyed also felt that incorporating it into their current systems would be difficult (10.5%), and that lack of access to seedlings (7%) and negative soil fertility effects (7%) would hamper their uptake of the technique. Overall, this meant that 28% of those who had any knowledge or experience of alley cropping were, or would be, willing to use it.

4.5 Summary

We have summarised the biophysical limitations that are commonly outlined in the literature in an attempt to provide a 'database' of considerations that need to be taken into account when organic matter technology is used to supply N for soil fertility improvement. Here we once again try to summarise these as 'requirements' for low-input N management technology. Where a large number of these requirements can be met, we suggest that opportunities may present themselves for the adoption of some of these techniques. However, we would like to emphasise that there is no reason to suppose that adoption will be a foregone conclusion, even where the biophysical and socio-economic requirements noted below can be met. The use of new techniques may, in fact, be limited by factors that are far more specific and intangible than those we have discussed so far.

As before, a major requirement is for the provision of large quantities of biomass for incorporation into the soil, which in turn requires large areas of land to produce it. Producing adequate quantities of biomass will be most successful where climatic conditions, in particular solar radiation, temperature and rainfall, and soil conditions, are optimal for plant growth. On the whole, resource-poor FAI farmers are likely to have great difficulty supplying full N requirements with organic matter techniques. They may be useful in supplying some, but not all, of the N needs of a main crop, and relatively low yields are likely to occur as a result. This may partly explain why long fallow rotations are still practised despite the introduction of low-input N supply techniques.

A further major requirement is for the production of high quality organic matter. Where this cannot be obtained, mineral fertilisers may have to be used to supplement organic matter inputs to prevent immobilisation of N. There may be a need to compost the organic matter where mineral fertilisers cannot be integrated with the use of organic matter, to jump start the decomposition process.

One of the major difficulties in supplying N is in its mobility, which makes soil N management difficult. Nitrogen may be volatilised, leached, denitrified and adsorbed and in general, low recovery rates of N by the main crop are normal. A further requirement may therefore be to manage the biomass in such a way that mineralisation releases N to the crop during strategic growth periods. There is therefore a requirement to understand how to manage biomass for effective N-supply in location-specific contexts and to develop low-input N supply techniques to account for this. This may require a thorough understanding of N dynamics in different climatic and soil conditions and the use of techniques that are not directly related to N supply may be needed. For example, if volatilisation is high, techniques could be developed to reduce this. Similarly, if leaching is very high, techniques could be developed to reduce this, so that N supply to main crops is not reduced. These also would have to fall within the resource capability of the farmers and would perhaps have to be seen as important and useful in their own right if farmers are to adopt them.

Further major requirements relate to appropriate conditions for *rhizobia* growth and development. As has been shown, the appropriate soil moisture conditions, temperatures and *pH* are all important for N fixation. These are similar to conditions required for optimal plant growth. For example, *rhizobia* seem to grow best in temperatures of between about 25-35 °C, matric potentials of between 0.5-1.5 MPa and soil *pH* of between 6-7. Where these conditions are not met, N fixation rates may fall below a level that supplies useful quantities of fixed N to the soil.

Finally, a further requirement for techniques such as intercropping to be successful is for them to operate in such a way as to minimise competition between the two crops involved. This competition may be for environmental resources, such as light, water and nutrients, but competition for land is also problematic. With rotations, farmers may prefer lower yields every year, rather than larger yields every other year, unless the legume itself supplies them with a product that they value. Where this is the case, however, the benefits from N fixation may be greatly reduced, as much of the N will be removed in the harvest. This appears to be an insoluble problem for multi-benefit techniques such as grain legumes which can supply a useable product that will encourage the removal of fixed N from the land.

In broad terms, where the above biophysical requirements are met, low-input N techniques would appear to have a chance of contributing to the farmer's N requirements, at least from a biophysical perspective. However, the adoption of organic matter technology rests not on their biophysical compatibility alone, but also on their ability to mesh with existing socio-economic and cultural frameworks. Thus, farmers may have to find large areas of land to supply the full N needs of a main crop, even with N-fixing techniques. But where this is available, farmers may still prefer to use rotations, which are generally more labour efficient. Where land is limiting, biomass transfer and *in situ* techniques such as intercropping may be the only option, as long fallow rotations will not be acceptable. The former will, however, require large quantities of labour, whilst the latter at best will only provide low net N increases to the system and at worst reduce yields as a result of legume/main crop competition.

A further socio-economic requirement for low input N techniques may be to provide rapid results. Where the benefits of N management technology are not perceived within a relatively short time, farmers may be unwilling to continue with their use, particularly if this demands extra effort on their part, or commitment of other resources, in particular capital, for example for seed procurement.

Further socio-economic requirements appear to be good access to market and good infrastructure, as these may stimulate the agricultural economy as a whole and therefore the farmers willingness to invest in organic matter technology. Finally, security of tenure over land is an important requirement for effective technology use, although secure tenure does not have to mean land ownership as perceived in Western market economies. Still less do we suggest that this should lead to attempts at social engineering solutions, as traditional tenure arrangements, such as the usufruct agreements that occur in Ghana, may provide resource-poor farmers with access to land that they might not have at all where land is bought and sold. But the evidence does suggests that where farmers are confident within their own cultural expectations, and their security of tenure is good, they may be willing to invest in organic matter techniques in general.

5 Phosphorus management

5.1 Introduction

Phosphorus (P) is an essential component of adenosine diphosphate (ADP), adenosine triphosphate (ATP), deoxyribonucleic acid (DNA) and ribonucleic acid (RNA), all of which are important in cell metabolic and nucleic processes. P plays a vital role in photosynthesis, N fixation, crop maturation (flowering, fruiting and seed formation), root development (especially lateral and fibrous roots), stem strength in cereal crops (preventing lodging) and crop quality in general (particularly forages and vegetables) (Brady, 1990).

In general terms and as a soil nutrient, the importance of P is second only to N. Evidence indicates that P is one of the major limiting nutrients in tropical soils and that its provision can substantially improve crop growth. Phosphorus cannot be fixed from the atmosphere like N and must be supplied to the soil in organic material or as a mineral fertiliser. However, the problems of P management are threefold. Firstly, there is often a general lack of P in the soil, varying from 200-2000 kg P ha^{-1} in the top 20 cm. Secondly, 'native' P compounds are generally insoluble, and thirdly, soluble sources of P in organic matter or fertilisers rapidly become adsorbed and insoluble. Indeed, the greatest fraction of P in the soil (98-99%) may be locked up in primary or secondary minerals and SOM. About 1-2% is immobilised in microbial tissue, and only about 0.01% of total soil P may exist as soluble P, available for plant use. However, unlike N, there is little significant loss of P in gaseous forms or by leaching (Brady, 1990).

In order to counter these problems, it is often necessary to apply far more P than is removed by the crop. Generally only about 15% of mineral fertiliser applied to the soil is used by the crop in that year. Phosphorus is held in both inorganic and organic forms. Most inorganic forms are compounds of calcium, iron or aluminium. Many calcium compounds, such as apatite, are particularly insoluble; other simpler compounds, such as mono and di-calcium phosphates, may be available to plants, but are generally available only in very small quantities and can easily revert back to insoluble forms. Compounds of iron and aluminium phosphates are also relatively insoluble. Organic P compounds may comprise about half the P in the soil. the most important of which are inositol phosphates (typically 10-50%), nucleic acids (typically 1-5%), and phospholipids (typically 0.2-2.5%). Plants are thought to absorb only small quantities of compounds of organic P directly (Brady, 1990).

5.2 Phosphorus mobilising techniques

The main supply of P in the soil is through the incorporation of plant or animal residues and waste, and through the application of chemical fertilisers. Any organic matter technique may be also thought of as a P technique, although in general, the emphasis has been to use such techniques to supply N or SOM, rather than to use them for the specific objective of increasing soil P. Phosphorus management has always proved to be problematic for agriculture. Crops do not take up more than about 10-15% of the P supplied to the soil. Although the continued application of P may, with time, increase the quantity to a level where there is sufficient release from the soil reservoir for plants, this is an expensive option, not generally available to the resource-poor farmer. Maintaining the soil between pH 6-7 is also important to maximise P availability, and in general, liming is the method used to achieve this. Manure may be successfully used in conjunction with chemical fertilisers and in some cases, soluble P fertilisers can be applied directly to the foliage to reduce adsorption and immobilisation in the soil.

5.2.1 Tithonia diversifolia

Tithonia diversifolia has aroused research interest because of the relatively high nutrient concentrations that are found in its biomass, and because of its ability to extract relatively high amounts of P from the soil (Table 5.1). This is thought to be due to exudates of organic acids from the roots altering the pH in the rhizosphere, thereby increasing the amount of soluble P in the soil. The species originated in Mexico, but is now widely distributed throughout the humid and sub-humid tropics in Central and South America, Asia and Africa (Sonke, 1997).

Evidence suggests that *Tithonia* has been used for a wide variety of purposes. These include fodder, poultry feed, fuel, compost, land demarcation, soil erosion control, building materials, and shelter for poultry. The use of *Tithonia* as an effective source of biomass for annual crops has also been reported for rice (Nagaraj & Nizar, 1982). More recently it has been reported as a nutrient source for maize in Kenya, Malawi and Zimbabwe (Jama *et al*., 2000). *Tithonia diversifolia* is typically found growing as hedges, or as small areas of pure stands in an on-farm context, although it may also extend for large areas in pure stands on common land in less populated areas, for example, in the Busia District of western Kenya.

Table 5.1: Nutrient concentration in green leaves of selected shrubs and trees in Kenya. (Source: Jama et al., 2000).

Species	Nitrogen %		Phosphorus %		Potassium %	
	Mean	Range	Mean	Range	Mean	Range
Tithonia diversifolia	3.5	3.1 - 4.0	0.37	0.24 - 0.56	4.1	2.7 - 4.8
Calliandra calothyrus	3.4	1.1 - 4.5	0.15	.04 - 0.023	1.1	0.6 - 1.6
Crotalaria grahmiana	3.2	3.0 - 3.6	0.13	0.13 - 0.14	1.3	0.9 - 1.6
Lantana camara	2.8	2.3 - 4.0	0.25	0.18 - 0.3	2.1	1.8 - 2.4
Leucaena leucocephala	3.8	2.8 - 6.1	0.20	0.12 - 0.33	1.9	1.3 - 3.4
Sesbania sesban	3.7	1.4 - 4.8	0.23	0.11 - 0.43	1.7	1.1 - 2.5
Tephrosia vogelii	3.0	2.2 - 3.6	0.19	0.11 - 0.27	1.0	0.5 - 1.3

The major method of using *Tithonia diversifolia* as a P-mobilising technique is in biomass transfer systems (Jama *et al*., 2000). The P release from green biomass of *Tithonia* is thought to be at least as effective as an equivalent supply of P from soluble fertiliser. Experiments at Nyabeda and Khwisero in western Kenya showed that maize yields from *Tithonia* were at least as high as, and often higher than, the yield from applications of mineral fertiliser, when mineral fertilisers were applied in the equivalent quantities. The mean N content (3.5%) and P content (0.37%) are above the levels at which net N and P immobilisation generally occur (2.5% for N and 0.25% for P) (Jama *et al*., 2000). Data from the Organic Resources Database also suggest that lignin (6.5%) and polyphenol content (1.6%), are below the level at which decomposition is significantly reduced.

Although *Tithonia* is generally recognised for its superior ability to extract P from the soil, it also has the ability to supply relatively high concentrations of N and potassium when used as a green manure. However, as it is not a legume and cannot fix atmospheric N, this essentially results in a redistribution of N within the system, rather than a net addition.

In Kenya, King'ara (1998) found that biomass production varied depending on whether stems used for propagation were woody (4.2 t DM ha^{-1}), or on whether stems were soft (2.6 t ha^{-1}). Woody stems were prone to termite attack and this was found to reduce the biomass produced when propagated with woody stems. Soil fertility can also influence the amount of biomass produced by *Tithonia*. King'ara (1998) found that *Tithonia* propagated through 40 cm stems was capable of producing about 2-3.9 t DM ha^{-1} after about 8 months of growth.

Jama *et al*. (2000) showed that *Tithonia* growth could be greatly increased with the use of phosphorus fertiliser on P-deficient soils. Although the addition of 50 kg P ha^{-1} as mineral fertiliser to such soils appeared to have little effect on the concentration of P in the leaves of *Tithonia* after eight months, the total quantity of biomass generated was greater, and consequently the total quantity of P available in the biomass was also greater (Jama *et al*., 2000). Very high P concentrations (0.70% and 0.73%) have been found in *Tithonia* grown on two phosphate deposits in eastern Uganda (Jama *et al*., 2000).

The typical biomass produced by *Tithonia* in hedges can vary considerably, in part because it is rare for hedges to be composed of pure *Tithonia*. In western Kenya, Ng'inja *et al*. (1998) found that the dry weight of *Tithonia* biomass was about 0.2 kg m^{-1}, whereas the DM production in a pure *Tithonia* hedge in Rwanda reported by Drechsel & Reck (1998) was about 1 kg m^{-1}.

It is important to consider the time and age at which *Tithonia* leaves are used as a nutrient source for plants, as the concentration of nutrients in *Tithonia* can vary in time, greatly affecting the quantities of biomass that might have to be applied to the main crop. In Kenya, for example, senesced leaves contained a mean N content of only 1.1%, as compared with an N content of 3.2% for green leaves. Nutrient concentrations also vary depending on the plant part used, with nutrient concentrations being relatively low in litter-fall and woody material, and relatively high in green leaves. Clearly, the age of the plant, the position of the leaf in the canopy, the soil fertility, and provenance could also affect the nutrient content of *Tithonia* biomass. The P concentration of green leaves in Kenya was found to be about 0.37%, whereas for litter-fall and stems it was only 0.08%. *Tithonia* leaves typically contain about 35-40% of the above-ground plant P, although this may come from only 15-17% of the above-ground biomass. In general, however, green leaves contain P at a level above the critical threshold of about 0.25%, below which net P immobilisation is thought to occur (Jama *et al*., 2000).

5.2.2 Other species

Tithonia is not the only plant that has the potential to extract relatively high levels of P from the soil. According to the Organic Resources Database, several of these have higher mean P concentrations than *Tithonia diversifolia* (Table 5.2).

Table 5.2: Plants or plant parts with P concentrations equivalent to or higher than Tithonia diversifolia*.*

Species	Plant part	Mean P %	Min P %	Max P %	Legume
Vicia villosa	Shoot	1.24	1.24	1.24	Yes
Flemingia macrophylla	Leaf	0.54	0.21	1.19	Yes
Glycine schliebenii	Foliage	0.42	0.42	0.42	Yes
Vigna unguiculata	plant top	0.41	0.41	0.41	Yes
Sesbania cinerascens	Foliage	0.40	0.40	0.40	Yes
Sesbania bispinosa	Stem	0.39	0.39	0.39	Yes
Centrosema pubescens	Leaf	0.38	0.38	0.38	Yes
Sesbania aculeata	Whole plant	0.37	0.37	0.37	Yes
Lotononis angolensis	Foliage	0.37	0.37	0.37	Yes
Tithonia diversifolia	Leaf	0.37	0.24	0.56	No

(Developed from the Organic Resource Database).

The plants shown here and many other plants have similar P concentrations to *Tithonia diversifolia*, but are also leguminous. This may give them an advantage over *Tithonia* as they would also be capable of increasing net soil N through nitrogen fixation, as well as transferring soil nutrients from one place to another. *Vicia villosa*, for example, is leguminous, but also has a high concentration of P in its shoots.

The use of plants for P supply clearly necessitates the use of plant biomass transfer – soil P levels can only be increased by transferring it from one place to another. An increase in soil P *in situ* would only occur where significant amounts of P could be extracted from deeper in the soil profile, below the level that can normally be reached by crop roots.

5.2.3 Animal manure

Animal manure can also be used to transfer and increase the availability of P. As well as providing a source of organic P, which is mineralised into soluble P forms, it also provides other organic compounds that can combine with iron and aluminium ions and hydrous oxides to prevent these from reacting with the P to form insoluble compounds. The solubility of calcium phosphates may also be increased with the addition of manure (El-Baruni & Olsen, 1979). Thus, the addition of manure can increase the availability of soluble P; data from El-Baruni *et al*. (1979) suggest that there is a linear relationship between the quantity of manure added and the availability of soluble P in the soil (Figure 5.1).

In an experiment in Madya Pradesh in India, Reddy *et al*. (2000) found that applications of manure over six years significantly increased crop yields as compared with a zero rate of application, at all levels of application (4, 8 and 16 t ha^{-1}), either alone or combined with fertiliser. The results also showed that the application of manure at the equivalent rate of 22 kg ha^{-1} of mineral fertiliser (16 t ha^{-1}) had a greater impact on the yields of both soybean and wheat. This may have been due to the provision of other limiting nutrients, the improvement of soil physical structure, or both. Alternatively, this might also have been because compounds in the manure may have prevented iron and aluminium ions and hydrous oxides from adsorbing P (Table 5.3).

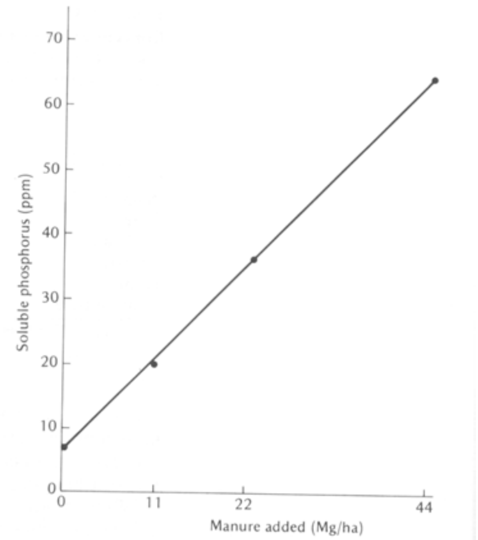


Figure 5.1. The relationship between added manure and soluble P (Source: El-Baruni & Olsen, 1979).

In the combined fertiliser and manure treatment, a response to 16 t ha^{-1} and 22 kg ha^{-1} fertiliser applications was observed in wheat. The soybean result was not significantly different to the combined 8 t ha^{-1} manure and 22 kg ha^{-1} fertiliser treatment, suggesting that large amounts of P would be required to maximise yields. Clearly there was a diminishing marginal crop return to increasing quantities of manure.

Table 5.3: Effect of cattle manure applied at the equivalent rate of 22 kg P ha^{-1} and mineral fertiliser applied at 22 kg P ha^{-1} on soybean and wheat yields in Madhya Pradesh, India.

	Soybean (t ha^{-1})	Wheat (t ha^{-1})	Soybean (% increase over control)	Wheat (% increase over control)
Control	1.13	1.52		
Manure at 22 kg P ha^{-1} equivalent (16 t ha^{-1})	1.98	3.7	85%	218%
Fertiliser (22 kg P ha^{-1})	1.86	3.34	73%	182%

Developed from Reddy *et al*. (2000).

The Organic Resource Database shows that the P concentration in cattle manure can vary from between 0.06-0.67% P, with a mean value of 0.23% P. Clearly, the amount of manure that would have to be applied to satisfy crop P requirements could vary substantially. The P content of manure is largely dependent on the diet of the animal. Poultry manure may also be used as a source of nutrients for agriculture, and in keeping with the general rule that nutrient concentrations are higher in smaller animals, the mean concentration of P in poultry manure is approximately 1.8%, which is significantly higher than the levels recorded for cattle manure.

5.3 Biophysical constraints

Many of the biophysical constraints for low-input P management techniques are similar to those that have already been discussed for SOM and N management technologies. Environmental factors that are not conducive to the growth of plants and animals will limit the quantity of biomass or manure generated, and therefore the quantity of P that can be added to the soil. However, there are factors that influence the availability of P once it is in the soil.

5.3.1 Quantity of biomass

5.3.1.1 *Tithonia diversifolia*

The production of sufficient quantities of biomass to correct P-deficient soils is clearly problematic, for similar reasons to those already discussed for the SOM and N techniques. Jama *et al*. (2000) calculated, assuming mean concentrations of 3.5% for N, 0.37% for P and 4.1% for K, that between 2-4 t DM ha^{-1} should be sufficient to supply crops with N (70-140 kg N ha^{-1}) and K (80-165 kg K ha^{-1}), but that 5 t DM ha^{-1} would be required to overcome moderate P deficiencies, supplying about 18 kg P ha^{-1}. In severely P-deficient soils, even more would be required.

Table 5.4: Tithonia *biomass requirements based on various levels of P fertilisation assuming a mean P concentration of 0.37% in the dry matter, and a dry matter content of 15%.*

Phosphorus requirement (kg ha^{-1})	Dry biomass requirement (t ha^{-1})	Fresh biomass requirement (t ha^{-1})
5	1.4	9.0
10	2.7	18.0
15	4.0	27.0
20	5.4	36.0
25	6.8	45.0
30	8.1	54.0
35	9.5	63.1
40	10.8	72.1
45	12.2	81.1
50	13.5	90.1
55	14.9	99.0

Developed from data in Jama *et al*. (2000).

Jama *et al*. (2000) found that the addition of 50 kg P ha^{-1} of mineral fertiliser to 6 kg P ha^{-1} equivalent of *Tithonia* biomass increased maize yields from 1.3 t ha^{-1} to 4.2 t ha^{-1}. To supply the equivalent P (56 kg P ha^{-1}) using *Tithonia* biomass alone would require about 15 DM t ha^{-1}. Assuming a dry matter content of about 15%, the amount of fresh biomass that would, therefore, have to be cut and transported would be about 100 t ha^{-1} (Table 5.4).

Assuming that a pure *Tithonia* hedge produces about 8 kg fresh biomass m^{-1} (about 1 kg DM m^{-1}) (Drechsel & Reck, 1998), the length of the hedge required to supply 56 kg P would be about 15 km. However, hedges in many areas are not composed purely of *Tithonia*, and this would therefore increase the length of the hedge required to supply adequate levels of P. Additionally, this assumes a recovery rate of 100%; in practice, it is much lower than this, especially for the first crop following application. This would, therefore, necessitate the application of much larger quantities of organic P than the P removed from the farm by the main crop. The application of such large quantities of plant biomass in the soil clearly requires land and labour that is unlikely to be available to resource-poor farmers.

5.3.1.2 Manure

In Rwanda, Roose *et al*. (1997) found that the application of manure at 10 t ha^{-1} and leguminous mulch at 6 t ha^{-1} had no effect on maize yields. Even the effect of applying manure at the rate of 20 t ha^{-1} was limited to a single season, as the yield of the second crop (sorghum), showed no significant difference compared to the other treatments. They calculated that, depending on the P deficiency of the soil and the yield required, between 30-100 kg P ha^{-1} y^{-1} would be needed to provide sufficient P.

In India, Reddy *et al*. (2000) showed that response to P could still be expected even with relatively high applications of P in combined cattle manure and mineral form. Yield responses were observed even at levels of 30 kg P ha^{-1} for soybean and 40 kg P ha^{-1} for wheat. Assuming that the mean concentration of P found in the manure was 0.14%, the amount of manure required to supply 1 ha of soybean with 30 kg P ha^{-1} would be about 22 t ha^{-1}. Similarly, the amount of cattle manure required to supply the wheat with 40 kg P ha^{-1} would be about 29 t ha^{-1}. Clearly, resource-poor farmers will find it difficult to supply quantities of manure at these levels. The provision of so much manure necessitates areas of land for the procurement of fodder and large numbers of cattle. Even if these are available to resource-poor farmers, the amount of labour required to collect and transport the manure may also be problematic. Alternatively, off-farm supplies could be used, but this might require expenditure of capital, again a limitation as far as resource-poor farmers are concerned.

The Organic Resource Database shows that poultry manure has a much higher levels of P than cattle manure. The amount of poultry manure needed to supply the requisite amounts of P would therefore be correspondingly less. Supplying 30 kg P ha^{-1} to a crop would require the application of poultry manure at about 1.7 t ha^{-1} compared to the 21.7 t ha^{-1} of cattle manure (Table 5.5). The labour requirements for transporting the poultry manure would be correspondingly lower. However, finding poultry manure in sufficient quantities could prove to be difficult, and it is unlikely that the numbers of poultry typically found on resource-poor farms at the FAI would supply more than a few kilograms of manure annually.

Supplying animals with sufficient feed is also problematic. Clearly, other advantages in maintaining cattle exist, such as milk and meat. Manure is also widely used as a fuel, which further limits the amount available for nutrient supply functions.

Table 5.5: Cattle and poultry manure requirements based on various levels of P requirement assuming a mean P concentrations of 0. 14% in cattle manure and 1.81% in poultry manure.

Phosphorus requirement (kg ha^{-1})	Cattle manure requirement (t ha^{-1})	Poultry manure requirement (t ha^{-1})

5	3.62	0.28
10	7.25	0.55
15	10.87	0.83
20	14.49	1.10
25	18.12	1.38
30	21.74	1.66
35	25.36	1.93
40	28.99	2.21
45	32.61	2.49
50	36.23	2.76
55	39.86	3.04

Developed from data in Reddy *et al*. (2000) and the Organic Resources Database.

5.3.2 Nutrient mining by Tithonia

The particular characteristic of *Tithonia diversifolia* is its ability to scavenge relatively large quantities of P from the soil and to provide biomass with relatively high concentrations of P for incorporation as organic matter. However, it does not add to the net amount of P in the soil in the same way that legumes do with N by fixing it from the atmosphere. Clearly, *Tithonia* will eventually mine the soil of P and other nutrients, and in an on-farm situation this is unsustainable. Unless resource-poor farmers have access to large areas of common land under *Tithonia*, it is unlikely that the system can be sustained for long periods of time. One solution might be to fertilise the on-farm biomass banks or hedges, but in this case farmers may as well fertilise the crops directly.

5.3.3 Phosphorus adsorbtion in soils

In most soils, at any one time, a large proportion of P is unavailable to the plant, even though there may adequate P in the soil to satisfy the requirements of the crop if it could be made available. Phosphorus is rapidly adsorbed, and this plays a major role in limiting the amount of P that is available to plants.

5.3.4 Soil pH

Soil pH also plays a major role in determining the availability of P to plants. Where soils are very acidic, the dominant form of soluble P tends to be $H_2PO_4^-$. At *p*H values between 6-7, the $H_2PO_4^-$ and HPO_4^{2-} forms predominate, whereas in very alkaline soils, the dominant form is PO_4^{3-} (Brady, 1990).

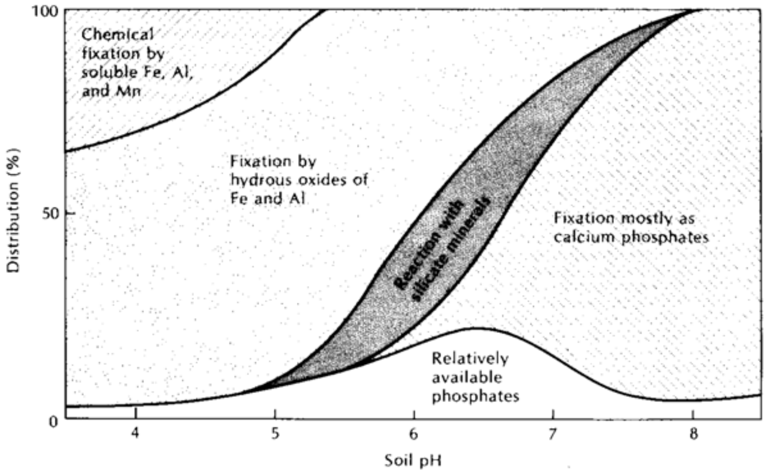


Figure 5.2. The fate of phosphorus at various pH values, showing the relative increase in availability between pH 6-7 (Source: Brady, 1990).

The amount of P in normal mineral soils is also complicated by the presence of other elements. In acid mineral soils, the presence of soluble iron, aluminium and manganese ions or hydrous oxides of these elements, such as gibbsite and goethite, generally occur in much larger quantities than the $H_2PO_4^-$ ions. These combine with the $H_2PO_4^-$ ions to form hydroxyl phosphates that are insoluble and therefore unavailable to plants. The amount of P fixed by the ionic and hydrous forms of iron, and aluminium in particular, is believed to be extremely large, occurring over a wide pH range. As well as being adsorbed by hydrous oxides of iron and aluminium, and ions of iron, aluminium and manganese, in moderately acid soils, adsorbtion may also occur with silicate clays such as kaolinite, although the exact mechanism is not yet fully understood (Brady, 1990).

In alkaline soils, the availability of P to plants is largely determined by the solubility of calcium compounds in which the P is found. There are a number of inorganic calcium compounds of P, and when $H_2PO_4^-$ ions are added (e.g. in fertiliser), the conversion of $H_2PO_4^-$ ions into calcium phosphates can be relatively fast. While monocalcium phosphate is relatively soluble, a compound such as florapatite is thousands of times less soluble. The availability of soluble P in alkaline soils may, therefore, be as low as in acidic soils (Brady, 1990).

5.3.5 Ageing and phosphorus availability

When large amounts of P ions are added to the soil, the availability of soluble P is relatively high for a short time. Even when some adsorbtion of P has taken place, much of it may still be effectively available, as an equilibrium exists between the soluble P fraction and that adsorbed on the surface of the soil particles, termed the 'labile' fraction. Uptake of the soluble ions by plants can result in a fairly rapid release of the adsorbed P back into solution to redress the balance. However, with time, the adsorbed P migrates towards the centre of the soil particles and its effective availability decreases, greatly reducing the amount that is soluble and available for plants (Brady, 1990). Clearly the ageing process is of significance to resource-poor farmers at the FAI, as P that has been added becomes increasingly unavailable to plants even though the original quantities of P may have been large.

5.3.6 Soil texture

There is a strong relationship between the adsorption of P and the quantity of clay in a soil, particularly if this clay is rich in Fe and Al oxides, and if it is amorphous rather than crystalline (Figure 5.3). This is because most of the compounds that react with P tend to be held in the finer soil fractions (Brady, 1990). Clearly, the success of P management techniques will depend on the amount of clay in the soil. In soil with a high clay content, the adsorbtion of P may also be high and it is likely that the effects of any P-enhancing technique will be reduced (Brady, 1990).

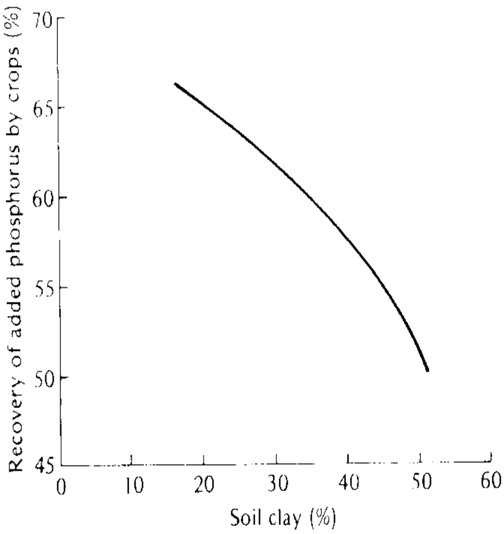


Figure 5.3. The relationship between soil clay content and the recovery of added phosphorus by crops (Source: Olsen et al., 1977).

Texture also influences the concentration of P in the soil solution. Although critical values vary for different crops, data from Fox (1981) suggests that in general, if the concentration is above 0.2 mg kg^{-1}, the supply of P to most crops should be adequate (Table 5.6). In sandy soils, the quantity of P in labile form required to supply a given amount of P to the soil solution is far less than for a soil high in clay. This is because much less of the P is fixed in combination with the iron, aluminium and magnesium typically found in clayey soils.

Thus, much more P needs to be applied to a heavy soil to supply the same amount of P to the plant than in a light soil. However, the corollary to this is that the amount of soluble P is much more rapidly reduced by crop uptake in a light soil than in a heavy soil. Clearly, the issue of soil texture is important in the management of soil P. The use of P-enhancing techniques is likely to be more successful in light soils than in heavy soils, because P is much more mobile in the former.

Table 5.6: Critical P concentrations in soil solution required for various crops for two different soils in Hawaii.

Crop	Soil	Approximate P in soil solution ($mg\ kg^{-1}$)
Cassava	Halii	0.005
Peanut	Halii	0.01
Corn	Halii	0.05
Soybean	Halii	0.20
Cabbage	Kula	0.04
Tomato	Kula	0.20
Head lettuce	Kula	0.30

Developed from Fox (1981).

5.3.7 Microbial immobilisation of P

Microbial immobilisation of P can be problematic in much the same way as for nitrogen. When P is added to the soil through animal manure or plant residues, there may be a temporary shortage of P available to plants as the soil micro-organisms multiply in response to the increase in carbon substrate and also take up P at the same time. This may be of significance to a crop if it happens during a critical period of the growth cycle (Brady, 1990).

5.3.8 Soil organic matter content

In the context of the FAI, the availability of soluble P may be largely determined by the quantity of organic matter in the soil. Not only does organic matter contain P which can potentially be mineralised, but also certain organic compounds form complexes with Fe and Al ions and hydrous oxides, thereby preventing them from adsorbing soluble P ions. However, there is a counter to this, as humic compounds in the soil can also combine with organic P, protecting it from mineralisation, and, in turn, reducing the availability of soluble P to plants. The actual effect will depend on the balance of these various processes (Brady, 1990).

5.4 Socio-economic constraints

As low-input P management technology is essentially organic matter management technology, most of the generic constraints already discussed are also applicable here. In the following sections, we discuss these in the context of the specific P techniques we have just described.

5.4.1 Labour

The cutting and carrying of *Tithonia* is extremely labour intensive, particularly if it is to supply the full crop P requirements in a P-deficient soil (Buresh & Niang, 1997). Data from ICRAF (1997) suggest that a single person can harvest between 83-120 kg FW day^{-1}. For a typical crop requirement of 18 kg P ha^{-1} the application of about 5 t DM ha^{-1} of *Tithonia* biomass would be needed, equivalent to about 33 t ha^{-1} of fresh biomass. Harvesting at the rate of 120 kg FW day^{-1}, it would take 275 days of labour just to harvest the leaves. Clearly, it would require many man-days of labour to harvest the biomass required to supply the required quantities of P, particularly in very P-deficient soils (Table 5.7).

Table 5.7: Estimated labour requirements for the harvesting of Tithonia *biomass required to supply various levels of P, assuming a harvesting capacity of 120 kg FW day^{-1}.*

Phosphorus requirement (kg ha^{-1})	**Green biomass requirement (kg ha^{-1})**	**Labour requirement (days ha^{-1})**
5	9.01	75
10	18.02	150
15	27.03	225
20	36.04	300
25	45.05	375
30	54.05	450
35	63.06	526
40	72.07	601
45	81.08	676
50	90.09	751
55	99.10	826

Developed from ICRAF (1997) and Jama et al. (2000).

Tithonia also needs to be propagated and prepared for incorporation in to the soil (ICRAF, 1997). The implication of this is that labour must therefore be plentiful and cheap, or that the crops fertilised with *Tithonia* should be high-value crops. This is particularly so at the rate of application that can be managed by most resource-poor farmers. In western Kenya, Jama *et al*. (2000) cited data from ICRAF showing that under farmer-managed conditions, investing in *Tithonia* fertilisation was viable for high value kale (*Brassica olecacea*), but uneconomical when used with a low-value crop such as maize.

Although *Tithonia* has no thorns, it is sticky and exudes a pungent smell which does not facilitate handling (Jiri & Waddington, 1998). Also, because of its ability to regenerate, *Tithonia* may invade farmland, thereby increasing the labour required by a farmer to control it (Jama *et al*., 2000).

Supplying sufficient P through animal manure is also problematic. Large quantities are required to supply fairly small amounts of P. For example, the supply of 30 kg P ha^{-1} through cattle manure would, assuming a mean concentration of P of 0.138%, require 22 t manure ha^{-1}. Assuming that the farmer had to transport the manure manually, and that he/she could lift and carry 20 kg of manure per load at 5 km hr^{-1}, and that this load had to be transported 100 m from the source, supplying this 30 kg P would require about 44 hours of labour. In comparison, poultry manure, supplying the same amount of P a similar distance, would require only about 3.3 hrs.

Table 5.8: Estimate of the time needed for a single person to transport cattle and poultry manure 100 m, assuming transport by head-load at a mean speed of 5 km hr^{-1} with a mean load of 20 kg.

P requirement (kg ha^{-1})	Cattle manure needed (t ha^{-1})	Time needed to transport cattle manure 100 m (hrs)	Poultry manure needed (t ha^{-1})	Time needed to transport poultry manure 100 m (hrs)
5	3.6	7.2	0.3	0.6
10	7.3	14.5	0.6	1.1
15	10.8	21.7	0.8	1.7
20	14.5	29.0	1.1	2.2
25	18.1	36.2	1.4	2.8
30	21.7	43.5	1.7	3.3
35	25.4	50.7	1.9	3.9
40	29.0	58.0	2.2	4.4
45	32.6	65.2	2.5	5.0
50	36.2	72.5	2.8	5.5
55	39.9	79.7	3.0	6.1

Loads may often have to be carried much further than this, and where large amounts of manure have to be transported long distances, it will be difficult for farmers to provide the labour required. Where the manure has to be transported in mountainous terrain, the amount of time required to transport the manure will be even more. In Nepal, farmers are unwilling to transport large quantities of biomass uphill, although evidence suggests that they are prepared to transport biomass downhill.

5.4.2 Land

We have already seen that the quantity of biomass required to supply P to an effective level is considerable. To supply the 33 t FW ha^{-1} in the example given above, and assuming that a pure *Tithonia* hedge produces about 8 kg FW m^{-1} in a biannual pruning cycle (about 1 kg DM m^{-1}), the length of the hedge required would be about 5 km (Drechsel & Reck, 1998). However, hedges in many areas in Kenya are not composed purely of *Tithonia* and may supply as little as 0.2 kg DM m^{-1} of useable biomass. This would increase the length of hedge required to supply 18 kg P to about 25 km.

A landholding that is 1 ha in area, with a 400 m perimeter hedge of *Tithonia* producing 1 kg DW m^{-1} from biannual pruning, would therefore supply only 0.4 t DM ha^{-1} (Jama *et al*., 2000), or about 1.5 kg P ha^{-1}. Although the perimeter-to-area ratio increases as the size of the landholding decreases, and therefore the effective production of *Tithonia* increases, field size would have to be extremely small to supply the nutrient needs of many crops to the extent that almost all of the farm would be growing *Tithonia*!

In western Kenya, *Tithonia* biomass grown in pure stands contained the equivalent of 7.8 kg P ha^{-1} (Jama *et al*., 2000). This would necessitate setting aside about 2.3 hectares of land to supply 18 kg P ha^{-1} to a main crop on a single hectare of land. In the highly P-deficient soils described by Jama *et al*. (2000), where response to P fertilisation occurred even at a rate as high as 56 kg P ha^{-1}, the area of land required for growing *Tithonia* would be about 7 ha. Also, the 7.8 kg P ha^{-1} mentioned above includes the woody stem material – in most cases, farmers would only apply leafy biomass because it of its higher quality. This would contain only about 3.2 kg P ha^{-1}, which would more than double the area of land required.

Values for length of hedge and area of land are shown for typical P concentrations in *Tithonia* biomass and for typical values of biomass production per unit area of land in western Kenya (Table 5.9).

Table 5.9: The length of Tithonia *hedge and land area required to supply various levels of P, assuming that the hedge produces 0.4 kg DM m^{-1} of useable biomass with a concentration of 0.37% P and that the* Tithonia *produces 8.4 t DM ha^{-1} biomass (P yield of 3.2 kg P ha^{-1} from leaves and litter (1 t DM ha^{-1}) which is the immediately useable as green manure), and a total P yield of 7.8 kg P ha^{-1} with stem material, after 8 months.*

Phosphorus requirement (kg)	Hedge (km)	Leaves and litter (ha)	Leaves, litter and stems (ha)
5	3.4	1.6	0.6
10	6.8	3.1	1.3
15	10.1	4.7	1.9
20	13.5	6.3	2.6
25	16.9	7.8	3.2

Developed using data from the Organic Resources Database and Jama *et al*. (2000).

Clearly, large amounts of *Tithonia* biomass are required to supply enough P for most crops, which farmers are unlikely to be able to produce on their own farms. It may be possible for some of this requirement to be obtained from common resource pools, although if many farmers are involved, extensive areas of land would be required.

5.4.3 Knowledge

In many areas, *Tithonia* is already used as a material for composting. However, there appears to be less use made of it as a high quality green manure that can be applied to the fields directly. Jama *et al*. (2000) suggest that there is merit to applying it directly, but do not say what the advantages and disadvantages are of doing this compared to composting. If direct application does prove to be a better method of application, this information needs to be disseminated to farmers.

5.4.4 Competing demands for resources

The area occupied by hedgerows of *Tithonia* represents valuable space that is often needed for other plants. Trees or annuals might be grown for fodder, food, fuel or construction material, all of which may be at least as important, if not more so, as the nutrients supplied by *Tithonia*. Clearly, there are competing demands for the resources used by *Tithonia*, and the overall impact may be to greatly reduce the amount of *Tithonia* that can be grown to a level that is inadequate for satisfactory P supply to crops.

5.5 Summary

Clearly, the use of *Tithonia* biomass offers only a marginal solution to any phosphorus problems facing resource-poor farmers at the FAI. This does not detract from the value of using it as far as possible to augment SOM and offer partial solutions to other nutrient problems. Although *Tithonia* has relatively high concentrations of P in its biomass, this is not sufficient to meet the needs of most crops without access to large areas of land and large quantities of labour. In addition, as *Tithonia* is not capable of adding nutrients from the atmosphere, as with biological N fixation, at best its use results in a transfer of nutrients within the landscape, and at worst, there is the danger that soil nutrients will be mined. *Tithonia* might, however, be used in conjunction with P fertiliser, as it supplies other nutrients and micro-nutrients in relatively high quantities that are essential for good crop growth. The addition of large amounts of organic matter to the soil is also important for good soil structure.

It is important to determine the economics of different ways of using *Tithonia* biomass. Research suggests that *Tithonia* is most usefully applied in relatively large amounts to small areas of high value crops (Jama *et al*., 2000), and future research should examine what options are available to the farmer under realistic quantities of *Tithonia* biomass supply. There may also be some merit in determining how best to apply *Tithonia* to soils, as most of the trials in western Kenya involved spreading it over the field and incorporating it just before planting of the main crop (Jama *et al*., 2000). Leaving the biomass to dry and decompose on the soil surface may be relatively wasteful; further research could determine if there are more effective methods of application.

Management strategies also need to be developed to reduce the amount of labour that is required to cut, carry and incorporate biomass before planting of the main crop. For example, split applications of *Tithonia* may spread the labour load and allow farmers to use the technique more effectively. It is imperative to shift the labour demand for *Tithonia* use away from the peak labour demand of other more essential farming operations.

Manure is a useful source of P, but this also requires the application of large quantities. Where cattle are allowed to graze freely over large areas of land, collecting manure to apply to crops may be impractical. Where cattle are stall-fed, on the other hand, the manure can be collected relatively easily. However, it should be noted that there are competing demands for manure, especially for use as a fuel, which overrides its importance as a source of P, SOM or N, in many cases. Stall-fed cattle, which are only likely to be found in land-scarce areas, may also require relatively large amounts of labour, and the ability of resource-poor farmers to supply full P solutions with manure is limited, unless they have access to it from off-farm sources. Again, it may be best to view it as a partial solution to the problem of P supply to be used in a niche context along with other organic matter management techniques.

6 Weed control

6.1 Introduction

The impact of weeds on the yields of field crops is of great significance in both temperate and tropical agriculture. Estimates suggest that globally up to 12% of all agricultural crops are lost to weeds, although this figure may be as high as 25% in certain tropical countries. Much energy and expense may be involved in controlling weeds and if allowed to proliferate, weeds can make agriculture unprofitable altogether (Auld *et al*., 1987). Weeding crops manually increases the drudgery of agricultural labour, increases agricultural labour requirements, and reduces the area of land that can be cultivated (Gallagher *et al*., 1999).

Weeds share some common characteristics (Auld *et al*., 1987). In general, they are plants that are ecologically well adapted to the ecosystem provided by agricultural activity, which is why they proliferate. They grow rapidly, reproduce abundantly, and disperse easily, usually as a result of human activity. Their reproductive structures may also survive for long periods of time in the soil. They compete for resources such as water, light and nutrients, reducing crop yields as a result. They may also make agricultural operations, such as harvesting, difficult to undertake, and some weeds may cause physical damage or are poisonous to humans and animals (Auld *et al*., 1987).

For many FAI farmers, the problem of controlling weeds on their farms may be of more immediate importance than the long-term issue of maintaining soil fertility (Pound *et al*., 1999). Yet in humid tropical regions, weeds can grow year round (Rouw, 1995). Various methods are available to control weeds, which can be grouped into physical, chemical, biological, ecological, and integrated methods. Resource-poor farmers at the FAI tend to use physical methods, such as manual weeding of the plots cleared for cultivation or the use of fire, and ecological methods. The secondary vegetation that regenerates naturally in traditional shifting cultivation or long fallow systems, helps to suppress weed development and to reduce the viability of weed seed bank populations, by influencing the temperature, water content, chemistry and microbial activity of the soil (Gallagher *et al*., 1999). Controlling weeds has become increasingly important as traditional techniques of allowing long periods of fallow to break the life cycle of invasive weed species are becoming less suitable as pressure on land resources increase. Castro (1994) found that a ten-fold increase in weed population was associated with a five-fold reduction in grain yield. Being poor, these farmers were unable to afford the more capital-intensive inputs required to control weeds in an increasingly settled system of production.

The high labour requirement for manual weeding places an upper limit on the total area of land that can be cultivated by an individual resource-poor farmer. Reichelderfer (1984, cited in Auld *et al*., 1987) has suggested that were labour to be released from the task of weeding it could be used to increase the area of land cultivated by resource-poor farmers. Various authors cited by Auld (1987) have also suggested that there appears to be considerable scope for improving the design of implements used in weeding so that weeding efficiency can be increased.

6.2 Weed suppressing techniques

There are various techniques for suppressing the build-up of weeds. Traditionally, resource-poor farmers have used forest fallows or bush fallows as ways of controlling weeds (Boserup, 1981; Rouw, 1995). Boserup (1981) has also outlined the use of fire and of various tillage methods, such as the hand-hoe and the plough, to suppress weed populations.

DFID NRSP projects have focused on improving the technologies available in the ecological suppression of weeds, for example, by using cover crops such as *Canavalia ensiformis*, *Mucuna pruriens*, and *Crotalaria juncea.* The main characteristic of these in relation to weed control is to provide rapid and spreading growth that suppresses the growth of weeds by dominating them, whilst at the same time fixing N, providing protection to the soil from rain, and helping to reduce surface evaporation.

6.2.1 Cover crops

Bourke (1975) has described the characteristics that an 'ideal' cover crop should have. It should be able to grow and produce rapid ground cover. It should be capable of competing with weeds and prevent erosion. High biomass production, leaf production and litter fall is desirable. Ideally it should also be able to fix nitrogen leave and residual N for following crops. Additional benefits such as utility as food or fodder would also be useful, as would strong resistance to diseases and pests. It is unlikely that any single cover crops species can fulfil all these needs. This is particularly so where conditions vary dramatically within short distances, such as in the mountainous environment of Nepal (Keatinge *et al*., 1998).

Evidence suggests that the effects of cover crops are noted and appreciated by farmers. In Ghana, in on-farm trials, Jackson *et al*. (1999) found that farmers were impressed by the ability of *Mucuna pruriens* and *Canavalia ensiformis* to suppress weeds. Both species were found to grow rapidly and to spread, thereby shading out and suppressing weed growth. Farmers also felt that cover crops used as green manures increased the water holding capacity of the soil, and that they also 'cooled' the soil by protecting it from the sun and thereby reducing evaporation. Farmers in both Bolivia (Pound *et al*., 1999) and Ghana (Kiff *et al*., 1999) have observed that the use of particular cover crops such as *Mucuna pruriens* appears to make the soil darker, softer or moister. Pound *et al*. (1999) found that growing *Mucuna pruriens* for a year reduced the bulk density of soil - soil penetrometer readings were 21 kg cm^{-1} in the *Mucuna pruriens* plots after one year compared to 76 kg cm^{-1} in the control plots.

In the Santa Cruz Department of Bolivia, the use of *Canavalia ensiformis*, *Mucuna pruriens*, *Mucuna nivea* and *Dolichos lablab* as winter fallow in rice cultivation systems was examined (Southgate *et al*., 1999). In experiments aimed at trying to find an improved winter cover, data showed that yields of rice increased following the use of the four legume cover crops as compared to those following a weedy winter fallow. The effect of these treatments on weed growth is shown (Table 6.1). The best, *Macuna nivea*, was able to reduce weed biomass by as much as 40% compared to the weedy fallow, and even the least effective, *Dolichos lablab*, gave an 18% reduction in weed growth. .However, in most cases, the summer weed growth appeared to be greater in the plots with a cover crop than a weedy fallow. For *Mucuna pruriens* this increase was significant ($P<0.05\%$).

Table 6.1: Effect of Canavalia ensiformis*,* Mucuna pruriens*,* Mucuna nivea*, and* Dolichos lablab *and a weedy fallow on weed populations in winter and summer in Bolivia (Source: Southgate et al., 1999).*

Winter cover crop	**Biomass of weeds in winter ($g\ m^{-2}$)**	**Biomass of weeds in summer ($g\ m^{-2}$)**
Weedy fallow	689.4	789
Canavalia ensiformis	492.2	839
Mucuna pruriens	453.7	1069
Mucuna nivea	414.6	988
Dolichos lablab	565.6	777
S.E.D	68.84	106.4
F test probability	P<0.001	P<0.05

Curran *et al*. (1994) have suggested that cover crops can reduce weed populations by minimising the accumulation of weed seeds during the winter and inhibiting weed seedling germination and development. Gallagher *et al*. (1999) and Rouw (1995) have noted that one of the major functions of fallow periods may be to reduce the viability and number of weed seeds in the seed bank. However, in this case Southgate *et al*. (1999) suggested that there appeared to be little evidence that the effects of weed suppression during the winter fallow were being carried over into the next cropping cycle, indicating that additional measures would be needed to control weeds.

Table 6.2: The effect of Canavalia ensiformis*,* Mucuna pruriens*,* Mucuna nivea*, and* Dolichos lablab *and a weedy fallow on seedling emergence, total dry biomass and grain yield in Bolivia (Source: Southgate et al., 1999).*

Winter cover crop	**Seedling emergence (plants m^{-2})**	**Total dry biomass ($g\ m^{-1}$)**	**Total dry grain yield ($g\ m^{-1}$)**
Weedy fallow	19	68	27
Canavalia ensiformis	77	404	162
Mucuna pruriens	59	260	112
Mucuna nivea	72	403	174
Dolichos lablab	40	130	52
S.E.D	14	55	21
F test probability	P<0.01	P<0.001	P<0.001

Although, the cover crops (especially *Canavalia ensiformis* and *Mucuna nivea*) increased the concentration of N, K, Mg and Na to some extent, the major reason for the improved rice crop yields appears to have been due to the protection given by the legume residues to emerging rice seedlings (Table 6.2). The weedy fallow produced much less biomass, and therefore provided less protection for the soil and seedlings, in particular from the heavy rainfalls about five days after sowing. These visibly waterlogged those plots without residue, and the soils formed caps after they dried (Southgate *et al*., 1999). Linear regression across all four cover crops indicated a strong positive relationship between the total quantity of biomass produced by the cover crops and rice yields (Southgate *et al*., 1999).

Pound *et al*. (1999) looked at the effect of sowing rice and the legume *Calopogonium mucunoides* simultaneously on 20 validation plots. Although farmers noted some reduction in weed populations, they also indicated that *Calopogonium* tended to dominate the rice, causing it to lodge, and that the difficulty of harvesting the rice also increased. Farmers therefore suggested that it might be useful to undertake trials aimed at establishing more suitable sowing densities and times of planting. Thus, in further researcher-led trials, Pound *et al*. (1999) looked at the effect of planting *Calopogonium* as an intercrop with main season rice on weed control and crop yields. The *Calopogonium* was planted as a relay intercrop at different times into the rice crop: at 25 and 45 days after sowing (DAS) the rice crop, and also after the rice crop was harvested. These trials were undertaken on long cycle (120 day) rice and short cycle (90 day) rice, with sowing densities of 4 and 8 kg seeds ha^{-1}. The treatments were organised in a randomised block design with 4 replicates. The crop management practices, including weeding, were similar to farmer practices. The trials was conducted over three years.

There appeared to be little practical difference on *Calopogonium* cover due to the different densities of seed sowing and as a result the lower density might be recommended. However, the earlier sowing of the *Calopogonium* (25 DAS) appeared to be the most successful in reducing weeds compared to the other two treatments. This may have been because growing conditions would be fairly optimal at this time and also because the rice might have been too immature to as yet pose a major competitive threat to the *Calopogonium*. Biomass cover and residues for the 25 DAS treatment were maintained at a good level throughout winter and until the next cropping season. The least successful means of providing good ground cover appears to have been through the post-harvest planting of *Calopogonium*, where growth was reduced, possibly as a result of cold and dry conditions at this time. The 45 DAS treatment was intermediate and may have suffered as result of the competition experienced from the rice, which was more mature, when *Calopogonium* was sown in at this time.

As the establishment of a uniform rice crop was important, to ensure that the effect of different sowing dates on *Calopogonium* establishment could be determined, the cover crop residue was burnt before the planting of the rice. This may have prevented the possibility of determining the overall benefits from the *Calopogonium* as a cover crop, especially as the benefits to the soil physical qualities and biologically fixed N, which is removed by burning (Nye & Greenland, 1960), may have been reduced. The advantage perhaps is that the results may have produced a more direct assessment of the *Calopogonium* on weed populations (Pound *et al*., 1999). The cover crops generally appeared to demonstrate relatively good weed-suppressing abilities in comparison to the traditional weedy fallow (Table 6.3). The 25 DAS treatment showed a distinct advantage over the other treatments. Nevertheless, despite these differences, there was still a large increase of grass and broad-leaved weeds in all treatments, with counts in the 25 DAS treatment in the third year more than 300-400% of the first year's count (Pound *et al*., 1999). This suggested that *Calopogonium* alone is not able to maintain weed populations at a manageable level.

Table 6.3. The experimental effect of different Calopogonium *treatments on the population of grass and broad-leaved weeds in a rice based cropping system in Bolivia (Source: Pound et al., 1999).*

	October 1996		**October 1997**		**October 1998**	
Treatment	**Grass**	**Broad-leaves**	**Grass**	**Broad-leaves**	**Grass**	**Broad-leaves**
25 DAS	6.06	10.81	16.06	18.87	19.37	44.81
45 DAS	7.87	10.96	20.12	28.31	32.75	49.43
Post-harvest	7.18	16.78	69.68	76.43	35.12	80.00
No *Calopogonium*	10.50	20.18	48.87	69.75	55.50	65.12
S.E.M of treatment	6.06	1.34	6.07	5.33	4.64	4.89
S.E.M. of control	10.50	1.9	8.58	7.54	6.57	6.91

With the 25 DAS treatment, the weeding and total labour requirement of the system was reduced and rice yields increased slightly (Table 6.4). However, although these increases were statistically significant, the magnitudes of the differences were so small as to have little practical relevance to the farmer. The cumulative yield difference between the manual treatment and the highest intercropped system in Site 1 was about 100 kg ha^{-1} after three years. For the less fertile area in Site 2 the difference was greater (about 500 kg ha^{-1}) after three years. However, even this amounts to an average yield difference of about 150 kg ha^{-1} per year, and would probably be unable to make any practical difference to the livelihoods of resource-poor farmers living at the FAI.

Table 6.4: Yields (kg ha^{-1}) as a result of planting Calopogonium *with rice 25 days after sowing (25 DAS), 45 days after rice sowing (45 DAS) and post harvest of rice, compared with manual weeding. (Source: Pound et al., 1999).*

Sowing date	**Year 1**	**Year 2**	**Year 3**	**Total**
25 DAS				
(Site 1)	4258	1818	1452	7528
(Site 2)	2143	893	714	3750
45 DAS				
(Site 1)	4224	1708	1602	7534
(Site 2)	2378	889	743	4010
Post-Harvest				
(Site 1)	4406	1904	1226	7536
(Site 2)	2108	740	599	3447
S.E.				
(Site 1)	129	87	125	
(Site 2)	99	52	49	
No Calopogonium				
(Site 1)	4210	1781	1473	7464
(Site 2)	2199	743	596	3538

The yield decline over the three years of the trials was similar in all treatments, and the increase in weed biomass over this period, despite the use of *Calopogonium*, clearly demonstrate that the use of a cover crop in this case does not contribute a practical improvement to the farming system. There was no evidence that weed control with cover crops could either increase crop yields or lengthen the duration of the cropping period. It should be noted that it is difficult to determine to what extent the decline in rice yield was due to the decrease in fertility of the soil over three years and to what extent it was due to the invasion of weeds. However, it seems reasonable to expect that the weeds are major contributors to yield decline.

6.2.2 Integrated weed control

Where possible, farmers often use an integrated approach to weed suppression, applying herbicide to dense patches of weeds, hand-hoeing or tilling, burning and using cover crops in their efforts to suppress the weed cover. Further trials were undertaken to determine if an integrated combination of approaches could improve the suppression of weeds (Pound *et al*., 1999). Five management options were selected that attempted to vary the inputs primarily according to the resources already available to the farmers (Table 6.5). Trials were conducted over a period of two years on both long-duration (120-day) and short-duration (90-day) rice varieties. All the treatments also included a second weeding at 70 DAS, which was later than the traditional practice, to try and prevent the development of weeds. The herbicide treatments were half the recommended dose in order to reduce costs. As farmers generally apply herbicide strategically rather than blanket apply, the total quantity used was similar (Pound *et al*., 1999).

Table 6.5: Treatments undertaken to find improved farmer level input strategies for weed suppression in Bolivia. (Source: Pound et al., 1999).

Treatment No.	Treatment description
1	Hand hoeing at 20-25 DAS and 70 DAS
2	Hand hoeing at 20-25 DAS and machete/hand pulling at 70 DAS
3	Reduced dose 2, 4-D (0.5 l ha^{-1}) at 15 DAS; hoeing at 25 DAS and machete/hand pulling at 70 DAS
4	Reduced dose propanil (4 l ha^{-1}) at 15 DAS; hoeing at 25 DAS and machete/hand pulling at 70 DAS
5	Reduced does 2, 4-D (0.5 l ha^{-1}) and reduced dose propanil at 15 DAS; hoeing at 25 DAS and machete/hand pulling at 70 DAS

Variations between these treatments were found. In particular, treatments 3 and 5 performed better than treatments 1, 2 and 4. However, none of the treatments alone was sufficient to prevent a considerable increase in weed density between years 1 and 2, and a shift from a predominantly broad-leaved weed flora in year 1 to a grass dominated flora by year 2. The treatments did, therefore, appear to be having some effect on the populations of broad-leaved weeds. The grass weeds, which were the main target of the trials, were still able to proliferate, despite the various modifications to the system examined by the trial (Table 6.6).

Table 6.6. The effect of integrated weed management strategies at typical farmer levels of input on the development of Cyperaceae, and grass and broad-leaved weeds (Source: Pound et al., 1999).

		Year 1			Year 2	
Treatment	**Grass**	**Broad-leaves**	**Cyperaceae**	**Grass**	**Broad-leaves**	**Cyperaceae**
1						
(Site 1)	8.3	70.2	5.0	65.9	53.1	4.9
(Site 2)	14.5	28.6	79.3	30.5	65.1	43.5
2						
(Site 1)	8.8	66.5	9.2	65.2	49.2	9.5
(Site 2)	13.6	31.0	74.5	35.2	54.1	52.0
3						
(Site 1)	12.0	49.0	15.5	51.2	25.1	12.8
(Site 2)	11.5	21.4	63.3	42.7	28.1	35.6
4						
(Site 1)	2.7	47.9	7.1	27.8	38.7	4.6
(Site 2)	9.7	29.0	85.1	23.9	44.7	41.3
5						
(Site 1)	2.7	36.4	5.0	20.5	12.1	6.3
(Site 2)	13.8	24.7	77.2	24.9	14.6	28.4
S.E.D						
(Site 1)	2.7	8.8	0.5	10.5	8.33	4.1
(Site 2)	2.6	3.8	10.7	7.43	7.89	9.8

The development of weed flora was generally similar to that observed under traditional practices and was accompanied by a decline in crop yield, again similar to that in the traditional system (Pound *et al*., 1999). Rice yields in Year 1 in all the treatments were substantially greater than in Year 2 (Table 6.7). The data does suggest that some benefit may be gained from the relatively early control of weeds with herbicides, although the evidence indicates that sustainable agriculture may be difficult to achieve at farmer levels of input, especially under continuous cropping regimes. At some point, there may be no choice but to fallow the land for a number of years (or apply capital intensive chemicals for weed control, if the farmer is wealthy enough).

Table 6.7. The effect of weed development on the yield of rice (kg ha^{-1}) under integrated weed management strategies at typical farmer input levels (Source: Pound et al., 1999).

	Site 1		Site 2	
Treatment	**Year 1**	**Year 2**	**Year 1**	**Year 2**
1	4045	2234	2585	1131
2	4073	2219	2600	1025
3	4423	2571	2751	1149
4	4107	2468	2650	1041
5	4547	2681	2789	1259
SED	88	117	58	84

Pound *et al*. (1999) did find that weeds could be controlled with the integrated use of cover crops, herbicides and burning, so long as sufficient time was available. Some farmers, who had abandoned banana plots to *Imperata contracta*, managed to bring it under control through the integrated use of *Mucuna pruriens*, herbicides and burning. The process appears to have required at least two years of this integrated management, but has now allowed the farmers to return the land to more intensive use without the expense of having to blanket apply herbicide at high levels. Pound *et al*. (1999) further suggested that future options may be to try and develop techniques that integrate the use of the mechanical and chemical measures described above with the relay intercropping of *Calopogonium* or *Mucuna*, to suppress the development of weeds over the fallow winter period.

6.3 Biophysical constraints

6.3.1 Cover crops

There may be several important factors limiting the ability of cover crops to make a significant contribution to weed suppression. The most important of these are related to the ability of the cover crop to compete effectively with weeds for environmental resources.

6.3.1.1 Ineffective competition with weeds for environmental resources

Weeds by definition are aggressive plants and the cover crop may simply be unable to compete with them for environmental resources. Any biophysical factors that limit plant growth in general will therefore also limit the effectiveness of cover crops in suppressing weeds. These factors have been explored in the previous sections outlining the biophysical limitations of low-input SOM, BNF, and P-mobilising techniques. Adverse climatic conditions, such as very high or very low temperatures, inadequate rainfall will severely restrict plant growth. Pound *et al*. (1999) noted, for example, that the growth of *Mucuna pruriens* and *Calopagonium* was reduced when sown in winter. Whereas *Mucuna* seemed to tolerate wider climatic extremes, *Calopogonium* growth was reduced by flooding. Lack of macro and micro nutrients may reduce the ability of cover crops to compete with weeds which, after all, owe their presence to the fact that they are better suited to local conditions than other plants in the area. Some weeds may simply be capable of surviving the competition from cover crops.

6.3.1.2 Insufficient spatial coverage

Cover crops need to have an appropriate canopy architecture. A spreading cover crop is more likely to suppress weeds than a cover crop that has an erect habit. For example, in trials in rice systems, in the Ichilo Sara area of Bolivia, Pound *et al*. (1999) noted that the performance of *Arachis pintoi* as a cover crop was highly variable and rejected by farmers due to its inability to suppress weeds, largely as a result of poor growth and lack of full cover. It grew slowly, and was ineffective in controlling *Imperata contracta*. Similarly, in Ghana, Jackson *et al*. (1999) found that *Cajanus cajan* (pigeonpea) was low yielding, whilst at the same time being slow-growing and incapable of suppressing weeds due to its poor ground coverage.

However, even the use of aggressive cover crops that spread and shade well may fail to suppress the growth of certain shade tolerant weed species. Pound *et al*. (1999) found that even *Mucuna pruriens* and *Calopogonium mucunoides* could not suppress the growth of weed species such as *Panicum* spp., *Axonopus compressus*, *Leersia* spp., *Cyperaceas* and shade tolerant species such as *Drymaria*, *Commelina* and *Talinum*.

6.3.1.3 <u>Insufficient temporal coverage</u>

The duration of the cover crop is another important factor that may limit its effectiveness in controlling weed growth. If its duration is less than the fallow period between harvest of the main crop and the planting of the next, weeds may proliferate in the gap (Figure 6.1). In this situation, the cover crop might even release nutrients for use by the weed rather than by the subsequent crop.

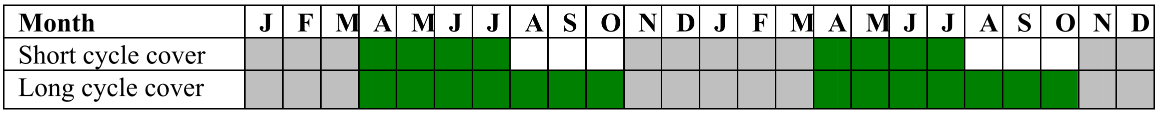


Figure 6.1. Short cycle cover crop providing window of opportunity (unshaded) for weed proliferation compared with a longer duration cover crop or traditional fallow. (Developed from Pound et al., 1999).

For example, in further experiments on winter cover crops grown in rotation with rice, Pound *et al*. (1999) found that certain crops with relatively short durations could actually increase the number of weeds in comparison with the traditional practice of leaving a winter fallow (Table 6.8). In these cases, the weeds had time to multiply before the planting date of the next rice crop. Possibly, the weeds may also have taken advantage of any N that was fixed by the leguminous cover crops, although this was not specified.

Table 6.8: Response of grass weeds, broad-leaved weeds, and Cyperaceae *(m^{-2}) in a field trial in the Ichiligo-Sara area of Bolivia in response to selected winter cover crops. (Developed from Pound et al., 1999).*

Winter cover	**Grasses**	**Broadleaves**	***Cyperaceae***
Winter fallow	19	27	31
Canivalia ensiformis	22	30	44
Mucuna pruriens (negra)	8	28	12
Mucuna pruriens (ceniza)	8	23	16
Cajanus cajan	32	56	27
Tropical alfalfa	142	36	20
Carioca beans	132	38	51
Cowpea	100	57	36
Crotalaria juncea	70	23	25
S.E.	16	9	12

Crops such as alfalfa, cowpea, carioca beans or *Mucuna deeringiana* had very short durations, and tended to produce comparatively little biomass as a result. Weed counts in these plots were substantially greater than for the traditional fallow. Species with a longer duration, such as *Mucuna pruriens*, *Cajanus cajan*, and *Canavalia ensiformis*, that continued growing up to the first planting of the rice, also produced more biomass and continued to suppress the growth of weeds over this time. Weed counts in these plots were relatively low although they offered few significant advantages to the traditional fallow treatment in terms of grass weed and broadleaf weed control. Rice yields also showed no significant differences between different cover-crop treatments in Year 2 of the treatments, despite the great variation in grass weed density. The effect of decreases or increases in weed population may carry over and multiply into the next season (Pound *et al*., 1999). Cover-crops that encourage the proliferation of weeds, may have unwanted future ramifications, although it is unlikely that a farmer would continue to use such a cover crop for any length of time, should he observe this happening.

Using a cover crop with too long a duration may also cause problems. If the use of cover crop in the system is to be sustained, particularly in isolated areas, farmers need to be able to collect seed for the next season. If the crop fails to flower and seed before the next main crop planting, then seed must be obtained externally. Most legume genotypes appear to be adapted to quite narrow biophysical conditions (Summerfield, 1999), and, therefore, must be tailored to specific environments if they are to be successful. Keatinge *et al*. (1998) make the point that a knowledge of the photothermal requirements of a potential cover crop genotype will help in matching its duration to a specific environment. They used a simple crop phenology model to examine the suitability of six legume cover species for use in farming systems of the mid-hills region of Nepal (Keatinge *et al*., 1999). The criteria was that they must reach maturity prior to the sowing period for the principal summer cereal crops. Results showed that *Vicia faba*, *Vicia villosa* ssp. *dasycarpa*, and *Lupinus mutabilis* would be suitable as autumn-sown crops across most of the mid-hills if early sowing is possible. *Vicia sativa* and *Trifolium resupinatum*, on the other hand, are only likely to mature early enough at lower elevations. Similar exercises were conducted for hillside regions in Bolivia (Wheeler *et al*., 1999) in which potential cover crops, not grown locally, were recommended for further trials, and also in Uganda (Keatinge *et al*., 1999), the results of which were taken up by CARE International in designing field trials. It was concluded that the models were useful tools to pre-screen a wide range of legume genotypes to eliminate unsuitable germplasm from further field testing, and had potential for scaling up field tests to produce suitable recommendation domains.

6.3.1.4 Competition with the main crop

In some cases, the growth of cover crops has been found to be *too* aggressive, resulting in undue competition with the main crop for nutrients, space, water and light. If left unchecked this can lead to complete domination of the main crop by the cover crop, i.e. the latter is beginning to behave like a weed itself. For example, Pound *et al*. (1999) found that *Mucuna pruriens* was rejected by some farmers in the Ichilo-Sara area of Bolivia because it dominated *Bactris gasipaes*, a local palm, and banana, limiting their growth and development.

In on-farm trials with *Calopogonium*/rice intercropping system, farmers found that *Calopogonium* tended to climb over the rice and cause it too lodge. This occurred especially when rice and *Calopogonium* were sown simultaneously or when long-duration rice varieties were used (Pound *et al*., 1999).

6.3.1.5 Introduction of pests

The use of cover crops (traditional or new) may sometimes encourage the introduction of pests, which may hamper the growth of the main crop or cause harm to the farmers themselves. In Ghana, farmers have been reluctant to use cover crops as they tend to harbour snakes and scorpions (Quashie-Sam, *pers. comm.*; Owsou-Bennoah, *pers. comm.*). In Bolivia, Pound *et al*. (1999) noted the increased presence of rats, snakes, and red spider mites, with the use of *Pueraria phaseoloides* and *Arachis pintoi* as cover crops.

6.4 Socio-economic constraints

6.4.1.1 Labour

Weeding for many farmers may be one of the most labour-demanding activities undertaken. Gill (1982) found that hand hoe weeding in India required between 200-400 man-hours ha^{-1} and that two weedings were needed during the growth and development of field crops. Tienhoven *et al*. (1982) found in the Jinotega region of Nicaragua that between 13-37 man-days ha^{-1} of labour were required to weed a maize bean production system. This accounted for between 21-35% of family labour. From various sources Ruthenberg (1980) compiled data of labour requirements for weeding. In Ghana, for example, weeding in a maize system required 31% of total labour (about 186 man-hours ha^{-1}), while in Columbia, weeding a cassava crop required about 55% of total farm labour (about 408 man-hours ha^{-1}). Other traditional agricultural systems cited were less intensive, although they also required at least 20% of total labour requirements for weeding.

Table 6.9: Weeding and total labour requirements (days ha^{-1}) in Calopogonium*/rice intercropping systems from trials in Ichiligo-Sara area of Bolivia.* Calopogonium *was intercropped, 25 days after sowing rice (25 DAS), 45 days after sowing rice (45 DAS), post harvest. The 'No Calopogonium' treatment was manually weeded. (Source: Pound et al., 1999).*

	Site 1		Site 2	
Sowing date	**Year 1**	**Year 3**	**Year 1**	**Year 3**
25 DAS				
(weeding labour)	32	33	39	28
(total labour)		57		42
45 DAS				
(weeding labour)	37	53	44	30
(total labour)		62		44
Post-Harvest				
(weeding labour)	38	63	50	41
(total labour)		76		60
No Calopogonium				
(weeding labour)	35	53	40	36
(total labour)		66		47

In the Ichilo-Sara area of Bolivia, Pound *et al*. (1999) found that weeding could require from 34 days ha^{-1} of labour in the first year of a cropping cycle to 53 days ha^{-1} in the third year as weeds started to dominate the system. The increase in weed cover was associated with large declines in rice yield, with year three yields being about 30% of year one yields. This was probably due to the combined effect of weeds and declining soil fertility.

The use of cover crops may not always reduce the labour requirement of the agricultural system to a significant degree; that is, to a level that may allow the farmer to make substantial investments of his/her time elsewhere. The labour requirement of *Calopogonium*/rice intercropping systems was compared with the control (manual weeding) at farmer levels of input in trials by Pound *et al*. (1999). The weeding labour requirement was reduced when *Calopogonium* was sown 25 days after the rice planting compared to the traditional system, but the other treatments showed no difference to the control (Table 6.9). If anything, the weeding labour requirement for other treatments (45 days after sowing and post harvest sowing) appeared to be slightly more. The total labour requirement for the 25-day treatment was slightly less than the control. However, the same pattern as for the weeding labour requirements was repeated for the total labour requirements with the other treatment options.

Pound *et al*. (1999) suggest that these differences were not great enough to be of practical significance to FAI farmers, and clearly, such reductions in labour would be unlikely to make a substantial difference to the livelihoods of such farmers.

6.4.1.2 Land

In general, the use of cover crops to suppress weeds on a given area of land may be considered to be land neutral, where for example, the farmer is growing the cover crop in rotation at a time when there is no main crop, so long as this does not necessitate taking land out of production. This could be during a fallow period or dry season, for example. However, the use of cover crops to suppress weeds is not always land neutral. Intercropping cover crops may be seen as land demanding by the farmers if it involves lower yields of the main crop on a per hectare basis, necessitating greater usage of land to maintain the same level of main crop production.

6.4.1.3 Capital

FAI farmers are limited by the amount of capital that they can mobilise to improve their agricultural systems. Techniques that require a substantial investment of capital for their success are unlikely to be adopted widely by such farmers. In the integrated weed management strategies examined by Pound *et al*. (1999) the cost of herbicide at the levels applied may represent a significant capital expenditure for FAI farmers. In any case, the use of herbicide in these strategies did not give decisive advantages over the more labour intensive options.

6.5 Summary

The discussion here has centred around the constraints and limitations that may be encountered when using cover crops to control weeds, using the results of Pound *et al*. (1999) as case study material. It seems from this work that despite the potential ability of cover crops to reduce weed populations and labour, and increase yields slightly in some cases, there may not always be a practical benefit in terms of the main crop yields, over the traditional practices that might already be prevalent.

However, it should be noted that evidence from other countries does suggest that *Mucuna,* for example, can suppress the development of weeds, particularly in improved fallows (Buckles & Triomphe, 1999). Masuolff (1995) has shown that the overall benefits of using *Mucuna* in Honduras include increasing yields and decreasing costs relative to more chemical intensive alternatives. In Uganda (Fischler *et al*., 1999) and in Benin (Tarawali *et al*., 1999), farmers note that one of the main impacts of cover crops such as *Mucuna* and *Dolichos lablab* is to suppress the development of weeds. Gallagher *et al*. (1999), in a review of literature, also showed that improved fallows of woody perennials and herbaceous cover crops could suppress weeds, particularly over a number of years, and would be an important component of Integrated Weed Management (IWM) strategies. Other benefits, such as improvement to soil structure, making them looser and easier to cultivate, enhancement of nutrient status, contributing to improved soil N status in the case of legumes, and helping to conserve soil moisture will also weigh in their favour.

When intercropped, cover crops should be fast growing, producing large quantities of biomass, but not to the extent that they become a threat to the main crop. This may preclude the use of genotypes with long durations. Additionally, it may be beneficial to plant the cover crop into the main crop so as to allow the latter to establish and have a head start. When grown in the fallow period following the main crop, cover crops should also produce good ground cover and high quantities of biomass. However, there is the additional factor of ensuring that the duration of the cover crop does not fall short of the next planting date of the main crop. Such a situation may allow a window of opportunity for weeds to proliferate, perhaps making use of the improved environment left by the cover crop.

As the biomass from cover crops may often be incorporated into the soil, it is important to ensure that it is of sufficient quality to prevent the net immobilisation of N and P. The lignin and polyphenol content should also be within the boundaries required for net mineralisation of nutrients. Where cover crop biomass is of low quality it might be necessary to supplement N or P. Cover crops producing very low quality biomass should probably not be used.

Even the improved and integrated use of herbicides and tillage technologies at levels that farmers can afford to use may not be sufficient to reduce weeds to a level that can make a practical difference to the farmer. Clearly, weed control is one of the key elements in establishing more settled forms of agriculture, and until alternatives can be found to provide FAI farmers with a decisive advantage, it would appear that slash-and-burn agriculture still appears to be the most viable option in terms of weed control.

7 Synthesis

7.1 Introduction

The previous chapters have presented an analysis of the biophysical and socio-economic requirements of a number of technologies being evaluated for forest/agriculture interface production systems. The technologies were analysed in terms of their ability to address natural resource issues such as the management of SOM, N and P, and weed growth, which have been identified as major problems encountered after long-term bush and forest fallow (or forests) are cleared for agricultural use. By using this reductionist approach, we have shown that, within the resource constraints of resource-poor farmers, the technologies are unlikely to be able to fully supply SOM, N and P requirements, or repress weed development, for the purpose of helping to stabilise cultivation systems at the FAI. In terms of addressing these problems alone, there seems to be little advantage in farmers using the techniques over their current practices.

Although the reductionist approach is a powerful analytical tool and can tell us much about what can and cannot be achieved through the use of the techniques, it is also important to consider the overall attributes of each technique in relation to their usefulness to farmers. There may be benefits to using a particular technique that are unrelated to the particular biophysical problem that scientists are using the technique to address. Thus the value of *Tithonia diversifolia* may lie not only in its capacity to supply P (and we have shown that it may be difficult to justify its use from this perspective alone), but also in its capacity to supply, at the same time, biomass for SOM, N, K, and micro-nutrients. The value of these multiple effects on fertility is often greater than the value of any single effect - for example, Jama *et al*. (2000) showed that *Tithonia* biomass produced higher crop yields than inorganic fertilisers applied at equivalent rates of P. The value of *Tithonia* to farmers may also be for other reasons, including demarcation of field boundaries, provision of fodder, reduction of erosion, or the provision of live fencing, to name but a few.

In this chapter, we take a more ‘holistic’ view of the technologies, and consider whether they possess other characteristics that may benefit farmers adopting them, and indeed, whether they have been adopted by farmers for any reason whatsoever. We have also broadened the discussion to include other potential techniques, such as composting and multipurpose trees, not included in the projects that we reviewed, but that may have some relevance in FAI cultivation systems. We then examine how they may or may not be useful in the farming systems of each of the focus countries, Nepal, Ghana, Brazil and Bolivia.

7.2 The techniques

7.2.1 Alley cropping

We have seen from the preceding chapters that alley-cropping does not seem to have been very successful as a soil fertility enhancing technique, and that there are good biophysical reasons for its lack of success, namely its competition with the main crop for land and resources such as light, water and nutrients. In conditions of less than optimal growth, there is considerable evidence that alley cropping actually reduces main crop yields (e.g. Manu *et al*., 1994).

However, variants of alley-cropping have had some success for other reasons than soil fertility improvement. Contour alley planting, for example, is a useful erosion control measure, and it is probably in hilly areas, where erosion rates are naturally high, that alley-cropping may find its primary biophysical niche. Similarly, needs unrelated to soil fertility enhancement or erosion control have also resulted in limited adoption - for example, to meet the need for fodder for animals (Field *et al*., 1992). The provision of poles, medicines, plants, fibre, fruit, and fuel have also been put forward as reasons for adoption of alley-cropping (Cenas *et al*., 1996). In the Amarasi district of Indonesia, Field *et al*. (1992) suggested that alley cropping could be used to allow farmers to develop intensive livestock systems, if *Leucaena* is planted for fodder at the beginning of a natural fallow. The return from the sale of cattle could be used for the purchase of food, and as farmers become less reliant on annual crops for subsistence, more appropriate perennial plant systems could be established on steeper land prone to erosion.

It is interesting to note that farmers have sometimes altered the practice of alley-cropping, and even the purpose for which it was originally designed, to fit their own needs. For example, in the Philippines, farmers often increased alley spacing, and planted single rather than double hedgerows to reduce planting density. They often used alternative tree species, so that the hedgerow could be used for other purposes, and also reduced trimming frequencies and mulch application (Garcia *et al*., 1998). These farmer modifications may have reduced the value of alley cropping as a soil fertility enhancing technique, but have at least allowed it to fit within the constraints of the farmer and to answer a wider set of needs. Attention given to the overall concerns and goals of the household may influence the adoptability of alley cropping (Garcia *et al*., 1995). In some cases, these modifications have even resulted in an evolution away from alley-cropping altogether into intercropping two crop species. For example, in eastern Indonesia, Harsono (1996) describes the replacement of hedgerows with strips of grain legumes such as soybean, which were shown to increase net profits. However, to make this system successful, the level of inputs such as labour, fertiliser, pesticide, seed and capital were substantial. These modifications by farmers illustrate an important point regarding adoption of alley-cropping – if it is to be successful, farmers must feel that it can address their requirements in some way (Sombatpanit *et al*., 1993). These may not necessarily be issues of soil fertility enhancement and erosion control, and if the technology cannot be modified to supply the needs of both men (e.g. poles or fodder) and women (e.g. fibre, fuel-wood and mulch) it stands less chance of being adopted (Rocheleau & Rocheleau, 1990).

Other factors that make alley-cropping unattractive for farmers as a soil fertility enhancing technique are more socio-economic in nature. The extra labour required for establishment and management of the hedgerows and incorporation of the biomass into the soil is an important issue, and has been discussed in more detail previously. Relative land scarcity (so that shifting cultivation and long rotation fallows are no longer adequate) may encourage the use of alley-cropping, although if land is too scarce, the loss of main crop area to hedgerows may not be acceptable. Access to capital appears to be necessary for adoption of alley-cropping. For example, Cenas *et al*. (1996) have shown that adoption may be higher where farmers have off-farm sources of income, relatively large farms, and were interested in cash cropping. Lack of capital may limit uptake, not only because alley cropping cannot maintain total fertility requirements and money must therefore be spent on fertiliser for full benefits (Wendt *et al*., 1993), but also because establishment costs of hedgerows (primarily because of labour costs) are high (Nelson *et al*., 1996). Benefits may take some time to accrue (Carter, 1995) and farmers may feel that these are not realised rapidly enough and do not outweigh the cost of establishment (Nelson & Cramb, 1998). Indeed traditional cropping practices may be economically more viable than alley cropping over the first 4-5 years (Nelson *et al*., 1996). The future value of alley cropping (and new techniques in general) is discounted at high rates by farmers (Nelson *et al*., 1998), shrinking future benefits, especially in the long term.

Security of tenure and long-term access to land are important issues in some countries. Tenant farmers are unlikely to want to bear the full cost of the technique while the benefit is shared with the landlord (Nelson *et al*., 1998). Similarly, systems based on revolving cultivation of land amongst family members, short term tenancy, and share cropping tenancy are likely to have the same effect. Where farmers have long term security of tenure over discrete areas of land, alley-cropping may be more relevant (Carter, 1995).

Thus, there may be a need for incentives to encourage alley-cropping, and strong extension services to provide support in the use of the technique (Cramb *et al*., 1994). Some form of capital provision may be necessary for resource-poor farmers, particularly as rates of interest make informal sector borrowing unappealing (Nelson *et al*., 1996). Further suggestions aimed at reducing the establishment costs of hedgerows have been suggested, for example, the use of alleys of naturally occurring vegetation and/or grass strips (Nelson & Cramb, 1998). Many of these steps may act as an intermediate step to full adoption of alley-cropping, but ultimately much larger changes may be required. Some of these may include rural finance, commodity pricing and agrarian reform policies to create an enabling environment (Nelson *et al*., 1996). However, even an enabling environment may not convince the farmer to adopt alley-cropping, and on the whole its value appears to be limited to sloping land, and to areas where the technique can be modified to suit a much broader set of aims, in particular the direct generation of income, rather than fertility and erosion control. This means that the hedgerow itself must also have some immediate cash benefits and wider ranging benefits. Alley-cropping (and agroforestry technologies in general) must become more agronomically and socio-economically 'versatile', capable of shifting emphasis from one component of the 'package' to another, as production needs change and be capable of responding rapidly to changes in the socio-economic circumstances of the farmer (Vosti *et al*., 1998).

7.2.2 Intercropping

The use of intercropping is widespread in many developing countries (Jodha, 1979). However, while it has often been put forward as a technique for soil fertility enhancement or weed control (Hikwa *et al*., 1999), the evidence suggests that farmers are more interested in using intercropping and other forms of mixed cropping as a way to diversify food production (and/or cash crop production, Jodha, 1979), or to reduce risk, particularly in difficult conditions (Singh & Jodha, 1990). The failure of one crop may thus be offset by the production obtained from the other (Vandermeer, 1989). Intercropping may often result from intensification of mixed cropping techniques, as land scarcity increases and/or animal and mechanical traction replace hand cultivation methods (Ruthenberg, 1980).

Thus, any soil fertility benefits that can be obtained by intercropping leguminous grain crops with other food crops should probably be seen as a useful spin-off rather than the main purpose of the practice. This implies that the use of legumes that have no other purpose apart from fixing nitrogen, or providing green manure, may not satisfy farmers' priorities. As with alley-cropping, main crop yields may be reduced by intercropping techniques, both as a result of loss of land to the legume, and also to competition for resources (Vandermeer, 1989; Snapp *et al*., 1998). Thus, cereal/legume intercrops are still likely to require fertilisers for the provision of P, K and micro-nutrients in order to maintain satisfactory yields (Coultas *et al*., 1996; Kumwenda *et al*., 1993).

Intercropping is most likely to be adopted on small farms, in areas where land is scarce, forcing the simultaneous production of different crops on the same area of land. Low rainfall and/or a unimodal distribution of rain may encourage intercropping as farmers try to maximise their use of a scarce resource, in this case water. Mixed-cropping techniques are also more likely to be used by farmers relying on hand-held implements for tillage (Ruthenberg, 1980). The need for simultaneous production of different food crops and/or cash crops may also encourage intercropping, as might the perception and reality of risk in a particular area. Relatively better-off farmers with large farms are probably not so interested in intercropping, preferring to fallow and/or control the risk of production with other inputs such as water and inorganic fertilisers.

In summary, intercropping should be seen as a risk reduction and crop diversification technique, and probably should not be promoted as a technique for improving soil fertility. A possible exception may be where intercropping techniques can be successfully developed to avoid competitive effects with the main crop, with good biomass production after the harvesting of the main crop. This might be possible with relay intercropping or the use of long-maturing legumes that reduce competition with the main crop. However, farmers may have to weigh up the opportunity cost of growing a legume against growing a more important food or cash crop. Although labour requirements are usually seen to be fairly neutral, excessively competitive legume intercrops could become very labour demanding if the farmer has to prevent the main crop from being stifled.

7.2.3 Biomass transfer techniques

Biomass transfer techniques have been traditionally used by tropical farmers to relocate nutrients from forests to agricultural land (e.g. Young, 1987; Nyathi & Campbell, 1993). In most cases, this has involved the use of naturally occurring biomass (i.e. tree or grass material), and rarely biomass that has been specifically planted for that purpose. Recently, however, the attention of researchers has focused on transfer of biomass from purposely planted 'biomass banks' of species such as *Tithonia diversifolia* (ICRAF, 1997; Gachengo *et al*., 1999; Jama *et al*., 2000), *Gliricidia sepium* (Rao & Mathuva, 2000), *Calliandra calothyrsus* and *Leucaena leucocephala* (Mugendi *et al*., 1999) as a means of providing nutrients for crop growth, and organic matter for soil physical improvement. The use of so-called cut-and-carry grasses is another technique where biomass is harvested and transported, in this case specifically to provide fodder for animals (e.g. Tanner *et al*., 1993; Kerridge *et al*., 1996; Ilao, 1997).

While similar in principle to alley-cropping, in that plant biomass is cut and incorporated into the soil to release nutrients for crops and to help improve soil organic matter levels, one of the advantages of biomass banks is that direct competition between the main crop and the crop used to supply the biomass is minimised, if not eliminated altogether. Often this can result in substantially increased crop yields for biomass transfer techniques (Mugendi *et al*., 1999).

The evidence so far suggests that biomass transfer techniques can help to increase soil fertility and sustain or increase crop yields (Dzowela & Kwesiga, 1993; Mugendi *et al*., 1999; Rao & Mathuva, 2000). However, for the technique to be successful, the quality of this biomass needs to be high (Snapp *et al*., 1998), very large amounts of biomass are required to supply 'ideal' quantities of nutrients to crops (Gachengo *et al*., 1999), and labour for the collection, transportation, and incorporation of the organic matter into the soil must also be plentiful (Gachengo *et al*., 1999; Snapp *et al*., 1998; Jama *et al*., 2000).

As we have seen previously, large areas of land are generally needed to grow sufficient quantities of biomass, which is often a limitation if land is scarce and the socio-economic circumstances of a farmer mean that his farm is small. Farmers may be interested in biomass transfer techniques if they cannot effectively use all their land for cultivation, but it is probably necessary for farms to be of a certain size before this happens. However, it is more likely that farmers who can afford to set aside some of their land will use other techniques to regenerate the soil fertility, such as fallow. It is possible that biomass banks could be established on strategically located common land, which would be especially valuable for poor farmers. However, for this to be workable, it would be necessary for a system of access agreements to be developed, possibly through traditionally recognised bodies of authority at the village-level. Questions of who was responsible for the establishment of such stands would also have to be solved, particularly as there is some cost involved in purchase of seedlings and the care required in the initial establishment (i.e. weeding, etc.). Similarly, the sustainability of the system, with constant removal of nutrients in the biomass, would need to be addressed.

In most cases, it is unlikely that biomass transfer techniques will be capable of supplying the full fertility needs of a farm, and as with other fertility enhancing techniques, it may best to see them as a partial solution to soil fertility problems as a component of an integrated nutrient management system involving external supplies of inorganic nutrients. It may be that there are specific niche roles which will make them useful on small areas within a single farm (e.g. for home gardens), or on degraded common land, although it is more likely in this case that they will fulfil other important needs, such as the provision of fuelwood and/or fodder. Here they would move closer to the role played by natural forests, in which case, they may help relieve some of the pressure on the latter.

Most literature on biomass banks appears to be technical in nature, and little evidence appears to exist of their successful introduction into farming systems, particularly on private land, probably for the reasons mentioned above. As there are large investments to be made and large land requirements, it is unlikely that biomass banks for soil fertility enhancement alone are likely to be accepted, particularly on private land, especially if farm sizes are small. There is also the disadvantage that there is a relatively long time-lag for benefits on soil fertility of such techniques to accrue (Snapp *et al*., 1998).

However, there is a greater likelihood of adoption of biomass transfer techniques where there is some immediate benefit to be obtained by the farmer. The use of cut-and-carry grasses as animal fodder, for example, has the advantage that some animal products, including draught power, milk and meat, are available almost immediately. Improvements to soil fertility through the application of manure and urine may be a secondary result. Farmers are usually well aware of the beneficial effects of manure on soil fertility – there is some evidence that they feed their livestock much more than they require for optimal live-weight gain to provide manure for arable crop production (Tanner *et al*., 1993). Nevertheless, the essential difference of 'processing' plant biomass through animals first to gain immediate benefits, rather than using the biomass directly to improve soil fertility, is likely to be a determining factor of whether biomass banks are adopted by farmers or not.

Of course, the intensification of agriculture with cut-and-carry grasses and/or fodder banks is most likely to occur where animals are already a major component of the agricultural system (Chau Chau *et al*., 1995) and where satisfactory and alternative feeding strategies do not already exist (Reynolds *et al*., 1991; Rachmat *et al*., 1992). In some areas, population increases may increase the importance of cut-and-carry and zero-grazing techniques, as less and less land becomes available for free-grazing on communal land (Murwira *et al*., 1995). However, sufficient land still needs to be found somewhere to grow the biomass (Gashaw *et al*., 1991).

As with other biomass transfer technologies, the evidence suggests that the amount of labour required for cut-and-carry techniques for fodder is often a disincentive (Mogaka, 1993; Wandera *et al*., 1993; Sanchez & Rosales Mendez, 1999). Cut-and-carry grasses may also not supply the full fodder requirements of livestock, necessitating supplementary feeding. Capital may be needed to pay for this, along with the inevitable veterinary fees associated with keeping livestock healthy (Mogaka, 1993). Also, the decline of productivity of the fodder banks as nutrients are removed may require investment in fertilisers to maintain productivity (Wandera *et al*., 1993). Finding suitable grasses, and issues related to land tenure are other important considerations. On the whole, cut-and-carry systems are probably most suitable for farmers of intermediate wealth, as the ownership of cattle and the establishment of biomass stands involves costs that very poor farmers are unlikely to be able to meet.

7.2.4 Improved fallows

The main advantage of improved and enriched fallow systems is that that they are a modification of an existing system, requiring only minor changes to existing farmer practice. From the biophysical point of view, due to the deeper-rooting characteristics of the woody species usually used in improved fallows, nutrients from below the rooting depth of arable crops can be made available again, and the use of appropriate leguminous species can result in improved rates of addition of N to the system. Also, there is no direct competition for resources with main crops (Sanchez, 1999). The downside is that production is lost from the land set aside for fallow, although this happens anyway in shifting cultivation systems in FAI production systems. Improved fallows can be seen as a natural progression from shifting cultivation and other long fallow rotations, and may, therefore, be one of the most adoptable ‘generic’ techniques for use at the FAI (Sanchez, 1999).

Compared to natural fallow systems, more labour is required for improved fallows, primarily for planting of the fallow species and weeding to ensure their establishment (Drechsel *et al*., 1996; Kamanga *et al*., 1997; Grist *et al*., 1999). There is a danger that this could coincide with labour demands for planting and management of other crops (Franzel, 1999), although the labour demand by improved fallows is relatively flexible, certainly compared to alternative systems such as alley-cropping where the timeliness of pruning is very important. Some capital input is needed for improved fallows, mainly for the purchase of seeds or seedlings of the species to be planted. Some evidence suggests that where farmers have insufficient capital, they tend to use natural fallows, but on the other hand, better-off farmers will tend to purchase inorganic fertilisers (Franzel, 1999). Improved fallows will, therefore, be most suitable for farmers at an intermediate level with some disposable income.

A major disadvantage of improved fallow systems (or any fallow system, for that matter) is the length of time it takes for any financial benefits to accumulate (Grist *et al*., 1999). Indeed, there may even be an opportunity cost to the use of improved fallows, as natural fallows may provide goods and services that improved fallows do not. Enriched fallows address this problem to some extent, in that species that are able to provide some economic benefit, such as fruit or nuts, are planted, rather than species that only improve soil fertility (Franzel, 1999). However, removal of harvestable products (and the nutrients they contain) lengthens the time taken for regeneration of soil fertility, and in extreme situations, may eventually mine the soil of nutrients (Franzel, 1999). These deficits will have to be made up with other sources of nutrients.

Improved fallows are more likely to be used by farmers in areas where increases in the population density is starting to make the long periods required by natural fallow impracticable. At higher population densities, however, scarcity of land means that there is a high opportunity cost in putting land to fallow, and intensive continuous cultivation systems may dominate (Drechsel *et al*., 1996). Improved fallows are, therefore, most relevant in the intermediate stage between extensive and intensive land use (Franzel, 1999).

If improved fallow techniques are to be adopted more widely, farmers need to be able to perceive that there is a problem to be addressed. This may be declining yields (Franzel, 1999) or fertility (Degrande *et al*., 2000), or controlling weeds (Tarawali *et al*., 1999). Security of land tenure is also an important consideration, as farmers will be unwilling to invest time and effort in establishing improved fallows if they are not the ones to receive the benefits (Seif El Din & Raintree, 1987; Long & Nair, 1999; Tarawali *et al*., 1999). Institutional support, in the form of seed programmes and training of extension agents and farmers, has also been found to be important in improving the adoption of improved fallow techniques (Franzel, 1999). Other important requirements may also be to provide adequate and/or improved germplasm (Place & Dewees, 1999).

Finding innovative ways of improving livelihoods during the fallow period may also aid adoption. Enriched fallows have already been mentioned and are discussed in more detail below. Completely new opportunities could also be considered, such as honey production from *Calliandra* (Franzel, 1999). Alternatively, the costs of establishing improved fallows might be reduced by certain techniques, for example, direct seeding or stump planting (Franzel, 1999). Other more practical benefits such as firewood or bean pole production from land under fallow may also be useful considerations for improved fallow (Drechsel *et al*., 1996), or light timber production for light construction (Franzel, 1999). In certain areas, for example where cattle are prevalent, it may be difficult to establish improved/enriched fallows, as farmers may not want to invest in fencing for protection.

There is certainly some evidence that improved fallow techniques are being adopted by farmers in some regions. Citing various sources, Sanchez (1999) claims that there is large scale adoption of improved short-term fallows (i.e. <5 years in duration) occurring in Central America, Brazil, Southeast Asia, East Africa, and southern Africa, with perhaps hundreds of thousands of farmers using the technique. The majority of species used are *Sesbania*, *Leucaena*, *Mucuna*, *Centrosema*, *Pueraria*, *Crotalaria*, *Cajanus*, *Indigofera* and *Mimosa*.

In summary, improved (woody or herbaceous) fallows represent an important part of the evolution of farming systems from extensive land use systems to intensive land use system. They may therefore be relatively useful at the FAI as they are an enhancement of an existing system. They do however require more labour and capital inputs than traditional alternatives. Enriched fallows that supply rapid and immediate cash/subsistence benefits offer a way of offsetting the opportunity cost of putting land to fallow. This should improve the flexibility of the system, and allow farmers to shift emphasis from one aspect of production to another according to needs. As with all agroforestry systems, it may be necessary to consider whether the local use of fire is a disincentive to the success of the technologies.

7.2.5 Enriched fallows

Enriching the fallow period with high value perennial plants for medicine, fruit, high value timber trees (Sanchez, 1999), may be one way of making the fallow period more productive (Cairns & Garrity, 1999). Where such techniques are successful, farmers may even be encouraged enough to develop the technique into a permanent agroforestry systems (Cairns & Garrity, 1999). The use of multipurpose tree species is, of course, not new, and farmers have traditionally enriched fallows with selected tree species. For example, farmers in Benin plant oil-palm trees in a fallow of about 12-15 years (Versteeg *et al*., 1998). This restores soil fertility, but also provides subsistence and cash income, even upon clearance of the trees when 'palm wine' is produced.

Various factors may encourage the development of enriched fallow systems. Security of tenure (customary or marketised) and access to markets can encourage farmers to use multipurpose trees species and enriched fallow techniques (Amyot *et al*., 1987; Pradeepmani *et al*., 1987; Hellin *et al*., 1999). A certain level of access to capital also appears to encourage adoption (Amyot *et al*., 1987). Evidently, where these factors are not in place, farmers often tend to increase the rate at which they discount future benefits, making such techniques socio-economically unviable and reducing both the 'action time horizon' and the 'planning time horizon' (Vosti & Witcover, 1996).

As an example of this, the 'Qezungual System' has been indigenously developed in western Honduras (Hellin *et al*., 1999). The technique can be described as a triple-level agroforestry system, combining crops such as maize, sorghum and beans, numerous pollarded trees and shrubs (about 1.5 m high) and high-value trees, particularly fruit trees and timber trees. The system has generally developed on land that has been under secondary vegetation, or less commonly, on land that is under primary forest.

The elegance of the technique is in reducing labour requirements for the establishment of the valuable fruit and timber trees species, as these are simply selected when the land is cleared for agriculture. Other less valuable trees and shrubs are pollarded and the land is prepared for cultivation. This also reduces the time required for benefits to accrue to the farmer, and may reduce the need for inputs requiring capital (for example, seedlings) and labour (maintenance of vulnerable seedlings). Competition between perennial plants and food crops is greatly reduced by the pollarding, and can be manipulated by gradual clearing of perennial plants, if necessary. The technique is used by farmers on slopes of up to 50% in soils where organic matter is between 2.8-3.9% and *p*H is between 4.0-4.8. Annual precipitation varies between 1400-2200 mm and annual temperature between about 17 and 25 °C. Strong winds during part of the year cause high evapotranspiration rates and severe water deficits.

Natural regeneration is managed by selecting specific trees for production, whilst others are pollarded. Within the pollarded areas, crops may be rotated and areas left fallow to control pests. From discussions with farmers, there appear to be several benefits to this technique. The main one is that agricultural production within the pollarded plots is higher than on plots without pollards. The pollarded plots can also be cultivated for a longer time than plots without pollards. Soil moisture is conserved at higher levels, possibly because of reduced evaporation at the soil surface due to the pollards, and perhaps because the pollards improve soil physical structure and allow increases in WHC. The system provides multiple benefits for subsistence and cash income (fruit, food crops, timber and firewood). Biomass from the pollarded material provides mulch for moisture conservation and disease reduction in beans. Disadvantages are that moisture levels can become too high in times of high rainfall, leading to fungal attacks on crops. Birds may also be attracted by the trees and pollards, causing reduction of food crop yields. Animal or mechanised traction cannot be used to cultivate the land due to the random presence of so many trees and pollards.

Various factors may encourage the adoption of the technique. Land scarcity is probably the most important factor (most farms are about 2.5 ha) as, where land is abundant, farmers generally continue to use natural fallows. Absence of fire as a management tool is also important, otherwise the trees are destroyed. Lack of animal or mechanised traction is another factor, as the pattern of trees and pollards is fairly random. (However, with selective thinning, it might also be possible to develop pathways for animal and mechanical traction tillage). Possibly the most important factor is that it addresses a problem that the farmers find important - soil moisture. Dissemination of the use of the system now promote it as a soil moisture technology, rather than an erosion control technology, although erosion is definitely a problem in some areas.

It is important to note that the form and architecture of successful agroforestry techniques such as this do not always need to follow the rather rigid patterns that characterise western agroforestry practices. Indeed, it may be better if they don't. Additionally agroforestry technologies should not necessarily be geared primarily towards soil erosion control and fertility development. Other issues may be more convincing reasons for adoption by farmers. It is often better to use existing techniques that can be developed to address the problems that farmers find most relevant, as well those that scientists with broader perspectives might also see to be important. This has the potential of leading to the development of truly multifunctional technologies, addressing a wide range of farmer- and scientist-perceived problems.

7.2.6 Multipurpose tree species

All trees are multipurpose, although some are more multipurpose than others (Nair, 1993). Farmers have appreciated these multiple benefits for centuries (Negi, 1995) and still use trees for fodder, medicine, food, fruit, fibre, construction tools, etc. Ethnobotanical literature shows that there is often important and detailed knowledge on the multi-dimensional uses of plants in indigenous societies (e.g. Jery *et al*., ; Kothari & Rao, 1999; Singh, 1999; Costa Neto & Oliveira, 2000). In Madagascar, Styger *et al*.(1999) have suggested that the judicial identification, selection and domestication of preferred forest fruit trees could be used as a means of preserving biodiversity in FAI areas that are under pressure.

Pradeepmani (1987) discussed some of the issues affecting farmers' decisions to plant multipurpose trees species. These included having adequate land, time, labour, knowledge, and inputs, being able to protect trees properly, and success with tree survival (Pradeepmani *et al*., 1987). Traditional or marketised security of tenure may also encourage investment in multipurpose trees (Huxley, 1980; Christanty *et al*., 1989; Mahamoudou & Meritan, 1998). Efforts to encourage planting of multipurpose trees species through training visits, effective methods for protecting trees (which is often expensive), and government land tax incentives, were also noted as important factors (Pradeepmani *et al*., 1987).

There is potential for promoting the use of multipurpose tree species, but this will depend on doing so in the right context, which will probably be locally defined, unless good access to markets is available. For example, in FAI areas where tree cover is abundant, such as in Ghana, planting timber trees for cash or for subsistence needs is not likely to meet with success, as timber is available as a common resource anyway, and prices are likely to be low (Pound *et al*., 1999). Similarly, in areas where past efforts have resulted in large amounts of timber trees being planted, gluts in the market can depress values (Jitendra & Sharma, 1996). Fruit, nut or plantation trees may have some role to play in either the subsistence or cash economy, although such needs may equally well be met directly from the natural forest. There may be little use in continuing to encourage the planting of the same species.

Although the multipurpose nature of many trees may serve as 'pull' factors, strong 'push' factors may also operate at the localised scale. For example, shortages of agricultural labour, high cost of agricultural inputs, and shortages of power and water have all been reported to encourage farmers to plant multipurpose trees (Dasthagir *et* *al*., 1996). Economic, rather than ecological, factors may influence farmers' decisions to plant multipurpose trees (Mahamoudou & Meritan, 1998).

Multipurpose trees may also be more important in FAI areas, where land scarcity is high, and access to common tree resources relatively limited. In a study of the reasons for the adoption of multipurpose trees on homestead land by farmers in Bangladesh, direct economic concerns were uppermost in their minds of farmers (Salam *et al*., 2000). Other factors in order of importance were the provision of fruit, firewood, and building materials for subsistence, emergency cash needs, maintenance of ecological balance and protection from strong winds (Salam *et al*., 2000). Further analysis showed that tree planting increased with increases in the amount of land owned, the level of non-agricultural income, the market costs of fuel-wood, the male membership of the household, and the knowledge of extension activities (Salam *et al*., 2000).

Competitive effects of certain species (Srinivasan *et al*., 1990; Gaddanakeri *et al*., 1993; Nissen *et al*., 1999), and allelopathic effects might be problematic (Suresh & Rai, 1988; Srinivasan *et al*., 1990; Bhatt *et al*., 1997), particularly where main staple crops are very important. Reducing such competitive effects may be essential, although farmers often trade off benefits with costs in such cases before deciding to plant trees or not. In some cases, complementarity through reduced competition and facilitation may also be achieved with the right species selection and system architecture (Vandermeer, 1989; Droppelmann *et al*., 2000).

Many ingenious agroforestry techniques making use of multipurpose trees already exist. These mostly suggest that it is direct economic or subsistence benefit that is the major impetus for the use of multipurpose trees rather than fertility provision and/or erosion control (Peltier & Pity, 1993; Mahamoudou & Meritan, 1998; Salam *et al*., 2000). A possible way forward may be to concentrate on seedlings of species that are identified by local farmers as important in their economy to begin with, suggesting other species for fertility and/or erosion control if they are omitted. Some species may be very multifunctional, providing fruit, fodder, firewood as well as being capable of fixing N, in which case these can be focussed on if farmers accept them. There may be some progress to be made in spreading knowledge about trees and their uses from one area to another. *Tamarindus indica* is widely used for food and fodder in India and fixes N. However, in Ghana it appears not to be widely used for consumption (Quashie-Sam, *pers. comm.*), although it does grow there.

The above discussion has focussed around the income and subsistence value of multipurpose trees rather than the ecological value and provides an idea as to the most promising context for adoption, mainly because these appear to be the main reasons for use of multipurpose trees by farmers. We suggest that it may be best to accept that the planting of multipurpose trees appears to be primarily an economic and subsistence activity, and that once again, any fertility benefits that they provide will be an added bonus. As many trees may provide these benefits, it could be possible to emphasise these in the way that the technique is developed. Evidently, although farmers are often well aware of the benefits of planting multipurpose trees, various considerations can prevent them from doing so. A wider support structure is often needed, included seedling nurseries, capital provision, and methods of protecting and maintaining valuable seedlings through the establishment phase. Technical knowledge and sound management practices may also be important (Saroj *et al*., 1996). Often, where these support structures are available, farmers usually seem to be keen to plant multipurpose trees.

7.2.7 Compost

Compared to techniques such as alley-cropping, composting in relation to subsistence agriculture seems to have received little research attention. Much of the literature available tends to be from a purely technical standpoint, and is often from the perspective of agriculture in developed countries. Relatively few studies have considered the on-farm issues of using compost, although the few that do give a good indication of the constraints involved.

Composting is not a new technique for the improvement of soil fertility and structure, and tropical farmers have been aware for centuries of its impact on crop yields, soil structure and fertility, crop growth and vigour (Dalzell *et al*., 1979; Diop, 1999; Onduru *et al*., 1999). Other benefits noted are the reduced need for capital inputs (Onduru *et al*., 1999), although other evidence suggests that some capital may be necessary for farmers to adopt the technology (Girish & Chandrashekar, 2000; Slingerland & Stork, 2000).

The major problem associated with the use of compost is the high labour requirements (Feldman, 1977; Dalzell *et al*., 1979; Onduru *et al*., 1999). For example, in Nepal, Feldman (1977) calculated that about 50 ha^{-1} y^{-1} of forest leaves were needed to maintain soil fertility. This ideal input level would obviously involve considerable labour for collection, processing, and application. Female-headed households may have considerable difficulty undertaking some of the heavier tasks involved in composting, such as preparing compost pits (Diop, 1999). Transportation of biomass and compost is also problematic (Apiradee, 1988; Adeoye *et al*., 1996). Also, like the other low-input organic matter techniques already discussed, large quantities of biomass are required, and questions arise as to where farmers can obtain this (Feldman, 1977; Onduru *et al*., 1999). This is particularly relevant where there are competing demands for such resources, for example as mulch, fuel or fodder (Drechsel & Reck, 1998), and where land to produce the biomass is scarce. Very small farmers may have problems providing land for processing of 'ideal' quantities of biomass, although this is not generally cited as a limitation, probably because fairly small quantities of compost are usually produced. Composting may sometimes be constrained by lack of water (Apiradee, 1988; Diop, 1999) which is needed to aid decomposition, and by lack of biostarter (Apiradee, 1988), although it appears that animal manure and inorganic fertiliser may be used.

As composting is labour intensive, it may be most sensibly applied relatively close to the homestead, on specific crops. Evidence also suggests that progress may be made by improving the technical knowledge of farmers, so that composting practice is improved (e.g. Sutihar, ; Adeoye *et al*., 1996; Wakle *et al*., 1999). For example, the quality of compost can be greatly enhanced by mixing it with a combination of inorganic chemicals (Berghe *et al*., 1994), or by combining it with manure (Onduru *et al*., 1999). During processing, protecting it from heat and direct light may reduce volatilisation of the nutrients, while protecting it from rain may prevent similar losses by leaching (Diop, 1999).

It seems unlikely that composting would be a new technique in many FAI areas, unless a rapid transition from an abundance of land to scarcity is occurring. Progress is more likely to be made by determining whether composting practices can be improved within the socio-economic constraints of FAI farmers. Recommending the use of animal manure in compost, for example, would not be appropriate if animal manure is the only source of fuel.

As with other organic matter management techniques, composting is unlikely to provide a total solution to the problem of decline in soil fertility and soil structure at the FAI, but should be an important component in the basket of options that a farmer could use. As it is very labour intensive, it will probably be most used close to the homestead, on small areas of high value crops. Increasing these quantities to large or distant fields may require capital investment for procurement and labour, an option that is more relevant to the wealthier sections of society.

7.2.8 Animal manure

The beneficial impacts of animal manure are well documented, and many tropical farmers are well aware of the effects of applying manure to land. In certain areas of western Africa, some arable farmers may still make arrangements with herdsmen to corral livestock on their land (Enyong *et al*., 1999). Farmers may also move their homesteads from place to place so that crops can be grown on that land to benefit from the manure left over by livestock (Ruthenberg, 1980). In upland Java, livestock may be fed with far greater amounts of biomass than is needed for optimal live-weight gain, the rationale being the production of manure-compost that is collected for intensive upland agriculture (Tanner *et al*., 1993).

The use of manure can not only enhance immediate crop yields (Selvarajan & Krishnamoorthy, ; Ali, 1996; Karki, 1996; Drechsel & Reck, 1998), but can also provide some residual benefit for following years (Singh & Desai, 1991; Karki, 1996). Mixed livestock and arable farming interface in other ways. In particular, residues can be used as feed for livestock, which in turn provide draft for tillage and transport and other farm operations, as well as manure for fertiliser, and milk for human consumption (Rangnekar, 1993). Other benefits of manure include the provision of material for plastering and building, and fuel for heating and cooking (Jeffery *et al*., 1989; Rangnekar, 1993; Sevilla & Carangal, 1993; Murwira *et al*., 1995). Many of these activities (e.g. the production of fuel cakes or milk) have direct economic value in themselves (Jeffery *et al*., 1989). The opportunity cost of using manure as a fertiliser may be high in certain cases, and farmers may often value it more highly for uses other than soil fertility maintenance. This inevitably reduces the amount of manure that is available for soil chemical and physical improvement. The sheer quantity of manure required for optimal satisfaction all of these needs can often be well beyond the means of resource-poor farmers.

If manure is to be used in FAI areas to enhance soil fertility, it will need to be culturally acceptable to farmers, which is most likely to occur where livestock are already an integral part of the farming system (Sevilla & Carangal, 1993). This is more likely to be in FAI systems that are spatial in nature, where population pressure is higher, labour availability is higher, and land is scarce, as in Nepal (Murwira *et al*., 1995). Where the FAI is temporal and land availability is high, farmers may find it more practical to improve soil fertility and structure through natural or improved fallow, although they may use manure on plots close to the homestead if they own smallstock or cattle.

Other major areas of possible use are likely where temperatures are very low/high or precipitation is low. Such conditions may make arable production difficult anyway, but also reduce the decomposition rate of organic matter. The use of animals means that organic matter decomposition can occur in the ideal conditions of the rumen, instead of the soil. However, in these areas, it is likely that manure-compost will already be a known fertiliser and soil conditioner, and the need may be to concentrate on ways of improving its production and management. For example, saving N excreted in urine could improve manure quality. ‘Enriching’ manure with inorganic fertiliser can also improve its quality. Developing techniques and practices for using manure in integrated nutrient management technologies, or improving the timeliness of application in relation to location-specific biophysical conditions, could also be useful (Murwira *et al*., 1995). There may also be merit to developing cut-and-carry techniques for animal fodder, particularly where social reform allows small farmers control over new areas of land, as, for example, in Nepal with the Community Forestry Schemes.

In some FAI areas, cattle may be absent altogether due to the prevalence of disease. This has generally prevented the development of mixed-farming systems to such an extent that the use of cattle is relatively alien to farmers concerned. For animal manure to become an integral component of such systems, therefore, considerable cultural resistance will need to be overcome, and farmers will have to learn how to deal with the disease problems. It may not be appropriate to consider the use of cattle in such areas, unless intensification of agriculture makes mixed farming more acceptable. Other sources of manure may, however, be used - perhaps poultry manure from chicken farms or manure from smallstock that are kept around the homestead. It is worth noting that what is ‘culturally’ acceptable practice now can also ‘evolve’ in the future. For example, farmers may be willing to accept the use of manure where there is pressure for change resulting from land scarcity as the population increases, particularly if large benefits are demonstrated.

Evidence in the literature suggests that the use of manure as a fertiliser is often related to the initial wealth of farmers and their ability to supply labour. The application of manure at ‘ideal’ levels for fertility maintenance may simply not be possible for most resource-poor farmers, as these quantities can be several tons per hectare. Credit provision at reasonable rates and opportunities to earn income from off-farm activities may ease this situation. The benefits to the soil, however, are probably more related to improvements in physical characteristics rather than the provision of nutrients, especially in the quantities that farmers can supply (Singh & Desai, 1991).

In densely populated areas, factors such as further population increase, land scarcity for fodder production, and decreasing fuelwood availability (Ali, 1996), may all increase the opportunity cost of using manure as a fertiliser. Manure is generally regarded as valuable by farmers, but not always as a fertiliser or soil conditioner. Manure needs to be seen as a multi-benefit resource, often contributing more to sustainable livelihoods when used for purposes other than soil chemical and soil physical improvement. Where it is used for crop production, particularly at the levels that resource-poor farmers can manage to supply, it is probably better seen as a technique for soil physical improvement rather than fertility improvement.

Again, the use of manure should be seen as a partial solution, either as a component in an integrated nutrient management system, or for use in certain niches with specialised crops. The fragmentation of fields occurring in many developing countries may also make it more difficult to transport manure, reducing farmers’ willingness to apply it to areas located at a distance from the homestead (Enyong *et al*., 1999). Thus, it may be most rational to apply it to close to the homestead on high-value crops. Only wealthier farmers may own, or be capable of purchasing, transport for the application of manure to distant fields. In some areas where cattle traditionally tend to roam free, it may be possible to 'walk' the manure to the field and corral cattle for a certain amount of time (Enyong *et al*., 1999). This requires culturally-binding social contracts of some sort.

The easy availability of substitutes for other services supplied by manure (for example cheap fuelwood), may also encourage its use in crop production. Farmers with access to credit may be more likely to buy manure, and may also be more likely to own their own livestock to produce manure. It is worth noting, however, that notions of value vary from place to place depending on the cost of alternatives and some farmers may see it as a relatively low-cost technique (Enyong *et al*., 1999).

The production and use of manure is labour intensive (Enyong *et al*., 1999), and households without adequate labour, or the means to procure it (e.g. in communal work groups or through purchase), may only be able to use limited amounts of manure. In general, investment in manure as a soil conditioner and fertiliser increases where an enabling environment for agriculture is provided. For example, in areas where there are market outlets and effective extension networks providing technical guidelines on good manure practice, farmers may be encouraged to increase productivity, stimulating the use of manure as one of the various options available for increasing crop production (Enyong *et al*., 1999).

7.2.9 Cover crops

Considerations for adoption of cover crops are probably similar to those noted for improved fallows above. Intermediate intensities of land use are likely to be the best context, as the opportunity cost of land will be high in land extensive systems, while the opportunity cost of labour and capital will be high in land extensive systems (Tarawali *et al*., 1999). Security of land tenure is also important as several years are required to reduce weeds (Tarawali *et al*., 1999) and enhance soil physical and chemical properties to a level that might sustain another arable rotation. Cover crops may also require some financial and labour investment, and the farmer will want to be able to return to benefit from this. Capital expenditure could include that for herbicides and fertiliser as some evidence suggests that cover crops are not capable of indefinitely sustaining arable crop production, even in rotations (Tarawali *et al*., 1999). Purchase of seed can also be costly and this has been identified as a major constraint in some areas. Those farmers with intermediate levels of wealth and/or off-farm incomes may be best placed to use cover crops in improved fallow (Tarawali *et al*., 1999). For them, the opportunity cost of agricultural labour may be relatively high, which is why they may decide to fallow land (Franzel, 1999). Poorer farmers are likely to make use of natural fallow unless they are provided with credit facilities and/or other incentives (Tarawali *et al*., 1999) or have a large labour pool. However, the opportunity cost of capital, land and labour may be relatively high. Wealthier farmers may decide to use inorganic fertilisers during the cropping cycle, although as they may often have fairly large farms, part of the farms may be under fallow. Labour demand and the timeliness of that demand may also be problematic and cover crops will probably have the best chance of being adopted by households with some surplus labour. This can sometimes be difficult as labour availability in rural areas may often be declining as farmers attempt to broaden their livelihood strategies with off farm work.

Cover crops do seem to have had some success in addressing problems of soil fertility and weed control. It has been shown that short-term fallows of herbaceous crops such as *Mucuna* can help increase main crop yields compared with continuous cropping, and that weed densities can be reduced (Tarawali *et al*., 1999). Farmers seem to be well aware of these benefits (Buckles & Triomphe, 1999; Franzel, 1999). Because of this, the adoption of cover crops by farmers has been relatively widespread (Sanchez, 1999). In Benin, for example, it was estimated that about 10,000 farmers tested *Mucuna* between the years of 1988-1996 (Tarawali *et al*., 1999). Other estimates suggests that about 100,000 farmers in Benin know about *Mucuna*. (Versteeg *et al*., 1998).

Various formal and informal sector organisations have promoted *Mucuna* in Benin - for example the Insitute National de la Recherche Agricole du Benin (INRAB), the Centre d'Action Regional pour le le Developpement Rural (CARDER), the Recherche Appliquee en Milieu Reel (RAMR), the Royal Tropical Institute of the Netherlands, SG2000, the International Institute of Tropical Agriculture, amongst others. An adoption study by RAMR suggests that about 25% of farmers have used the technique at least twice (classified as adopters), whilst about 35% have rejected the technique, defined as those have used it once and not intending to use it again whilst still having a speargrass control problem on their plots (Versteeg *et al*., 1998). Farmers have cited the need to control speargrass infestations as the primary motivation for *Mucuna* use, rather than soil fertility enhancement. Non-adopters have cited leaving the field unproductive during the minor season as a major disincentive as well as the lack of a use for the grain produced by *Mucuna*, which is toxic unless treated properly (Versteeg *et al*., 1998).

Widespread adoption of *Mucuna* as a cover crop is also evident in Honduras, where, without any extension support, it has spread from farmer to farmer since the 1970s when hillside areas were first used for agricultural production due to population pressure on the plains (Buckles & Triomphe, 1999). The species may have been introduced from neighbouring Guatemala, but is now used exclusively as a soil fertility technology. Farmers plant *Mucuna* in the first season and maize in the second. On average, those who have adopted the *Mucuna* technique planted twice as much maize as those who did not. Despite this, the total amount of land occupied by their cropping system was less, as they no longer needed large areas to fallow, although, interestingly, overall deforestation rates continued to increase because of an influx of migrants into the area (Humphries, 1996). Experimental evidence indicates that this system is capable of maintaining soil N and OC, Ca, *p*H and P levels. This is largely achieved through a large biomass production of about 10-12 t ha^{-1}, and large amounts of N (about 300 N kg ha^{-1}) being contributed through this biomass, although, of course, only a proportion of this represents a net addition to the system through nitrogen fixation. This high biomass production is due to the relatively ideal growing conditions - mean annual precipitation is about 3000 mm in a bimodal pattern, and mean annual temperatures at sea level are about 26 °C with an annual variation of about 10 °C. Soils are relatively rich (OC%=2-3%), undegraded, and deep (60-80 cm), with high levels of exchangeable bases, and a *p*H of about 6.0.

Various socio-economic factors have also contributed to the widespread use of *Mucuna* as a cover crop. Farmers have perceived and accepted the benefits of the technique, citing the fertiliser effect, ease of land preparation, and moisture conservation as important advantages, with weed control and erosion control of lesser importance. The seasonality of maize prices has also encouraged the use of the technique, as maize planted during the second season commands a higher than average value. These factors all help to improve productivity both to land and to labour. The benefits are such that farmers who rent land are even willing to pay a premium on land that has been under the *Mucuna* technique. This has also encouraged landlords who own more land than they are able to cultivate under maize to invest in the technique. Thus, while rental of land generally discourages investment in techniques by tenants, the availability of land and the value placed on *Mucuna*-treated fields has encouraged the spread of the technique.

Access to a rental market at reasonable rates has also allowed farmers with relatively small areas of land to fallow it with *Mucuna* to restore soil physical and chemical status. Access to land has been relatively secure as squatters could claim ownership of the land by clearing and cultivating it, and so far, land availability has been high enough to ensure that the opportunity cost of the *Mucuna* crop is sufficiently low as to maintain continued use of the technique. However, the situation is dynamic and the opportunity cost of using *Mucuna* is increasing as the growth of large ranches into the hills also increases, reducing the availability of a land and driving up land rental prices. More and more farmers are likely to be unable to use the technique as they will be increasingly forced to use available capital, land and labour for the production of food rather than *Mucuna*.

In other areas cover crops have found niche uses with high value tree crops, even though little extension effort has been made for this. In Sri Lanka, for example, farmers are using cover crops to preserve soil moisture in coconut plantations (Mathes & Kularatne, 1996). Another possibility may be for feed meal production (Kerridge *et al*., 1996).

7.2.10 Summary

In the following, we have attempted to summarise the main biophysical and socio-economic characteristics of the various technologies, and make suggestions as to where they are most likely to be successfully adopted.

Temporal techniques

(Improved fallow)

Regenerative dynamic: Temporal, relying on fallow period of woody and herbaceous legumes to 'improve' fallow and rejuvenate fertility, soil organic matter and suppress weeds.

Positives: May fit well with the evolution of many FAI areas as populations rise (long fallow to short fallow). Therefore builds on a known technology - long fallow rotations. Multifunctional (SOM, nutrients and weed control). Relatively flexible as fallow can be extended or shortened. Could also be developed to provide other services, (fuelwood). No spatial competition between crops and regenerative trees.

Negatives: Temporal competition for land. Incapable of sustaining yields where fallow periods are therefore reduced below certain limits. Moderate capital and labour requirements.

Possible niches: Areas where short, natural fallow periods already exist, or are becoming more prevalent (Ghana). Areas located far from the homestead, therefore less intensively used (Ghana). Areas where land has been more or less abandoned, because of weeds or low fertility (Ghana, Nepal, Brazil, Bolivia).

Socio-economic considerations Ideally the farmer will be able to fallow the land for several years. Moderate capital availability for investment in seeds/seedlings; therefore credit at reasonable rates, some off-farm income or an 'intermediate' level of wealth may be required. 'Intermediate' level of land scarcity, security of tenure, good access to land markets at reasonable rates. 'Moderate' labour availability as more labour intensive than natural fallow. Possibly an opportunity cost to agricultural labour might encourage fallow.

Low opportunity cost of natural fallow, and 'intermediate' levels of population density.

Biophysical considerations Ideal climatic conditions for plant growth may result in the potential to reduce the fallow. However, sub-optimal conditions can be compensated for, by adjusting the length of the fallow. The same can be said for temperature. Soil *p*H should ideally be neutral for optimal BNF in legume/*rhizobial* association. Loamy to clayey soils may allow the fastest recovery of SOM and fertility. Sandy soils may require longer fallow periods.

Suggestions In Ghana, there may be opportunities, as natural fallow rotations are already important. In Nepal, land pressure may be too high, but some possibilities might exist on abandoned land. In Bolivia and Brazil, conversion of land to pasture may offer better economic opportunities than arable agriculture, but land might eventually be put under improved fallow if pastures also degenerate. Might be useful to integrate other services into the fallow, for example fuelwood. Some integrated use of herbicides may be necessary to kill weeds. Some fertiliser use may also be required if fallow period becomes very short. Could be used in less than optimal biophysical conditions.

Enriched fallow

Regenerative dynamic: Temporal, relying on multipurpose trees species to enrich the fallow period more and make them more productive, supplying cash and/or subsistence benefits.

Positives: May build on known techniques as enriched fallow may be traditionally practised at the FAI (e.g. oil palm in fallow). Multifunctional (SOM, nutrients and weed control), with additional cash income possibilities. Relatively low opportunity cost (natural fallow). Relatively easy exit route. Could potentially lead to permanent establishment of spatial agroforestry systems with high mixed cash and subsistence value. Spatial competition for land.

Negatives: Temporal competition for land. Requires relatively large areas of land. Difficult where population pressure, (or other considerations) cause land to be brought back into cultivation for staple crops, or before benefits of enriching plants can be felt. Suitable outlets may be needed for tree products. Investment in seedlings or seeds will be needed and some labour required for planting. May not be adopted where use of fire is widespread.

Possible niches: Could be used in areas where short, natural fallow or enriched fallow periods already exist. Alternatively where there is a high potential cash or subsistence value for tree products. Also on land nearest to the homestead, as such fallows may require relatively high labour requirements and protection from thieves.

Socio-economic requirements The length of fallow needs to be long enough to allow enriched plants to produce, unless they become a permanent feature of the system. Quite high capital availability for

	investment in seedlings; therefore credit at reasonable rates, some off-farm income or an intermediate level of wealth may be required. 'Intermediate' levels of land scarcity, and security of tenure. 'Moderate' labour availability will be required for planting and maintenance of seedlings. Low opportunity cost of natural fallow. 'Intermediate' levels of population density. Market or other outlets for tree products may be necessary.
Biophysical considerations	Good plant growing conditions will be needed for trees planted to enrich fallow and to ensure no competition with staple crops, if the system becomes permanent. Soil *p*H should ideally be neutral for good plant growth and loamy soils may be best for optimal tree growth.
Suggestions	Enriched fallow should be seen primarily as a diversification technique rather than as a fertility technique. Good support (nurseries) may be needed, as good fruit tree development requires access to good provenance. An alternative strategy may be to select valuable naturally occurring trees from the fallow for preservation in the cropping phase. Locating enriched fallows near the household might encourage development into permanent agroforestry systems as valuable trees could be kept. However, competition will have to be avoided with main crop. Location close to homestead is important, as high value trees are unlikely to be planted where they cannot be protected and maintained. In Ghana, there may be potential for developing permanent agroforestry systems, through enriched fallow, if competition with main crops can be avoided. In Nepal, land pressure may be too high for enriched fallow, although wealthier farmers may be able to develop permanent orchards in this way. In Bolivia and Brazil, conversion of land to pasture generally provides the best economic opportunity. However, land near the homestead could be turned into orchard through enriched fallow.

Sequential cropping with herbaceous or grain legume cover crops

Regenerative dynamic:	Temporal – N regeneration with single seasons herbaceous or grain legumes.
Positives:	No direct competition with main crop, fixes N, mobilises other nutrients, provides SOM, often improves soil physical structure, soil moisture content.
Negatives:	Quantity of N fixed is unlikely to provide sustainable basis for continuous cropping. Temporal niches may be difficult to find and the farmer may want a harvestable product, as in the case of grain legumes. In this case much of the N is removed with the harvest. Where cover crops do not provide full temporal coverage, weeds may benefit from added N rather than the crop and weed infestations may become even worse.
Possible niches:	Where natural off-season fallow is already practised. Useful for high value or staple crops. Most likely where land intensification is already relatively high and climatic conditions allow year round growth. Where weed infestations are problematic.
Socio-economic considerations	Some capital may be required for seeds as well as supplementary fertiliser and possibly herbicide. Land intensification may need to be high.
Biophysical considerations	Bimodal or year round rainfall. Suitable climatic conditions to allow for satisfactory off-season plant growth.
Suggestions	Sequential cover crops provide partial solutions to a variety of problems. In particular, farmers appreciate their impact on soil physical characteristics, such as softness and moistness. Where weeds are a problem, cover crops may also be useful. Good off-season plant growth conditions are required especially if weed control and rapid BNF is desired. Possible use in Nepal as a seasonal fallow if suitable temporal niches are available. Unlikely to be grown in summer, unless as a grain legume, as other crops take precedence. In Ghana, Bolivia and Brazil, most FAI areas may be too sparsely populated to make sequential intercropping suitable, except on more intensively cultivated high value plots of land.

Biomass transfer techniques

(Off-farm)

Regenerative dynamic:	Transfer. Herbaceous and perennial plants (often leguminous) may be used to transfer nutrients from one area to another.
Positives:	No direct competition with main crop for environmental resources. May provide a net increase of on-farm nutrients. May increase SOM.
Negatives:	Much labour is required for pruning, transport and incorporation of biomass. Establishment of biomass banks may be costly. Large quantities of biomass required for significant effects.

	Biomass transfer is most likely to occur from common land anyway. Unlikely to supply full crop requirements in quantities that farmers can supply.
Possible niches:	Where land intensification is leading to reduced possibility of fallow rotation. Supply of biomass to high value crops, especially in areas where biomass-supplying plants are very plentiful. Where areas of land have been given over to used groups or individuals, on areas of land that may be too distant for cultivation (Nepal). Where common resources have been degraded.
Socio-economic considerations	Large labour availability for prunning and transfer of biomass. Alternatively capital to be able to purchase labour for biomass transfer. Availability of high quality plants from common land.
Biophysical considerations	
Suggestions	Biomass transfer is generally widespread where there is access to large quantities of organic matter from common resources that already exist. It is unlikely that most resource-poor farmers at the FAI will be willing to develop biomass banks off farm on common land, although they may be willing to invest in their management. Development of biomass transfer from common resources may be possible in Nepal, where it is already a major technique. Also in areas where fodder is needed for stall-fed animals. Some development may also be possible where leasehold schemes or community management schemes give control of land to resource poor farmers. In Ghana, the relative availability of land may make fallow techniques more suitable. In Bolivia and Brazil, the high availability of land and the low availability of labour makes transfer of off-farm perennial biomass relatively unattractive, especially as the arable cycle is relatively short and the end aim is often conversion to pasture.

(On-farm)

Regenerative dynamic:	Transfer. Herbaceous and perennial plants (often leguminous) may be used to transfer nutrients from one area to another.
Positives:	Recycles leached nutrients from below crop root zone. Transfers nutrients from one area of the farm to another.
Negatives:	Very labour intensive, as much labour is required for pruning and incorporation of biomass. Establishment of biomass banks may be costly. Large quantities of biomass required for significant effects. Unlikely to supply full crop requirements in quantities that farmers can supply.
Possible niches:	Where the farmer has land that cannot be cultivated. Where other requirements such as fodder are important.
Socio-economic considerations	Access to large farm areas, or insufficient labour to fully cop land. Fodder requirements, especially in mixed farming systems.
Biophysical considerations	Good plant growing conditions, to make investment in fodder banks worthwhile
Suggestions	On-farm biomass transfer are most likely to be used where they have some other purpose, for example fodder provision for stall-fed livestock and where alternative fodder supplies are limited. Such conditions are likely to be very specific, but are probably likely to occur at spatial FAIs. On the whole it is not likely that on-farm biomass transfer will be used by farmers for the primary aim of SOM and soil fertility enhancement.

Compost

Regenerative dynamic:	Transfer - collection and transfer of nutrients from one area to another
Positives:	Increases the speed of decomposition of plant material and allows moderate grade material to be used with less risk of immobilisation. Short time horizon for benefit.
Negatives:	Requires manipulation of very large quantities of biomass for full soil and crop needs. Requires large labour resources for preparation and transport of compost. Requires good supply of water to help decomposition. There may be many competing demands for biomass used in compost.
Possible niches:	Most relevant to spatial FAIs where land intensification makes other fertility techniques less suitable. In both temporal and spatial FAIs, close to homestead on high value subsistence and cash crops.

Socio-economic considerations	Large labour resources for preparation and transport of compost. Some capital availability to improve the compost, or to pay for transportation and incorporation of compost.
Biophysical considerations	Access to water and large quantities of biomass. Alternatively, adequate rainfall to keep the compost moist.
Suggestions	Preparation, transportation and incorporation of compost can be extremely labour demanding and compost should seen as a partial solution to soil fertility. Low cost techniques of improving compost quality (by mixing with manure and/or fertiliser for example) and reducing labour input may therefore be useful. Compost may be most important on land near the homestead, especially in temporal FAIs such as Ghana, where fertility may be regenerated by fallow and in coloniser FAIs such as in Brazil and Bolivia, where land tends to be converted to pasture. In spatial FAIs such as in Nepal, more widespread use may be possible, especially by wealthier farmers. However, topography may make use difficult on isolated fields.

Animal manure

Regenerative dynamic:	Transfer – collection and transfer of nutrients from one place to another.
Positives:	Particularly useful in climatic conditions which do not favour decomposition, for example very cold or dry conditions, as the rumen provides good conditions for decomposition. The farmer has the added advantage of benefits from owning cattle, such as milk, meat and draught power.
Negatives:	Much of the N can be lost in urine if this is not collected, used or stored. N can be lost through volatilisation, leaching and denitrification. Very large quantities of animal manure may be required for ‘ideal’ effects on crops. Labour requirements for transportation and incorporation are therefore high. Low quality manure may cause immobilisation of N and P. There may be many competing demands for manure, for example as fuel. Water may be required to keep the manure-compost moist.
Possible niches:	In both spatial and temporal FAIs, locations close to the homestead, on high value subsistence or cash crops, may be most suitable for manure-compost. In general, will be most used in spatial FAIs where land intensity precludes fallow regeneration of soil. In areas where soil physical improvements are necessary.
Socio-economic considerations	Large household labour availability, or access to labour through cultural or capital means. Availability of stall-fed livestock and manure. Availability of suitable alternatives for other services provided by manure.
Biophysical considerations	Disease-free areas, especially from tse-tse fly.
Suggestions	Manure may be a partial solution to fertility problems at the FAI, due to the high labour requirements and the competing demands for its services. In both temporal and spatial FAIs it may be most suitably used close to the homestead on high value cash and subsistence crops. It may be best to concentrate on improving techniques of manure-compost production. For example, it could be enriched with fertiliser, which might aid decomposition and reduce the quantity of manure required for nutrient supply.

Spatial techniques

Alley cropping

Regenerative dynamic:	Spatial – BNF, mobilised nutrients and SOM through *in situ* banks of leguminous perennials
Positives:	Requires no fallow period. Useful on slopes, where erosion is problematic.
Negatives:	May result in suppression of main crop through excessive competition. Highly inflexible. High cost to not following prescribed practice. High initiation costs. Requires long planning horizon, as benefits from investment are slow to accrue. Difficult to use in a niche. Extra nutrients may be required to ensure that competition does not occur, making it difficult for resource-poor farmers to use. High exit cost in labour and capital terms (removing hedgerows). Hedgerow interference with tillage operations.
Possible niches:	On sloping land, where erosion is problematic.

Socio-economic considerations	Access to large amounts of capital for planting of hedgerows. Seedling availability. Labour availability, either through the household or purchased. Land scarcity may encourage use of alley cropping as rotational techniques will be unsuitable. Capital for inorganic fertiliser. Security of tenure.
Biophysical considerations	Neutral soil conditions, high fertility and inorganic fertilisers, adequate precipitation to ensure that competition with the main crop cannot occur.
Suggestions	Alley cropping may be most useful at FAIs where the hedgerows provide additional services, for example, fuelwood, fruit, fodder and medicine. Also in areas where soil erosion is a problem. The fertility function of alley cropping may probably be best seen as an added bonus if it occurs, particularly as nutrients may be required to keep the system sustainable and ensure that competition does not take place. And selecting for example leguminous trees species on the basis of large biomass requirements tends to make life difficult for the farmer, as the cost of not following prescribed practice can be disastrous for crop yield.

Multipurpose trees

Regenerative dynamic:	*In situ* provision of multiple benefits
Positives:	Provision of multiple benefits from trees including fodder, food, medicine, fuelwood. Once established, relatively low input requirements.
Negatives:	Long planning horizon required. Seedling availability. High capital requirement for seedling purchase, protection and maintenance. Competitive effects with crops in planted on arable land.
Possible niches:	In both temporal and spatial FAIs, most applicable on land close to the homestead. Wealthier farmers may be able to multipurpose orchards, particularly if demand exists for products.
Socio-economic considerations	Pressure on common resources. Land scarcity and increasing population pressure. High capital availability and long planning horizons. Poor farmers may be limited in the number of multipurpose trees they can plant by requirements to produce food. High capital requirements are needed and a means of protecting and maintaining seedlings during establishment. Security of tenure.
Biophysical considerations	Good plant growing conditions.
Suggestions	Multipurpose trees may be best seen as a means of providing for immediate subsistence and cash needs, rather than provision of soil fertility and organic matter. These may be seen as secondary benefits. Large collections of multipurpose trees may be best used on land close to the homestead where trees can be protected and tenure is secure. Good access to capital may be required on land that is planted with multipurpose trees away from the homestead in particular for protection and watering during establishment.

Full and relay intercropping with herbaceous or grain legume cover crops

Regenerative dynamic:	Spatial. Some BNF is provided during crop growth.
Positives:	May provide some nutrients without sacrificing land for legume. Reduced competition and/or facilitation of main crop.
Negatives:	The legume is unlikely to produce sufficient N to allow continuous cropping of the main crop. Competition for resources, such as water and nutrients may reduce main crop yields.
Possible niches:	Spatial FAIs where land intensification is high. Temporal FAIs where high value crops are grown together or with a grain legume of cash or subsistence value in optimal plant growing conditions.
Socio-economic considerations	Capital will be required for seeds, fertiliser and herbicides. Such techniques will not be capable of providing adequate N especially where grain legumes are valued for subsistence or cash value. Land intensification will increase likelihood of intercropping. Intercropping may also be most likely in areas of with animal or mechanised draught.
Biophysical considerations	Optimal climatic and soil conditions will be required to ensure that competition does not occur. This may even mean providing nutrients in certain conditions.
Suggestions	Intercropping should not be promoted as a fertility enhancing technique, but as a strategy for crop diversification and risk reduction. Full intercropping may be unlikely unless long season legumes prevent competition with main crop. Otherwise relay cropping will be most

useful. Grain legumes might be useful if competition with the main crop can be reduced. In Nepal there may be some scope for intercropping, but more probably as a risk reduction and crop diversification strategy rather than as a soil improvement technique. In Ghana, Bolivia and Brazil, intercropping may only be useful in intensively cultivated areas, for example near large population, possibly with high value crops.

7.3 Temporal, spatial and personal dimensions of the techniques

The analysis given by Boserup (1981) and discussed in Section 1.1.2, provides a useful framework for examining the position of the various techniques being evaluated for use at the FAI, in relation to population density. We have attempted in Table 7.1 to group the techniques according to Boserup's (1981) classification. Thus, where shifting agriculture still predominates but populations are increasing, as in Ghana, the introduction of improved and/or enriched fallows, and rotation technologies, possibly with perennial legumes, moving to annual legume rotations as population pressure increases, might be most appropriate. The promotion of greater use of animals within such systems would also seem to be a logical step.

On the other hand, where land is already scarce, temporal soil fertility techniques are unlikely to be suitable. The most appropriate techniques in such circumstances might be biomass transfer from off-farm sources (if possible), intercropping or relay cropping, and use of mineral fertilisers. Biomass transfer, of course, requires large amounts of labour and may require capital where sufficient organic matter cannot be supplied with household labour alone. Intercropping and relay cropping are capable of supplying only a partial solution to farmers' nutrient problems, and hence judicial use of mineral fertilisers is a requirement if reasonable crop yields are to be achieved. This is mostly the situation currently found in Nepal. As population densities increase still further, it may be increasingly necessary to integrate inorganic and organic technologies, and to use techniques offering multiple benefits. Fertility issues alone will not be sufficient to maintain a farmer's interest in a technology – the supply of edible food grains, fodder, or fuel, as well as short-term financial rewards, will become increasingly important.

The table only acts as a guide, and there are often exceptions. For example, it is quite possible that improved fallow could be used in densely populated areas, for example, where wealthier farmers own large areas of land or poorer farmers are largely involved in off-farm work, increasing the opportunity cost of agriculture (Swinkels *et al*., 1997). Alternatively, in low density areas, intensive use of land could take place near to homesteads (Ruthenberg, 1980), where labour intensive techniques such as biomass transfer could be used.

Table 7.1. Possible technological interventions for each of the agricultural systems defined according to Boserup (1981).

Boserup classification	Land availability (ha person^{-1})	Population density (persons ha^{-1})	Possible techniques
Hunter gatherer, pastoralism or forest fallow	>25	< 0.04	• Home gardens?
Bush fallow	6.3 - 25	0.04 - 0.16	• Home gardens?
Bush fallow and short fallow with domestic animals	3.1 - 6.3	0.16 - 0.32	• Home gardens? • Improved fallow • Enriched fallow • Cover crop rotation • Multipurpose trees species • Fruit trees
Annual cropping with intensive animal husbandry	0.4 - 3.1	0.32 - 2.56	• Improved fallow • Enriched fallow • Biomass transfer • Cut and carry grasses • Cover crop rotation • Intercrops • Crop residues • Animal manure • Compost • Integrated nutrient supply
Multi-cropping with little animal food	< 0.4	>2.56	• Grain legume rotations • Grain legume intercropping • Off-farm biomass transfer • Animal manure • Crop residues • Compost • Integrated nutrient supply

The context of the technique does however also need to be considered. Fast-growing timber plantations in agroforestry systems are unlikely to be adopted where local timber values are extremely low, or contractors are only interested in buying timber in quantities that farmers can't possibly supply. Land tenure is also important in the development of more intensive systems of agriculture. Insecure tenure or certain forms of tenancy such as share-cropping, may preclude the use of techniques whose benefits are long-term in nature. Agroforestry techniques may be particularly prone to rejection where the benefits from using the technique cannot be guaranteed through long term tenure or any other cultural mechanism. Resource-poor farmers may discount the future benefit from these techniques highly, making the value of interventions with them fairly minimal and techniques therefore need to be able to offer rapid results.

7.3.1 Temporal dimension

Figure 7.1 illustrates the temporal dimension of the low-input techniques we have reviewed. The usefulness of various techniques may change as agricultural systems change in response to population pressure on land. Population will also have a bearing on the labour available for agriculture. Farmers in countries where much land is still available for agriculture may find techniques with temporal dynamics (e.g. improved or enriched fallows) most useful. In countries where land is scarce and populations high, techniques with spatial dynamics (e.g. compost and manure, and possibly *in situ* intercropping of legumes) are likely to be most useful.

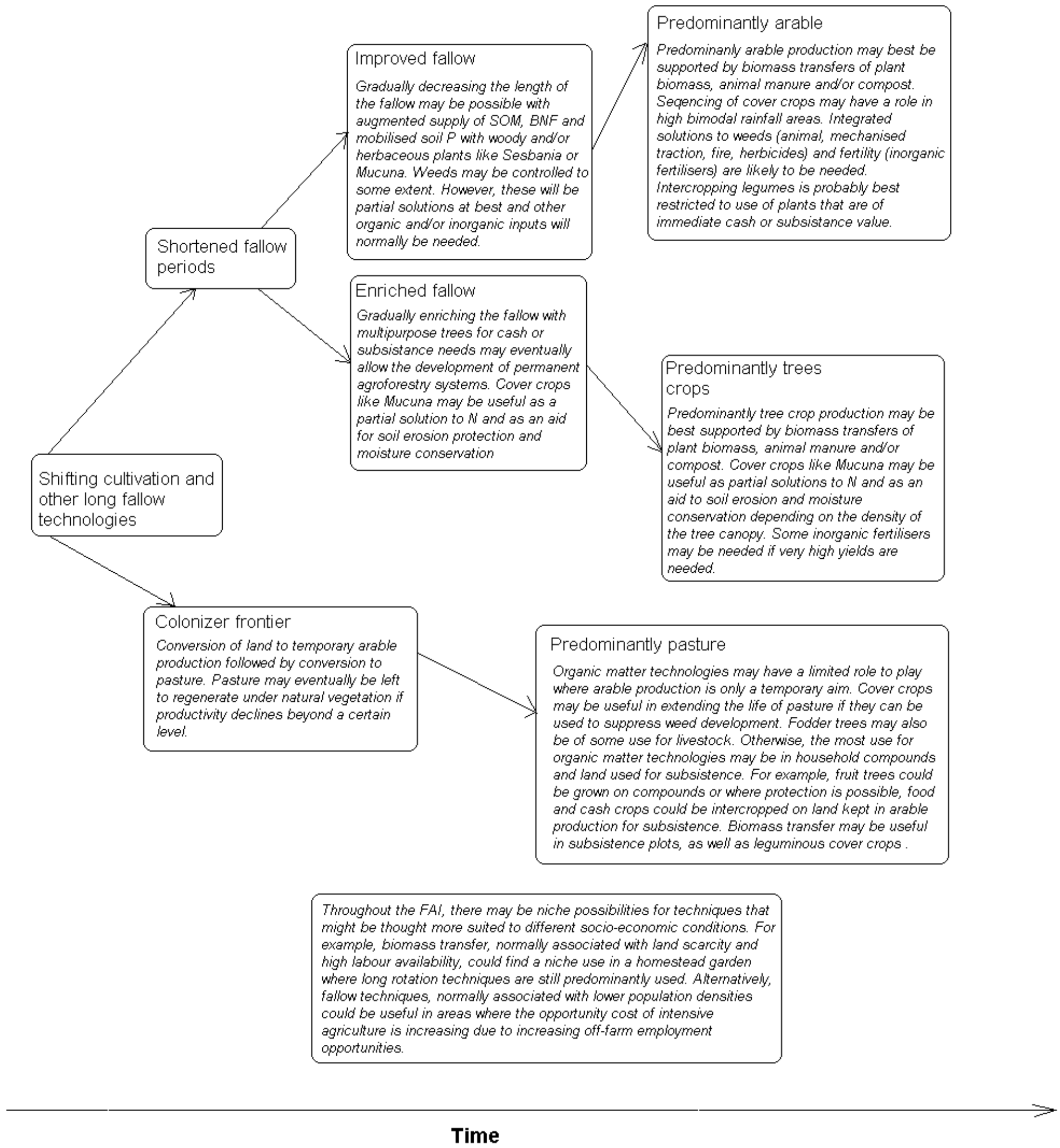


Figure 7.1. Time bound nature of low input organic techniques. Major temporal niches for the techniques exist as population increases and agricultural systems intensify with time.

7.3.2 Spatial dimensions

Often there is also a spatial dimension to the use of the low-input techniques even in FAI areas strongly dominated by temporal dynamics (Figure 7.2). Manure or compost, for example, may be most often used on land near the homestead, whilst rotational or fallow techniques might be more easily used on more distant fields.

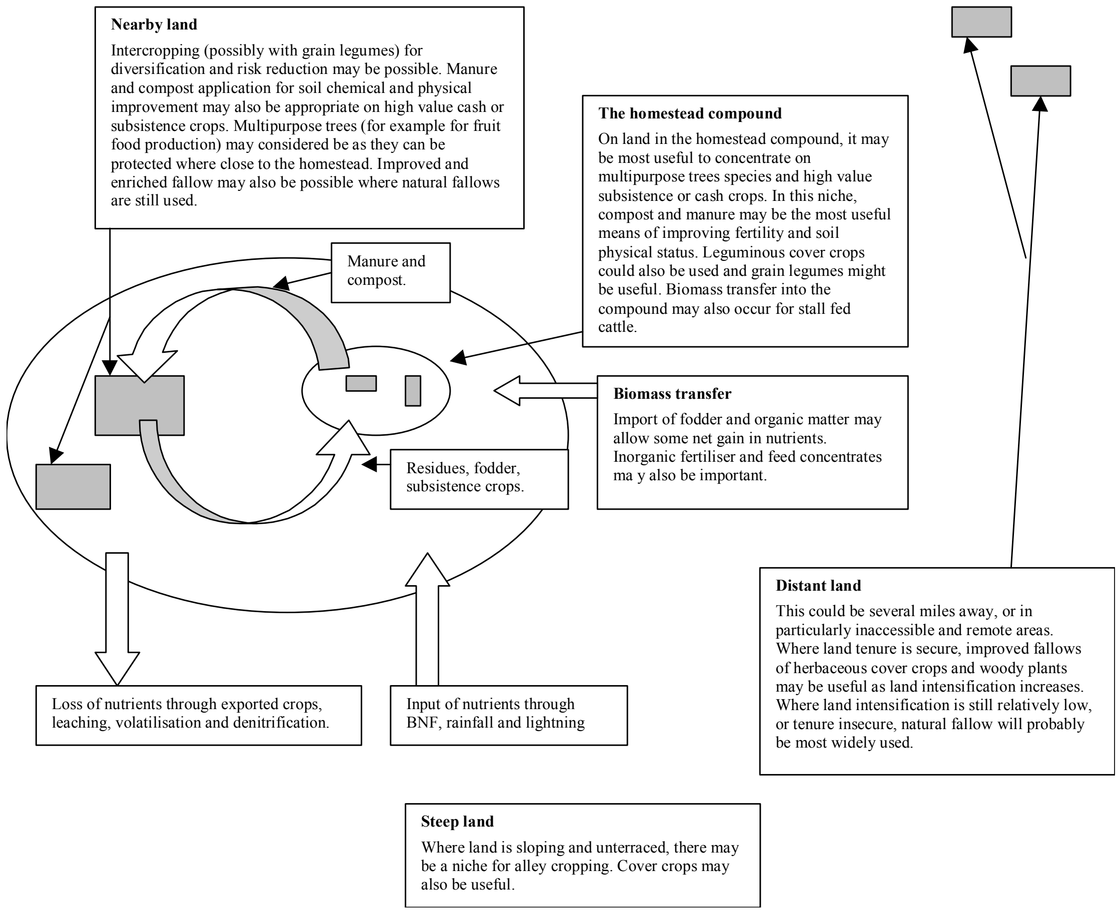


Figure 7.2. Space bound nature of low-input organic techniques and major spatial niches.

Once again, these provide guidelines on the spatial use of low-input techniques, derived from piecing together literary evidence. It is possible and reasonable that farmers may choose to use manure on far off-fields or rotations on nearby fields if this suits their circumstances better and if they have the resources to be able to do so.

The intensification of agriculture may have to go hand-in-hand with improvements in infrastructure. For example, there may be little point increasing productivity beyond subsistence with the use of a technique, if road access is so poor that transport of agricultural products to markets is impossible. Improving agricultural systems at the FAI, and therefore livelihoods, involves investing in infrastructure, the development of markets for agricultural products and a general enabling environment.

7.3.3 Personal context

There may be a personal perspective to the use of organic matter techniques and evidence suggests that farmers may often need to fulfil certain needs more urgently than other needs (Figure 7.3). These needs are represented by the concentric circles. Certain factors may influence the farmer's ability to think about these issues and these are shown on the radial lines overlaying the concentric circles. The diagram below should not be taken as the definitive truth, but rather as an attempt to understand how farmers may prioritise requirements from their agricultural systems. Meeting subsistence and providing some cash income from agricultural activities may often be the most important concerns of the farmer and these are shown as the innermost concentric circles. Stability of yield may be the next major priority, whilst productivity might be next. Once these considerations are satisfied, the farmer may feel able to consider the wider issues of fertility, erosion and indeed the wider externalities of agriculture, represented by the outermost of the concentric circles.

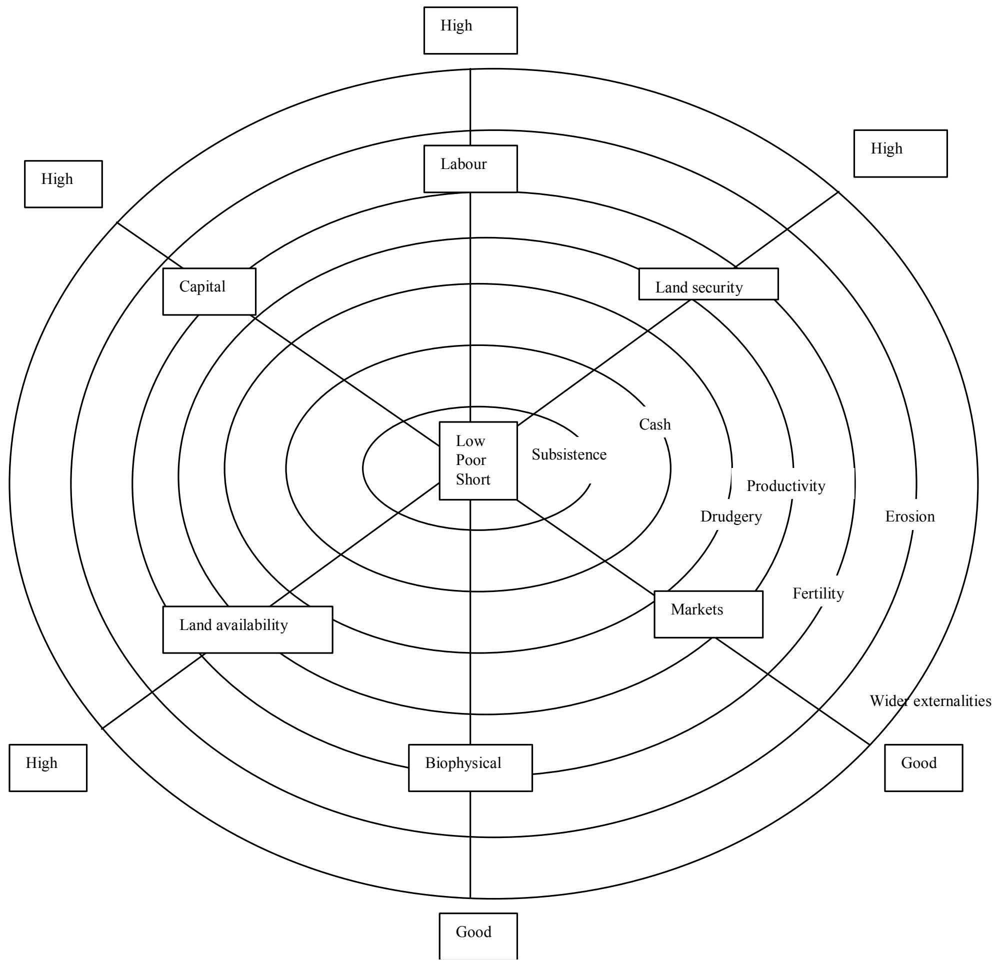


Figure 7.3. Schematic representation of possible priorities of farmers. These may be affected by various factors, such as capital or land security, which determine the ability of farmers to address various issues.

Various factors may influence the farmers' ability to consider these issues, in effect to expand or decreased the number of concentric circles, which he/she considers. For example, poor land security, poor access to capital may tend to push the farmers considerations inward along the radial lines, to consider only subsistence and cash needs. On the other hand, the greater the security of tenure of the farmer or their access to capital, the more their focus can travel outwards along the radial lines to consider issues of fertility erosion and possibly even, in exceptional circumstances, the wider externalities of their agricultural activities. Many technical solutions at the FAI may have been developed to operate on the outer areas of concern, addressing issues of productivity, erosion and wider externalities, rather than tackle what may be of most immediate concern to resource poor farmers, for example, reducing drudgery or promoting stability and cash income. The ‘gaps’ that occur need to be tackled in order for farmers to use organic matter techniques. For example, increasing security of tenure or access to capital, may allow farmers to broaden their horizons to the outer rings. Techniques may also be introduced, which tackle the farmers most immediate concerns, such as reducing the drudgery of labour and promoting stability of yields, rather than the wider concerns such as erosion and fertility. Possibly, the best solution may be to use both strategies at the same time.

7.4 The focus countries

7.4.1 Ghana

In Ghana, long fallow techniques are still used by farmers in many FAI areas to maintain soil fertility and suppress weeds. However, the use of these systems is becoming less sustainable as fallow periods are reduced due to population pressure. Short rotation fallows and organic matter management techniques are, therefore, likely to become increasingly widespread as populations rise further. However, there may be factors that restrict the uptake of some of these techniques. For example, the adoption of improved fallow techniques may be resisted, as they require extra labour and may not markedly improve yields of crops when the land is brought back to agriculture again. Similarly, the use of agroforestry may be limited in situations where fire is widely used as a labour saving technique to clear land. The use of leguminous cover crops, either in sequence or intercropped, may be possible where the farmer is growing high-value crops. Biomass transfer techniques may also be possible in such situations. However, uptake of both of these types of techniques may be limited if they cause labour to increase. It is interesting to note that the dense vegetation provided by cover crops is thought by farmers to be responsible for the multiplication of snakes and other pests, and there may be substantial resistance to cover crops for this reason. Even agroforestry systems are felt by farmers in some cases to encourage the presence of pests harmful to the main crop.

As discussed in the previous section, the promotion of greater use of animals within agricultural systems is a logical step in their intensification, and, indeed, is part of the National Soil Fertility Management Action Plan for Ghana (MoFA, 1998). However, as discussed in Section 2.5.2, considerable farmer training is required in livestock management, as many have no tradition of keeping and caring for animals. Issues relating to disease, particularly of cattle, will also need to be resolved.

Land tenancy is also likely to be a major stumbling block for the adoption of many of these techniques. Where farmers do not own the land they farm, they are less likely to want to invest in long-term approaches to soil fertility improvement. Planting of trees, for example, may be felt by land-owners to reduce the rental value of their land, while tenants may feel that the benefits they offer are too far into the future to be of significance to them.

The importance of niche roles for much of the technology should not be under-estimated. Thus, for example, a farmer may be willing to use agroforestry techniques around the homestead. Similarly, the use of animal manure is likely to find more acceptance near to the homestead, as this is where smallstock (i.e. goats, chickens, pigs, etc.) are kept. It is worth noting that there are relatively few cattle in the major

FAI areas of Ghana, and that animal manure, where applied at all, will generally be supplied by smallstock, unless other (commercial) sources are identified.

The wider economic context is also important in Ghana. Inflation rates are very high, and access to credit at reasonable rates of interest is a major problem. In these circumstances, the factors limiting stabilisation of cultivation systems at the forest/agriculture interface is more likely to be socio-economic in nature, such as proximity of markets and processing facilities, infrastructure, or access to credit at reasonable rates. Improved cultivation technologies may not actually make much impact in such circumstances.

7.4.2 Nepal

In Nepal, it is probably most useful to consider improved technology in the context of land scarcity. The FAI there is relatively stable, largely because much of the most suitable agricultural land is already being farmed. This is largely due to the impracticality of developing effective agricultural systems on very steep land. In addition, the best agricultural land may often be on the valley floor and the forest areas above perform an essential role in protecting the lower agricultural land from erosion by runoff, as well as providing organic matter for soil physical and chemical improvement.

The biophysical conditions vary so much within the country and are so extreme that generic technical recommendations become meaningless. Most literature divides the country up into several major areas, the *terai*, the low hills, the mid hills, the high hills, and the high mountains. Most of the forested areas of Nepal occur in the low-, mid- and high-hills, and not in the *terai*, which is very heavily cultivated, or the high mountains, which are mostly grasslands occupied by nomadic tribes. In forested areas, it is likely that improved techniques will have to be used in niche areas. Population pressure is likely to be too great to incorporate rotations or even intercrops of legumes without any subsistence or economic value on-farm.

In general, various forms of biomass transfer from off-farm locations seem to be the most relevant techniques in Nepal. These may be as plant biomass transported from off-farm areas, either for immediate incorporation into the soil, or fed first to stall-fed animals, and the manure incorporated. A mixture of cut and carry grasses, leguminous cover crops, perennial legumes, and even timber trees could be included. Fruit trees planted off farm are likely to be unpopular unless ways can be found to protect against thieves. Developing on-farm leguminous perennial plants, for example, on terrace risers, will hamper farming and terrace maintenance operations and compete with crops for light. There may be some possibility of biomass banks on these areas, but generally lack of space limits on-farm options, except possibly in the case of legume intercrops. A reliable legume intercrop, where main crop yields are not significantly lower than in monoculture, may have some chance of success, provided that the farmer perceives a need to reduce N applications. However, it is important to note that even at the best of times, (grain) legume intercrops provide only a partial solution to crop N requirements. Where a sizeable fraction of the crop is harvested, the benefit from N fixation will be reduced.

There is no doubt that the use of animal manure in the hills is important. Animal rumens provide the perfect environment for the decomposition of organic matter, and this may be valuable where temperatures are limiting, or where conditions are very dry. However, losses of N in urine can be high, and benefits can be obtained by reducing these. Additionally, some benefits could be obtained by developing ways to reduce leaching and volatilisation losses from compost heaps that are left exposed for long periods of time. Integrated nutrient management techniques are the best solution, as enough organic matter needs to be applied to maintain the physical attributes of the soil, but this is unlikely to be able to supply enough N and P die to the huge quantities required, so that judicial use of inorganic fertilisers is required.

7.4.3 Brazil/Bolivia

The expansion of the FAI in Brazil and Bolivia appears to be driven by forces that cannot be affected or changed with the introduction or development of improved cultivation technologies. The conversion of forest land to agricultural land is driven, not by the need to provide fertile land for arable agriculture, but by wider economic pressures. Converting forest land to pasture may triple the value of the land in a relatively short period of time, so that the pioneer farmer can then sell up to a rancher and repeat the process again. Additionally, the influx of new migrants to partake in this process adds further pressure. Huge logging concerns may also be involved in pushing back the forest frontier. The authorities have generally encouraged the exploitation of these areas.

In this situation, it is difficult to see how the FAI can be stabilised with improved cultivation techniques alone. There may be a short temporal niche where some of the techniques may be applied, but if farmers' final objectives are simply to convert the land to pasture as quickly as possible, there is little that such techniques aimed at more stable production can achieve until arable agriculture offers more secure prospects. As discussed previously, there may be niche roles for some of the techniques. Some agroforestry may be viable near homesteads, although the use of fire in many areas to control weed encroachment will limit its success. Moreover, the long-term nature of the benefits from agroforestry when farmers are selling and moving on after a few years, will not make it an attractive proposition. Animal manure is difficult to collect as land scarcity has not yet risen to a level where stall feeding is appropriate. Where farmers are prepared to maintain arable production, rotation techniques may mesh more closely with existing practices. However, the general rule of increasing population means that sooner or later rotation techniques as a means of providing soil fertility will not suffice. Where populations are already too high for rotations to be viable, intercropping and biomass transfer techniques will have to be used. These, of course, will supply some of the needs of the farm, but not all of them.

8 The way forward

So far, we have analysed the techniques that have been evaluated in DFID-NRSP projects in forest/agriculture interface production systems, and have seen that, in terms of the biophysical issues they were designed to address (i.e. organic matter improvement, nitrogen supply, phosphorus availability, and weed control), their success is likely to be limited. A similar conclusion was also reached by Sanchez *et al*. (2001), who argued that sole use of low-input systems is only likely to perpetuate food insecurity and poverty. As such, it is perhaps not surprising that, apart from those that resemble practices currently used by farmers, such techniques are not likely to be adopted widely in their present form.

In this final chapter, we broaden the discussion to consider the wider implications of research in the FAI context and what we might reasonably expect it to contribute to the livelihoods of the rural poor, and make suggestions as to possible ways forward.

8.1 A systems approach to FAI improvement

8.1.1 A farmer-centred approach

The DFID-NRSP projects we have reviewed have generally been aimed at specific biophysical problems associated with FAI production systems. The problems to be solved have been presented as relating to soil fertility decline and weed encroachment, and techniques designed to address these have been evaluated. In this report, in line with our remit to undertake a technical review of the techniques evaluated in these projects, we have followed the same paradigm of thinking by assessing these techniques in terms of the biophysical benefits they are expected to provide, i.e. improved organic matter management, nitrogen management, weed control, etc.

While these classifications are valuable from a scientific research point of view, farmers, however, do not necessarily think in these same terms. Rather, they are more concerned with how particular practices relate to their broader livelihoods. In considering whether or not to adopt a particular research product such as alley cropping, the kind of questions he/she is more likely to ask are ‘How will my livelihood benefit from this?’, or ‘Will I produce more food for my family if I do this?’, or ‘Will I earn more cash if I take this up?’, ‘Will my family’s quality of life be enhanced?’. For researchers, also thinking about products of the research process in these terms will be more likely to result in improvements to the production system.

It is important to realise that this is not an argument about a ‘reductionist’ versus an ‘holistic’ approach. In fact, the fallaciousness of drawing a dichotomy between the two approaches has been pointed out by Kline (1995). Neither is superior to the other, and we would argue that a ‘reductionist’ approach is essential, provided it is contextualised within a broader framework of analysis, such as the Sustainable Livelihoods Approach (see below). The real issue in the context of the FAI is for more accurate definition of the problems or limiting factors of the system. Thus, if the overall problem is defined as a need for livelihood improvement, rather than as enhanced soil fertility or improved weed control, then the next question that needs to be asked is how can livelihoods be improved? This may be by improved food security, by increased cash generation, or by enhanced quality of life. What technologies or techniques can address these questions? Perhaps improved food security can be obtained by the greater use of higher yielding varieties. Increased cash generation may be obtained through planting fruit trees and selling the produce in the market. Quality of life could be enhanced by a more varied diet or a reduction in labour requirements for different agricultural practices. We can then move on to thinking about particular practices – for example, is it better to try growing apples or bananas in this particular environment, or which of *Mucuna pruriens* or *Canavalia ensiformis* is a better cover crop for weed control? This approach is still reductionist in that the overall system has been reduced to its components, the only difference is that the definition of the problem and its solution has not been restricted to biophysical processes, but also includes the socio-economic processes of the system. The key point is that the FAI is seen as a system, rather than as simplified issues arising from single discipline perspectives.

We would argue, therefore, that a more appropriate classification of techniques and practices than that given in Section 1.4.1 would be one based on farmer perspectives. An illustrative example is provided in Table 8.1.

Table 8.1: Possible classification of FAI techniques and practices according to likely farmer perspectives.

Problem being addressed	**Technique**	**Possible reasons for adoption**
More food for the household	Improved varieties	Better yields
	Intercropping	Better yields?
	Cover crops	Extra crop, better following main crop yields
	Animal manure	Better yields
	Multipurpose trees	Extra food source
	Composting	Better yields
More cash generated for the household	Enriched fallow	Cash income from trees
	Cover crops	Cash from grain legume
	Animal manure	Cash from sale
	Multipurpose trees	Cash from sales of fruit
	Composting	Cash from sale?
	Crop residues	Cash from sale?
Enhanced quality of life for members of the household	Biomass banks	Less need to carry fodder from off-farm
	Cut-and-carry grasses	Less need to carry fodder from off-farm
	Cover crops	Ease of cultivation, more varied diet?
	Crop diversification	More varied diet
	Animal manure	Ease of cultivation, dairy products, fuel source
	Multipurpose trees	More varied diet, fuel source
	Composting	Repository for household waste
	Crop residues	Fuel source
	Tithonia hedgerows	Hedgerow for privacy/aesthetic value?

We do not claim that Table 8.1 is exhaustive, or even the only way of classifying these techniques. What we have attempted to do is present a different way of looking at them and evaluating their likely chances of 'success' through the eyes of farmers. Whether or not a particular technique is adopted will depend on the balance between the perceived benefits and the costs of these benefits, particularly, but not exclusively, in terms of the land, labour and capital that is required. This leads us to questions regarding the way that potential improved techniques fit into FAI agricultural systems. For example, how deeply are existing techniques embedded in the fabric of the local society? How do farmers perceive their own resource base? Does the introduction of a new technique create a 'tear' that disrupts the integrity of the rest of the farmer's survival strategy? Should the techniques be presented to farmers as ways of improving biophysical characteristics such as bulk density, WHC, CEC, etc., or should researchers perceive and discuss them in terms that are perhaps more relevant to farmers, for example as 'soil softening' or 'soil moistening' techniques which make cultivation easier? Will these changes in the perception of researchers lead to subtle changes in the process of technology development that can produce techniques and products more in tune with the fabric of local societies and ultimately more 'adoptable' by farmers? The abilities of the techniques to meet researchers' expectations such as soil fertility enhancement or better weed control is still important, but these abilities are not necessarily how the farmers value them.

The framework in Table 8.1 also allows the consideration of other options besides natural resource management techniques. For example, a cash-generating activity might be for some household members to seek work in the local town or abroad. In many cases, this may be a better option than trying to grow a cash crop for this purpose, as returns to labour may be greater. Thus, not only is there a much wider range of possible techniques that can be evaluated, but any improved techniques developed are much more likely to be adopted by farmers.

The classification in Table 8.1 fits neatly into the Sustainable Livelihoods (SL) framework (Figure 8.1) currently being promoting by DFID as a way of thinking more broadly about the objectives, scope and priorities for development in order to enhance progress on the elimination of poverty (Ashley & Carney, 1999). The three broad groups we have defined in Table 8.1 are included in the livelihood outcomes of the SL framework, while the various techniques we have been looking at contribute to the various livelihood strategies that FAI farmers adopt.

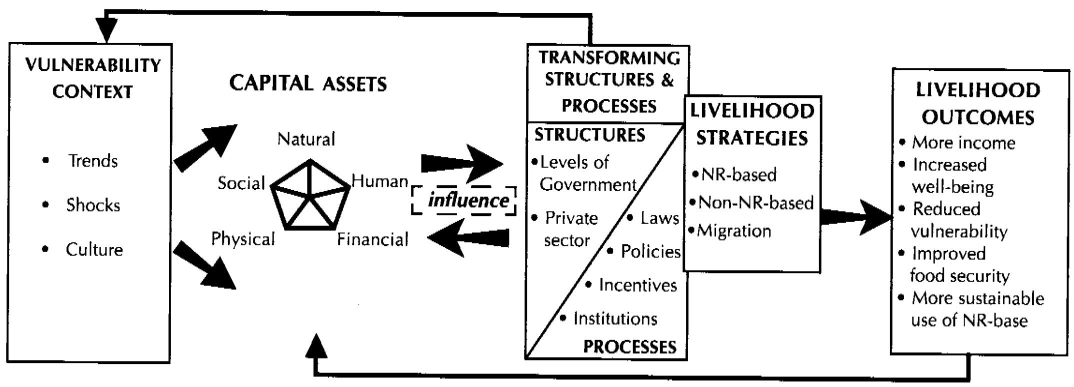


Figure 8.1: The Sustainable Livelihoods framework (from Carney, 1998).

The main feature of the SL approach is that it places people at ‘centre stage’, rather than natural resources or commodities as has been the case in the past, and considers their assets (natural, human, financial, physical and social capital) and their external environment (trends, shocks, and transforming structures and processes). A key concept is that of ‘sustainability’ - a livelihood is defined as sustainable where it can cope with, and recover from, stresses and shocks, and maintain or enhance its capabilities and assets both now and in the future, while not undermining the natural resource base (Carney, 1998). The SL framework may, therefore, herald a significant evolution in conceptualising key processes and relationships in rural development, and encourages researchers to think about the whole livelihood system rather than just some part of it.

The use of such an approach may also help to identify the real limitations of the livelihood system more clearly. For example, the destruction of primary forest at the forest/agriculture interface in Bolivia and Brazil is driven by other more powerful factors than soil fertility or weed encroachment issues. There, the underlying causes are economic in nature – driven by government subsidies, wealthy landowners buy out the frontier colonists to obtain land for cattle ranching, so that the latter then move on and clear new land. Consequently, the introduction of low-input soil fertility and weed management techniques in an attempt at stabilisation are almost irrelevant to the strategic process.

Evaluating the techniques in these terms is difficult at present, due to a shortage of studies that have taken this approach. Most studies we found in the literature have considered only the effect on the biophysical characteristics of the system, which may have been a consequence of the type of literature reviewed in line with our remit for a technical review. Nevertheless, there is clearly a need to re-orientate future research projects to consider the success or otherwise of techniques in enhancing livelihoods rather than soil characteristics, for example. An evaluation of the techniques reviewed in this report in terms of their contribution to livelihoods (food security, cash generation, quality of life, and vulnerability reduction) would seem to be a logical next step. A household livelihoods simulation model such as that described in Section 8.1.3 would be a useful tool to use in this respect.

We appreciate that part of the reason for the focus on particular techniques aimed at the solution of biophysical problems is due to the way in which knowledge is broken down into disciplines in general. Nevertheless, we feel that more progress might be made in research aimed at improving cultivation systems at the FAI by adopting a wider perspective of problems faced by farmers there through the application of a more livelihoods-based approach.

8.1.2 Wider environmental concerns

As mentioned in the Introduction, there is concern at the global level about the loss of forested area and the possible impacts this might have on such issues as global climate and biodiversity. At this level, stabilisation of the interface between forest and agriculture is generally seen as desirable in terms of preservation of the forested area. The question is, how might this stabilisation best be achieved?

It is important to remember that the forest/agriculture interface production systems and the people whose livelihoods depend on them are themselves part of larger systems. In a sense, people can be seen as ‘agents’ within their environment, carrying out their activities according to patterns of behaviour that have evolved over varying periods of time to meet their livelihood needs. The challenge, therefore, is to find ways that meet both the livelihood requirements of FAI farmers and address global environment concerns. Farmers should not be seen as part of the problem, but rather as part of the solution. One line of thinking is that by developing ways to improve the livelihoods of people at the forest/agriculture interface, there should be less need for them to move on and clear more forest, which contributes to solutions to the global problems (e.g. World Bank, 1992). According to this argument, stabilisation of the forest/agriculture interface in an environmental sense can be achieved by stabilisation of the livelihoods of people living there.

A number of further questions arise from this. In the first place, are we sure that shifting cultivation practices are responsible for destruction of primary forests in a particular area, or are farmers merely clearing secondary vegetation? Secondly, will stabilisation of farmers' livelihoods really result in environmental stabilisation, or are their existing practices the most efficient in terms of land, labour and capital for those particular biophysical and socio-economic conditions? In other words, is there any incentive for farmers to adopt more settled patterns of agriculture? Thirdly, can the adoption of improved techniques alone bring stabilisation, or is it necessary to have a concomitant improvement in infrastructure (i.e. roads, hospitals, schools) and markets? If so, is it desirable that this development should occur in FAI areas? Johns (1996), noted that where agriculture was successful in areas surrounding forest reserves, migration into the area was also increased, and worked against biodiversity. Perhaps the aim of stabilising the FAI should be re-evaluated - while there are many areas where farmers can no longer practise shifting cultivation due to population pressures, there may also be other areas where it still the most appropriate form of cultivation, and not necessarily destructive of virgin forest.

There is a weakness in our current understanding of the processes at work in agricultural systems such as those at the forest/agriculture interface that makes it difficult to answer the questions just raised. For this reason, we believe that it is important that effort is made in developing models of these systems so that the processes involved are made explicit and to identify gaps in our knowledge. Such models would also help to explore some of the issues just mentioned in relation of FAI stabilisation. Because of the long-term nature of many of the processes occurring, modelling offers a cost-effective and relatively quick way of obtaining answers to questions regarding potential interventions. We discuss this further in the next section.

8.1.3 Modelling

The type of modelling we propose to be the most appropriate at this stage is an integration of the key biophysical and socio-economic processes at the level of a household. Such a household model, named SLM, is currently being developed as part of project R7536 as a tool to help evaluate the relevance of potential soil fertility enhancing techniques to livelihoods of farmers in the mid-hills of Nepal. In addition to the biophysical processes of crop and animal growth, and water and nitrogen fluxes through the household, economic and labour flows are also incorporated, along with household resources such as food, money, manure, fodder, and fertiliser. The model, therefore, incorporates elements of the natural, human and financial capitals in the SL framework (Figure 8.1). Various types of household can be accommodated, ranging from resource-poor to resource-rich. SLM will be used in the first instance to evaluate potential interventions in the existing system and the likelihood of uptake of these interventions, using criteria such as their contribution to household finances, food production, alleviation of risk, and labour demands in relation to other farm enterprises. The approach is to try and evaluate the interventions as much as possible from the farmer's perspective, with the underlying question in each case being 'Does it make sense to the farmer to adopt this new technique?'. Effects of the interventions on the vulnerability of the household to external trends and shocks can also be examined. SLM differs to many previous household models in that it is a dynamic simulation model rather than a static balance or 'snapshot' model, and can, therefore, be used to investigate trends over long periods of time, a facility particularly valuable in evaluating effects of different practices on soil fertility.

It is also planned to incorporate household decision making processes within SLM, based on a labour and economic analysis each year of the various household enterprises (crops, livestock, off-farm work, etc.), also taking into account subsistence needs and attitude to risk. However, considerable thought needs to be given to the dynamic processes involved in household decision-making, and how these are influenced by the biophysical environment. Some progress has been made by Pagiola & Holden (2001) and Angelsen & Kaimowitz (2001) in determining when forest clearing is likely to be a rational decision for farmers. This is one area where multidisciplinary research involving biophysical scientists and social scientists is likely to be fruitful. Eventually, it is planned to link a number of households of differing resource-levels together to represent a community, to gain an understanding of the processes occurring at that level. Such a model will use multi-agent simulation (MAS) concepts, where each household will be an ' intelligent virtual agent' able to sense and interact both with its environment and with other households. The behaviour of the community as a whole will depend on these interactions between agents. SLM has already been constructed with this functionality in mind.

In relation to the forest/agriculture interface production system, some of the types of questions that can be addressed with such a MAS model are as follows:

1. <u>Trajectories out of poverty</u>: The question of whether there are 'natural' processes (in the broadest sense, including both biophysical and socio-economic processes) that can lead to the evolution of one agricultural system into another needs to be explored. Given that it is perfectly rational for poor people to adopt short-term strategies that attempt to maximise their livelihood outcomes (Figure 8.1), can improved or even new strategies be developed or promoted that hasten the change from shifting cultivation systems to more settled patterns of agriculture? Do low-input organic techniques have the capability of generating improved livelihoods even if they area used efficiently, or are external inputs essential? Are there particular policies that governments could adopt that would facilitate the transition process? How is the distribution of wealth influenced by different processes of transition? What are the long-term environmental consequences of such transitions? After all, while environmental degradation is ascribed to poverty in developing countries, it is due to wealth in developed countries.

2. <u>Understanding factors contributing to vulnerability</u>: Because the future is inherently unknown, it is probably not sensible to aim for specific endpoints – more important is the ability of the household to maintain the capacity to adapt to

changing circumstances. There are several factors that contribute to the adaptability and resilience (the opposite to vulnerability) of a household to outside influences. Being able to maintain a number of options is an important one. If current practices are reducing the resource base, for example, future options may be restricted (e.g.. a narrower range of crops can be grown) and the household will be more vulnerable. Similarly, the ability to transform capital from one form to another (e.g. from natural to financial) is another important factor. A model would help to understand the contributions that each of these make to the overall resilience of the household.

3. Effect of current socio-economic trends: In Nepal in recent years, a decline in soil fertility has been ascribed by farmers themselves to a decline in manure applications, due to in turn to a decline in livestock numbers brought about by a reduction in the household labour pool with more and more children going to school (Ellis-Jones, *pers. comm*.). School leavers are not interested in returning to work on the farm, preferring to find jobs in the towns and cities. What effect is this likely to have on the fertility of the soil in the first instance, and on the overall livelihood of the household, bearing in mind that urban jobs represent a potential source of cash income into the household in the future? Is it a good livelihood strategy to invest in the education of one's children, and at what cost is this to the biophysical environment? Should government policies aim to encourage the educated to take up farming, or is it desirable that hill agriculture continues to decline?

4. Optimum management of common pool resources (CPR): In addition to their own smallholding, many FAI farmers have access to communally controlled land which they use to supplement their livelihoods (e.g. community forests in Nepal). At the community level, the system is complex - different stakeholders seek to satisfy different and often competing objectives using resources that vary both temporally and spatially. Multi-agent simulation models, with the agents representing the different stakeholders, can be used to understand the complex system dynamics involved, and devise strategies at the community level to ensure equitable distribution and use of resources between all stakeholders. Such an approach has been used to resolve conflicts between farmers and herders in Senegal (Lynam *et al*., 2000)[1].

5. Managing variation in natural resources: By concentrating resources in one area at the expense of another, higher-value crops may be grown, leading to an improvement in cash income for the household, some of which could be re-invested in the poorer areas of the farm, thereby improving the overall fertility of the farm in the long-term. We discuss this idea of 'patch heterogeneity' further in Section 8.4.2, and have used a simple model to investigate the possibilities in a crude way. However, it needs looking at in greater detail to evaluate its feasibility.

6. Evaluation of fallow types: Natural fallows offer a way of regenerating soil fertility, but land must be set aside for long periods of time. Where land is

[1] Lynam, T., F Bousquet, C Le Page, P d'Aquino, O Barreteau, F Chinembiri, B Mombeshora, 2000. Adapting science to adaptive managers, - spidergrams, belief models, and multi-agent systems modelling. http://www.inrm.cgiar.org/Workshop2000/abstract/Lynam/fullLynam.htm.

relatively plentiful, natural fallowing is a rational strategy. However, where population increases and the availability of land decreases, the opportunity cost of setting aside land for long periods of time rises significantly. Improved fallows may be able to speed up the regeneration process, but at what level of land availability does it become worthwhile for a farmer to consider the technique? Is it ever actually worthwhile? Similar questions can be asked for enriched fallows, where the regenerative process is accompanied by income generation, taking into account the possibly slower regeneration rate due to removal of harvested material. Experimental determination of these issues is time-consuming and expensive, but modelling should be able to provide useful answers in relatively short time periods.

7. Effect of a change in farmer perceptions: Recent work in Ghana has shown that in evaluating different practices, farmers do not always value the opportunity cost of their own labour (Galpin *et al*., 2000). Participatory interaction, however, has brought some of them to consider that their own time and labour should be a factor taken account of in the evaluation. It would be interesting to compare the likelihood of adoption of various techniques (both traditional and researcher-generated) with and without consideration of the labour involved. Would patterns of development be different in each case? Do more sustainable practices result from taking labour into account? Or is the concept of opportunity cost of labour meaningless when there are no other options available in which it could be deployed, anyway?

8. The potential of low-input techniques: While low-input organic techniques such as the ones we have discussed in this report can make a useful contribution to maintenance of soil fertility, they are unable to supply enough nutrients required for high-yielding crops. However, it would be useful to know what level of crop yields could be sustained by the sole use of such techniques in different environments, and how farmer livelihoods are affected by this.

It is important to emphasise that such models can not be used to predict the behaviour of specific households precisely, but would be used more as a tool to understand and test hypotheses regarding the processes involved in interactions between the biophysical and socio-economic environments of people at the FAI, and how these relate to their livelihoods and poverty. Exploration of viable pathways out of poverty is more important than the prediction of final endpoints.

8.2 Are there any promising techniques?

8.2.1 What has 'worked'?

There is no doubt that some of the techniques that we have reviewed have 'worked' in that they have been either adopted by farmers recently, or have been used traditionally for long periods of time. In the following, we discuss some of these:

1. Cover crops: The use of *Mucuna* as a cover crop appears to have been adopted widely in Central America (Sanchez, 1999). In Benin, for example, it was estimated that about 10,000 farmers tested *Mucuna* between the years of 1988-1996, although it is not clear how many of these farmers actually adopted the

practice and are still using it. In Honduras, there has been considerable uptake of the technique since the 1970s (Buckles & Triomphe, 1999), where it is used to maintain soil fertility. Its success seems to be due to the large amounts of biomass produced through good growing conditions, and the associated high levels of biological N fixation. The system is discussed in more detail in Section 7.2.9.

2. Improved fallows: Similarly, Sanchez (1999) has described how there is large scale adoption of improved short-term fallows by perhaps hundreds of thousands of farmers in Central America, Brazil, Southeast Asia, East Africa, and southern Africa (Section 7.2.4).

3. Agroforestry: The 'Qezungual System' in western Honduras described by Hellin (1999) is an example of an agroforestry system that has been developed indigenously in response to intensification due to land shortages and a need for water conservation (see Section 7.2.5). Certain trees are selected for production of fruits and other products, while others are pollarded to allow growth of food crops underneath. Soil moisture is conserved, partly because of reduced soil surface evaporation due to the presence of pollards, and partly because of improved soil physical structure and increases in water holding capacity. The system also provides multiple benefits for subsistence and cash income (fruit, food crops, timber and firewood).

4. Intercropping: Intercropping of different food crops is a widespread technique in many tropical countries, and has been so for many years (see Section 7.2.2). Although it is primarily a food diversification technique (from the farmer's perspective), it may also be beneficial in contributing to soil fertility, particularly if one of the crops is a legume. However, in the case of grain legumes, the net contribution of N to the system is uncertain, as much of that which is fixed biologically will be removed in the harvested component. Nevertheless, the farmer is able to gain an extra crop with little or no cost in terms of extracting N from the system, and the following crop may in some cases benefit from residue N from decayed nodules.

5. Animal manure: The use of animal manure is another technique that has been used to improve soil fertility for centuries. In countries such as Nepal, and many parts of Africa, livestock have been an integral part of the farming system for a long time. An advantage is that farmers gain other products such as milk, fuel and meat, besides contributions to soil fertility. There may be possibilities of greater livestock integration into the intensifying agricultural systems in Ghana, where there is not so much of a tradition of keeping large livestock by FAI farmers.

8.2.2 Integrated nutrient management

It is clear from the analysis in previous chapters that the organic matter techniques being evaluated cannot meet crop nutrient requirements alone. However, they may have a useful role to play as part of integrated nutrient management strategies. In the following, we suggest areas of research that might be beneficial.

1. Reducing nutrient losses rather than increasing nutrient inputs: As it is difficult for resource-poor farmers to increase inputs, it may be worth examining to what extent it is possible to reduce losses of nutrients to farming systems. Simple changes in management of compost or manure to reduce losses by volatilisation or leaching might, for example, provide higher quality organic matter at little extra labour cost. Similarly, nutrient losses are thought to be high in the first year or so after clearing or burning due to rapid leaching of mobile ions such as NO_3^-. Can ways be developed to reduce these losses, say by adjusting the area cleared each year?

2. Developing new sources of organic SOM, N and P supply: The net flows of organic matter are often from rural areas to towns and cities. Outside many cities, substantial quantities of organic matter waste are often dumped. What are the options for processing this and moving this back onto farmers' fields? Is the quality high enough? Would it be possible to develop a small self-sustaining industry around this?

3. Manipulate the spatial distribution of nutrients within a farm: We generally think in terms of an 'average' level of soil fertility for a farm, and rarely think of how non-uniformity in nutrient concentrations in different parts of a farm may be beneficial. Are there ways in which this natural variability can be manipulated so that nutrients are concentrated in some parts of a farm at the expense of others, but which would allow the growing of higher-value crops such as vegetables? We discuss this point in more detail in Section 8.4.2 below.

4. Combination of organic and inorganic sources of nutrients: The advantage of organic inputs over inorganic fertilisers is that in addition to nutrients such as N, P and K, carbon is also provided, which can have a beneficial effect of soil carbon levels. Nutrient concentrations, however, are much higher in inorganic fertilisers, so that handling and incorporation into the soil is greatly facilitated. The logical conclusion is that the benefits of both sources can be obtained by a combined approach (e.g. Sanchez *et al.*, 2001). Nutrient combinations may also have additive effects from the two types of inputs (Palm *et al.*, 1997a). Sanchez *et al.* (2001) proposed a combination of (a) biological N fixation by short-term leguminous fallows, (b) applications of mineral P fertilisers, (c) enhanced P cycling using *Tithonia*, (d) use of trees to maximise nutrient cycling, (e) return of crop residues, (f) soil erosion prevention, (g) improved crop management practices such as the use of better varieties, and (h) improved availability and timeliness of supply of fertilisers.

8.2.3 Participatory crop improvement

The use of new crop varieties of crops has the advantage that improvements can generally be obtained with little or no modifications required to existing farmer practice. Disadvantages may be that seed of improved varieties is difficult to disseminate, although the recent development of participatory plant breeding (PPB) and participatory varietal selection (PVS) approaches has minimised this disadvantage considerably. DFID's Plant Sciences Research Program has had some success in introducing drought-tolerant and weed-competitive varieties of rice into small-scale subsistence farming systems in Ghana (Project R6826). Farmers in the three main agro-ecological zones of Ghana were involved in testing and evaluating these varieties in their own fields.

Similar projects aim at selecting improved crop varieties for Nepal. In Project R6636, for example, varieties of rice were identified through participatory plant breeding which were highly tolerant to cold stress and resistant to blast and bacterial sheath rot disease, resulting in the official release in 1996 of a new variety, M-3. Similarly, Project R7281 is currently evaluating different maize varieties for their ability to grow in the shade of trees growing on terrace risers. Project R7294 is developing resistance in rice and potatoes to nematodes. Other similar projects involving participatory techniques in Nepal include R6748 and R7542.

Opportunities to extend the work of project R6826 of the dissemination of new varieties by participatory varietal selection to FAI farmers should be investigated.

8.2.4 Extra crops in the sequence

An interesting example of how DFID research can contribute to improved livelihoods is that of seed-priming being evaluated by the Plant Sciences Programme. Seed-priming is the simple technique in which seed of a crop is soaked overnight in water, surface dried, and sown within the next few days. The resulting crop generally emerges sooner, has better establishment, more vigorous growth, may mature sooner, and has higher yields (Harris *et al*., 1999). Attractions of the technique are that it is simple for farmers to implement, requires no expensive inputs, and is aimed at resource-poor farmers rather than at those with mechanised systems.

Of particular interest is the possibility that it may allow significant improvement of an existing cropping system. In the Barind Tract of Bangladesh, for example, land is often left fallow during the dry season following the main rice crop, as it is often difficult to establish a second crop during this time due to drying of the soil surface layers. This is despite the fact that there is usually sufficient residual water further down in the soil profile left from the irrigated rice crop. In recent years, drought-tolerant crops such as chickpea have been introduced, but establishment is not certain, and complete crop failure may result. Recent research has shown that priming the chick-pea seed can result in a marked improvement in crop establishment, making the difference between a healthy crop and no crop at all (Musa *et al*., 2001). Farmers are adopting the technique, and it is even difficult now to persuade them not to prime their seeds for experimental comparison purposes (Harris, *pers. comm*.)! They welcome the ability to gain an extra crop in the sequence, particularly of chickpea which currently commands good prices in the market, at little extra cost in land, labour or capital.

It is certainly worth considering if the use of seed priming in some FAI systems to help establish a second crop, and so obtain extra food or income, is possible. Of course, there are questions of whether a system with increased intensification is sustainable, or whether soil fertility decline and possibly weed encroachment is faster than ever. The experience in Bangladesh, however, would suggest that this is not the case. The area in question was converted from forest about 150 years ago (Johansen, *pers. comm*.), and although current soil organic matter levels are very low (0.5-0.8%), reasonable main crop yields seem to be obtained year after year with appropriate inputs of inorganic fertilisers. Whether a further crop in the sequence will reduce SOM levels even lower remains to be seen.

8.2.5 Weed control

There may be other weed control techniques besides the ones evaluated in the projects reviewed. In recent years, DFID has funded about 60 projects in the Crop Protection Programme addressing weed issues, of which 13 are still on-going. In particular, a number of projects have focussed on an integrated approach to weed management (R7403, R7325, R6782, R5323, R5263, R5280, R5344, R6764). Other projects have investigated options of using animal-powered implements to control weeds (R7401, R6970, R5742). Other projects have involved improving the method and timing of inputs such as nitrogen (R6921, R5895), or determining how weed seed-banks can be reduced in fallow periods (R7471). Ecological methods, such as cover crops (R6008, R6657), and biological control (R6611, R6735), for example, with fungal pathogens of weeds (R6735), have also been investigated. Some attempts are being made to identify possible policy initiatives with regards to herbicide use (R7404).

Other potential techniques, recently reviewed by Pretty (2001) [1] include the use of providing borders of napier grass (weed) for to attract stem borer larvae away from the crops, and using *Desmodium* allelopathy against *Striga*.

There may be opportunities for evaluating some of these approaches in relation to enhancement of livelihoods of farmers in FAI production systems.

8.2.6 High-value products

Sanchez *et al*. (2001) have suggested that the growing of high-value crops may be the most direct way out of poverty. For example, they quote high value vegetables such as kale, tomatoes and onions in Kenya having been found to increase net profits from US\$91 to US\$1665 ha^{-1} y^{-1}. Whether this is viable on a large scale will depend on broad economic development and the availability of markets, storage and processing facilities, and urban population growth rates. High-value tree crops also may be promising. Extractions from the bark of *Prunus africana* can be used to treat prostate gland-related diseases, and has an annual market value of US\$220m per year. The demand has been so high that the species is now on the CITES list, but is now in the process of being domesticated. Other examples include bush mango (*Irvingia gabonensis*) in West Africa, and *Sclerocarya birrea* from the *miombo* woodlands of southern Africa, which is used to make liqueurs. Domestication of these species can make them higher yielding, with higher quality and more uniform products. Generally, tree crops have lower labour requirements than other crops, so that labour could be free for seeking off-farm work. High-value tree crops can also fit into niches on smallholdings, leaving open land available for growing staple crops.

In relation to the FAI, the search for high-value crops should continue. It is important that scientists work closely with the food and pharmaceutical industries, as it is important to know that there is a market for such products, and the industry needs to know that there will be a steady supply of products before it commits capital to develop the markets (Sanchez *et al*., 2001).

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[1] Pretty, J, 2001. Compendium of Land and SARD Cases: Supporting Document to Task Managers' Report to CSD+10 on the Land and Agriculture Cluster for Chapters 10, 12 and 14 of Agenda 21 (http://www.fao.org/rio10/land/stories_en.htm)

8.3 Uptake of improved techniques

8.3.1 The concern with poor uptake

> *"Considerable concern has been raised in NRSP documentation about the poor uptake of these (FAI) technologies. In large part it is assumed that poor uptake reflects inadequate attention to promotion pathways and dissemination … At the same time, there is some concern that a number of these technologies may not be viable for other more fundamental reasons" (NRSP, 1999[1])*

Underlying the original call for concept notes was a concern within NRSP that there had been a poor uptake of the techniques being evaluated in various FAI projects. Whilst it was acknowledged that reasons for 'poor uptake' might in many cases be attributable to failures in, say, research extension linkages, or possibly the extension services themselves, there was also concern that a number of techniques being generated simply did not and could not meet the problems purported to prevent stabilisation of FAI systems. It was in response to this latter concern that the present research project was commissioned to carry out a 'technical' review.

However, throughout the project we have been forced to wrestle with what is meant by uptake. And, further, what is the relationship between processes of uptake, and either technical success or, perhaps more significantly, 'strengthening rural livelihoods'? These are complex and wide-ranging issues that we cannot tackle fully here. We should, however, like to draw attention to some emerging aspects of the debate that we feel will need to be tackled to ensure an increasing improvement in the focus of FAI-directed research.

Firstly, from a broader perspective it is clear that criteria for success of FAI technology cannot be based solely upon the adoption of a technique, but should also encompass whether a significant technical impact had been made (for example, the improvement of soil fertility) and whether livelihoods have been enhanced. For example, if *Tithonia* was promoted as a low-input P-enhancing technique, and farmers actually adopted it widely, but for its aesthetic value as a hedgerow, could that still be called successful uptake? Or alternatively, if *Tithonia* was widely adopted as a P-enhancing technology but a negligible impact on rural livelihoods was witnessed, this would again call into question the relationship between uptake and 'technical' success.

Secondly, though related, this leads us to ask what exactly is being 'taken up'? From this review, we feel that there is presently considerable confusion insofar as there appears to be little agreement as to the precise meaning of key terms such as 'technology', the over-flexible use of which is as likely to obfuscate as to illuminate discussions of uptake. In an earlier section of this report (Section 1.4.1) we attempted to clarify the terminology used in this review in order to overcome these difficulties. It is worth briefly revisiting this discussion.

Earlier, for the purposes of this review, we proposed a hierarchical framework, in which knowledge is our understanding of the way that the world works, usually derived from experimentation and observation, and a technology is the application of this knowledge to address a particular problem, in our case, relating to agricultural production. Any particular technology, we suggested, could consist of a number of

[1] Call for Concept Notes (CNC99-01_FAI call text.doc).

related techniques, or practical and specific ways of doing something; a technology, therefore, could be seen as a 'family' of techniques. Finally, we suggested that a practice could be envisaged as relating to the specific details of the way that a particular technique is implemented. When we refer to improved techniques or practices developed by research, and not yet adopted by farmers, it may be more appropriate to think of techniques and practices as 'packages' or 'products', respectively.

We provided an example to clarify this hierarchy. Our knowledge includes the understanding that atmospheric N is fixed by *rhizobia* bacteria in association with legume plants. A technology would be the application of this knowledge to improve the N status in a cropping system, such as the use of legumes in cropping systems. There may be a number of techniques whereby this technology is implemented, such as alley cropping or crop rotations. Finally, a practice would include details of the particular combinations of legume species and strains of *rhizobia*, time of planting, planting arrangement and so on, used in a particular technique.

The question that still needs to be clarified is whether concern over 'uptake' properly refers to 'technology', 'technique' or 'practice'. Clearly, the reasons for low uptake of technology in the sense we have defined it, are likely to be very different from low uptake of any particular related practice. Certainly, low uptake of any particular practice might have more to do with the fact that there are already many other practices 'on offer' to farmers, and that each will only be adopted in niche conditions. Overproduction of similar practices aimed at a particular farming system could easily be misinterpreted by the scientific community as a more general 'lack of technology uptake', whereupon a closer examination might indicate a more widespread acceptance and use by the farming community.

In summary, we therefore suggest that further investigations into the 'phenomenon' of low uptake should make use of a more sophisticated scheme of terminology in order to differentiate more clearly the actual basis of concern.

8.3.2 The role of Participatory Technology Development (PTD) in FAI research

On the whole, we believe that technologies should not simply be 'delivered', but that a more participatory, evolving and flexible approach to seeking technical solutions for the FAI needs to be made, based on the understanding that technologies can and do affect many aspects of rural livelihoods.

Evidence from other DFID NR Research Programmes, for example Plant Sciences, suggests that the process of technology development is integral to the definition of the final product. Of particular interest here is the possibility that stakeholder participation during the research process may be a key factor in enhancing the likelihood of widespread adoption by the targeted beneficiaries. In other words, how research is being carried out for the FAI may be as important as the themes and topics of the research projects. A future investigation that compares and contrasts FAI research projects, which have explicitly adopted participatory approaches with those that have not done so, may yield interesting information concerning uptake processes.

However, that said, the 'farmer-first' paradigm is a very 'broad church' and a wide range of approaches towards participatory technology development can be found within the literature. For example, some scholars suggest that it may simply be best to introduce new ideas, technologies and plants to farmers and let them experiment

(Fischler *et al*., 1999), without trying to develop a package to be delivered to other areas. Farmers may come up with their own innovations that may tackle issues not at first considered by researchers, but of importance nevertheless.

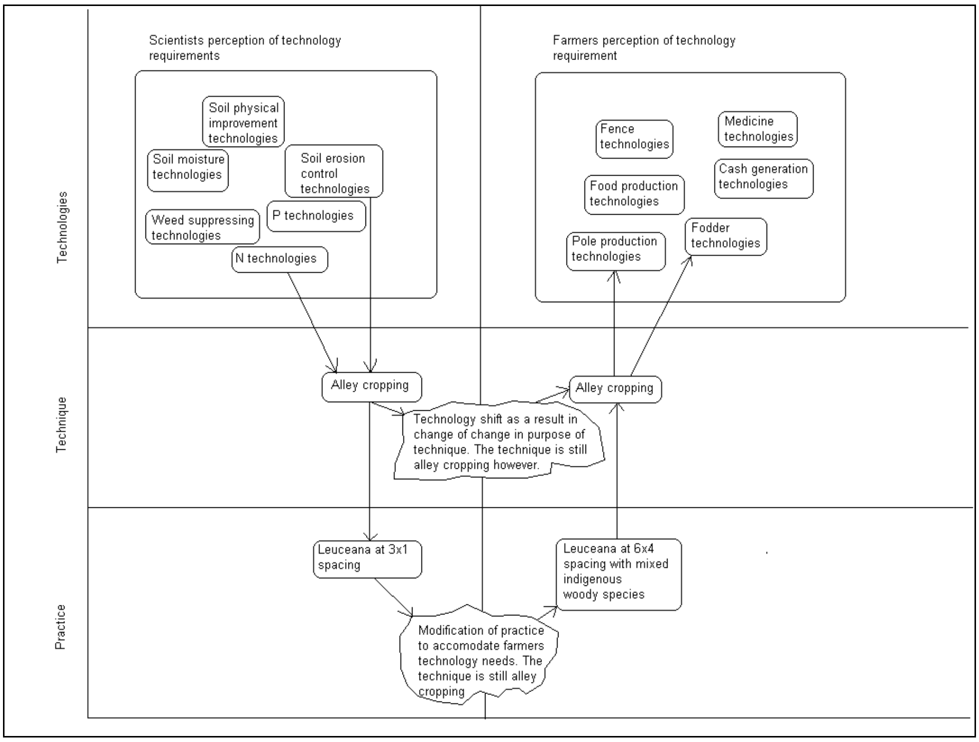

Figure 8.2. Perceived technology requirements between scientists and farmers may often differ. Farmers may often only adopt a technique once it goes through a process of farmer-led adaptation. This may change the role of the technique, so that the technique becomes part of a different technology, aimed at tackling different problems. Understanding the reasons for this 'shift' may help to define future research needs.

To reiterate the point made earlier, where new techniques are adopted the evidence often suggests that biophysical issues, such as soil fertility and erosion control, may not be the primary reasons for the adoption of new techniques. It may therefore be profitable to consider different entry points to the problem. For example, rather than introducing low-input organic methodologies to increase fertility, it may be important to introduce those that increase income. This however may require supporting infrastructure in terms of tree nurseries, seed banks, and other agronomic inputs. Indeed, the FAI might be better stabilised if people were to have the option of leaving agriculture altogether, through a general improvement in 'enabling' infrastructure, for example, roads, markets, credit, schools, clinics and so on.

Another option is to encourage farmer involvement in the adaptation of techniques to meet local circumstances. For this, techniques may need to be more 'flexible' and 'agile', so that farmers can modify them easily. This approach is likely to be particularly useful in FAI production systems, due to the enormous heterogeneity existing within farming systems there, a point that is discussed further in the next Section. A research product may not function as effectively as it could for the purpose for which it was originally designed (e.g. soil fertility), but modification of it by farmers may result in an improvement in livelihoods, whilst in part tackling the problems perceived by the scientists. For example, evidence suggests that where alley cropping has been adopted it has often gone through radical local adaptation, so that it effectively becomes a much more ‘holistic’ technique capable of providing for a larger variety of requirements (Figure 8.2). For want of a better phrase, this extreme form of adaptation might be considered as a ‘technology shift’.

However, we suggest that this process can still not occur unless scientists make the effort to develop a clear understanding of farming system requirements and problems. Despite all the rhetoric about participatory and on-farm research, there is still a tendency for technical packages to be conceived of and delivered that do not tackle the issues that farmers find important. As we have noted, the development of effective technical solutions for livelihoods improvement may be hindered by differing perceptions of farming systems problems between scientists and farmers. To some extent, changing this may involve a large paradigm shift in scientific perception on the normal role and method of science and the ‘hierarchical’ position of the scientist as the ‘definer of research domains’.

The most important step appears to be a recognition of the legitimate concerns of farmers, and of the importance of those concerns. These might for example be the satisfaction of immediate cash or subsistence needs, or a reduction in the quantity and drudgery of labour, rather than issues of long term soil fertility and erosion control, which may often be the focus of scientific concern. This means broadening current understanding of the technical requirements of the farmers and perhaps determining areas of common ground, a process illustrated in Figure 8.3. Whereas Figure 8.2 showed that the problems perceived by the farmers and the problems perceived by the scientists were quite separate, Figure 8.3 shows that the scientists has broadened his/her understanding of the farming system to encompass those problems that are of concern to the farmer. Common ground has been identified - ‘soil softening’ technologies may relate to our own perception of the need for technologies for soil physical improvement, and a technique identified to deal with these problems. In this way, common technical requirements should become a common starting point for the development of modified techniques and practices, whilst solutions to some of the scientists concerns may be built in to the technique.

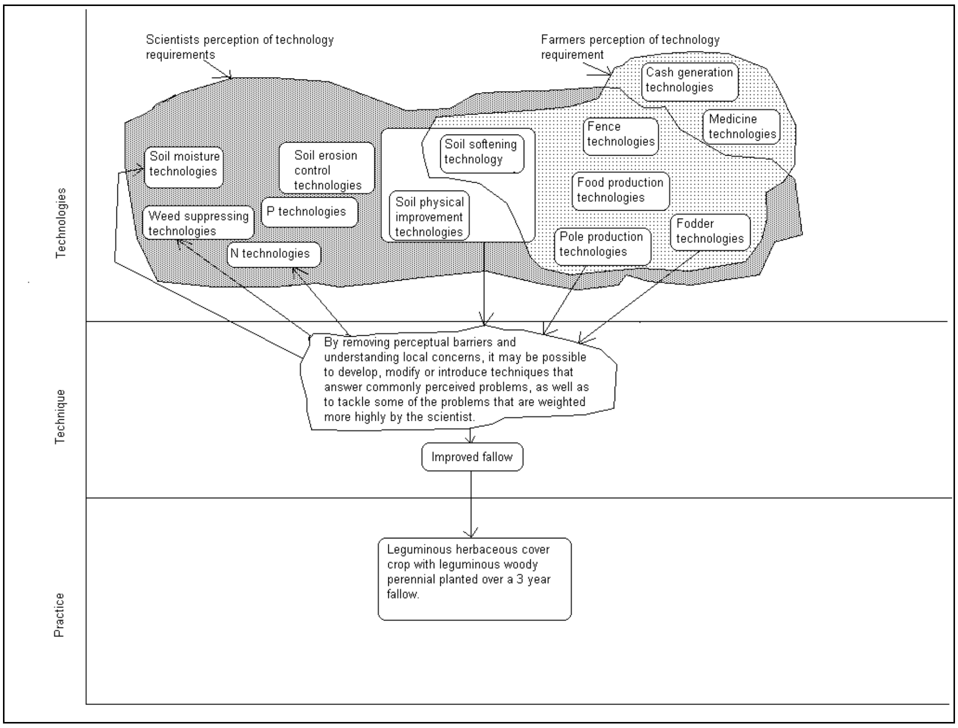

Figure 8.3. The scientist has broadened their understanding of the technical requirements of the farming system to encompass requirements that the farmer perceives. Identification of common ground acts as a starting point for the development of technical solutions.

As it often appears to be difficult to 'deliver' techniques that farmers are willing to use, one solution may be to identify techniques that are already in use. Such techniques could than be made more effective. For example, where shifting cultivation is predominant, improved short fallow may be useful. There may be little to be gained from introducing entirely new technical packages.

However, as we have noted, ideas about new techniques may be important, especially as societies constantly change and evolve. The process we envisage is illustrated below (Figure 8.4). The role of the scientist in this scenario is largely restricted to the facilitation of technical development rather than to the development of the techniques themselves. The knowledge available to the wider scientific community on technologies, techniques and practices in the wider world may be valuable, when meshed with the knowledge, technologies, techniques and practices of farmers in the area of work.

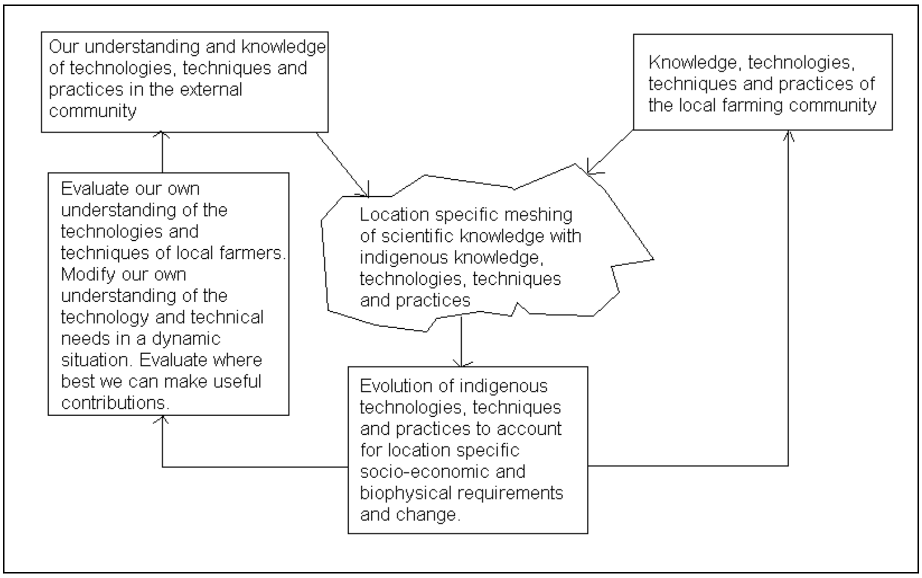

Figure 8.4. Possible model of interaction between scientists and farmers. The aim here is not to provide new technical solutions, but to try and improve existing technical solutions, with the wider knowledge that is available to scientists from other parts of the world.

8.3.3 Frameworks for the analysis of factors affecting uptake

During the course of the review, we have come across various frameworks that may be useful in the further analysis of factors affecting the uptake of organic matter techniques. We reproduce some of these below, with the aim of provoking ideas of how these might be further modified to become useful tools in the analysis of FAI technology.

Firstly Franzel (1999) in a study on socio-economic factors affecting the potential adoption of tree fallows suggested that 'feasibility', 'profitability' and 'acceptability' of the technique were defining considerations and that these were influenced by certain sub-features, described in the table below. (Table 8.2).

Table 8.2. Farm and household characteristics affecting feasibility, profitability and acceptability of improved tree species in southern Cameroon, eastern Zambia and western Kenya. (From Franzel, 1999).

Characteristics	Direction of effect	Strength of effect
Feasibility		
Labour constraints	-	M
Institutional support	+	H
Farmer experience with tree nurseries	+	L
Profitability		
High profitability of growing crops	-	M
High base crop yield	-	M
High opportunity cost of labour	+	M
Acceptability		
Perception of soil fertility problem	+	H
Past investment in soil fertility	+	H
Current fallowing	+	M
Economic importance of annual cropping	+	M
Wealth level	+	M
Gender	0	0
Access to off-farm income (intensive land use areas only)	+	M

- = unfavourable, + = favourable, 0 = no effect.
H = high effect, M = medium effect, L = low effect and 0 = no effect

Tarwali (1999) in a study on *Mucuna* and *Stylo* potential in West Africa adopted a checklist approach to evaluating benefits and constraints to the adoption of the two species in West Africa (Table 8.3).

Table 8.3. Comparison of mucuna and stylo cover crop technology in West Africa. (From: \Tarawali, 1999 #210}.

Characteristics	*Mucuna*	*Stylo*
Potential benefits		
Soil improvement	+++	++
Weed suppression	+++	++
Crop yield	+++	++
Livestock feed	+	+++
Revenue from seed	+	+
Management issues		
Ease of establishment	+++	+
Competition with crops	000	0
Susceptible to fire	000	00
Need for protection, i.e. fencing cover crop	00	000
Constraints to adoptions:		
Social	0	000
Land tenure	0	00
Economic/financial resources	0	0
Poor extension service	00	000
Disease	0	00
Seed availability	00	000
Labour	000	000
Lack of credit	0	000
Toxic substances	00	0

+ = positive attribute, 0 = negative attribute. + or 0 = minor benefit or constraint; ++ or 00 = intermediate benefit or constraint; +++ or 000 = major benefit or constraint.

Place & Dewees (1999), in a study on incentives and policy for improved fallow adoption, also developed a framework for socio-economic considerations. In particular they noted that the farmer's reason for adopting a technology could be greatly influenced by their knowledge and acceptance of a natural resources problem that could be tackled with improved fallow, the importance of the natural resource base to their livelihoods, their willingness to invest in proposed solutions, their capacity to invest in proposed solutions, economic incentives and institutional support. These factors could operate at the plot level, the farm level, the community level and the regional/national level.

Table 8.4. Potential constraints identified in sub-Saharan Africa to the adoption of improved fallows at different scales (From: Place & Dewees, 1999).

Category	Potential constraint			
	Plot level	Farm level	Community level	Region/nation level
Knowledge of natural resources problem	Lack of knowledge of soil fertility, erosion and weed problems	Lack of knowledge of soil fertility, erosion and weed problems	Lack of knowledge of soil fertility, erosion and weed problems	Lack of knowledge of impact on food security, water quality, and C sequestration
Importance of the natural resource	Distant of poor quality plots	Off-farm income is prominent income source	Agricultural contribution to community welfare relatively low	Agricultural contribution to gross domestic product relatively low
Willingness to invest	Short-term tenancies	Free grazing of livestock on farms; poverty and short-term horizons	Nomadic communities; free grazing rights and patterns	Lack of clarity of legal property rights
Capacity to invest	Small plots arising from land fragmentation	Land, labour, water or capital shortages	Peak season labour shortfalls (e.g. at planting); water scarcity	Lack of credit and credit policy
Economic incentives	Recommended crop for plot location may not respond to improved fallow	Limited access to markets; high tree germplasm costs	Labour shortages; low fuelwood prices; easy access to off-farm trees	Low process of crops following fallows; promotion of large farms rather than smallholders
Support services	Fragmentation or hilly terrain inhibits visits by extension	Poor extension services	Poor seed distribution	Poor roads; agriculture sector policy that depresses producer income; insufficient germplasm production

On the whole we do not believe that prescriptive tools are always the best means of identifying possible areas of use for FAI techniques. FAI biophysical and socio-economic conditions are often too complex to be reduced to a set of universally applicable principles. However, we do believe that tabulated information can provide a useful synthesis of factors that need to be considered by researchers and extension workers, and that such tables can be developed in such a way as to provide a general indication of where certain techniques may be useful, and what factors are important with these techniques (Table 8.5). However, we suggest that in the final analysis, it is people who should make decisions and not tools, which here at least, are intended to inform.

The following tables attempt to provide a means of synthesising what has gone before, in particular, so that the pertinent characteristics and requirements can be easily considered (Table 8.5). Note that we do this using the case of alley cropping as an example and that the intention here is simply to provide ideas for further work aimed at synthesising important considerations. Similar scoring systems could be developed for the other techniques. It may be more useful for individuals to develop such scoring systems for individual areas or countries, or FAI types. However, we have little possibly of exploring these issues here. We would also like to point out that even relatively high scores obtained with such systems, may not indicate that widespread adoption of a particular technique will occur, for reasons that we have already discussed, but rather that there may be more potential for that particular technique than other possible techniques.

Table 8.5. Synthesis of important characteristics and requirements for techniques of potential use at the FAI. For example, we have given a code of N, -2 against the 'Rapid benefits?' category. Literary evidence suggests that alley cropping may only start to return dividends several years after the system has been set up. This may heavily deter resource-poor farmers from its use and therefore 'Rapid benefits?' is given a score of N,-2.

		Alley cropping	Improved fallow	Enriched fallow	Cover crops	Etc.
Characteristics						
Multipurpose?		N,-1				
Flexible?		N,-1				
Agile?		N,-1				
Rapid benefits?		N,-2				
Widespread FAI relevance?		N,-2				
Ability to evolve?		N,-2				
Potential benefits						
Potential soil fertility impact		0				
Potential soil physical impact		0				
Potential soil erosion control impact		Y,2				
Potential weed control impact		0				
Potential competitive effects		Y,-2				
Sensitive to use of fire		Y,-2				
Sensitive to presence of cattle		Y,-1				
Socio-economic requirements						
Financial?Capital		Y,-2				
Labour		Y,-2				
Land tenure security		Y,-2				
Biophysical requirements						
Fertiliser		Y,-1				
Seed/seedlings		Y,-1				
Rainfall	Unimodal	N,-1				
	Bimodal	Y,1				

	High	Y,-1
	Low	N,1
Temperature:	High	N,-1
	Moderate	Y,1
	Low	N,-1
Soil *p*H:	Neutral	Y,1
	Other	N,-1
Soil texture:	Sandy	N,-1
	Loamy	N,1
	Clayey	N,1
Landscape:	Hilly	Y,2
	Flat	N,-1
Farm size requirement	Large	N,-1
	Intermediate	Y,1
	Small	N,-1
Land location	Accessible	Y,-1
	Remote	N,-1

Key: N = No, Y = Yes, -2 = very negatively important, -1 = negatively important, 0 = not important, 1 = important, 2 = very important

Although the table above gives some idea as to the nature and requirement of the technologies and could potentially be used for decision support, we suggest that it is also important to ask the right questions, in a more holistic context (Table 8.6). We use the alley cropping as an example in the table below, using literary evidence to pick out those consideration that have been shown to be important in the process of technology development and adoption. As before, we do not expect to have considered all the pertinent issues, but aim rather to provide a basis for further perhaps more location specific work. Such tables would need to be simplified, where appropriate, to make them easier to use.

Table 8.6. Synthesis and development of literary evidence indicating how tabulated information might be used to indicated possible niche uses of organic techniques. For example, alley cropping has been given a '✓1', by the 'Spatial?' category. Literary evidence suggests that where FAI dynamics are 'temporal', alley cropping is likely to have a more limited role, because in temporal FAIs, rotation techniques and clearing land for cropping may be the primary aim of farmers. However, alley cropping may have a role to play in FAIs with spatial dynamics, where scarcity of land is relatively high, giving this category a score of '✓1' indicating that for it to be used, there is likely to be 'some requirement' for spatial dynamics.

Considerations			Alley cropping	Enriched fallow	Cover crops	Etc.
The FAI:						
Is the predominant FAI dynamic:	Temporal?		0			
	Spatial?	✓	1			
Is land availability:	High?		0			
	Intermediate?	✓	1			

	Low?		0
Is there a fertility/erosion problem?	Yes	✓	1
	No	✗	0
Technology considerations			
Can the technology meet other needs? (e.g. immediate subsistence, cash income needs, fodder, poles, medicine, etc.)	Yes		1
	No	✗	-1
Can the technology fit in the FAI dynamic?	Yes		1
	No		-1
Can the technology mesh well with local practice?	Yes	✓	1
	No		-1
Can the technology reasonably contribute to tackling the resource problem?	Yes	✓	1
	No		-2
Farmer's perceptions:			
Does the farmer perceive a resource problem?	Yes	✓	1
	No	✗	-1
Is the resource base essential for livelihood?	Yes	✓	1
	No	✗	-1
Is the farmer willing to invest in technology?	Yes	✓	2
	No	✗	-2
Are immediate benefits very important?	Yes	✗	-2
	No	✓	1
Farmer's financial capital:			
Is the farmer's financial capital availability:	Moderate?	✓	1
	Low?	✗	-1
Does the household do much off-farm work?	Yes	✗	-1
	No		1
Farmer's labour:			
Does the household have a large availability of labour?	Yes	✓	2
	No		-2
(Can the farmer buy labour?)	Yes		1
	No		-2
(Can the farmer exchange labour?)	Yes		2
	No		-2
Land considerations:			
Is the farmers land tenure secure?	Yes	✓	2
	No	✗	-2
Is the farm size:	High		-1
	Intermediate		1
	Low		-1
Is the land:	Remote		-2
	Accessible	✓	1
Institutional considerations:			
Is there access to credit at reasonable rates?	Yes	✓	1
	No	✗	-1
Is fertiliser available?	Yes	✓	1
	No		0
Are seeds/seedlings easily available?	Yes	✓	1
	No		-2
Are common resources available?	Yes		-1
	No		1
Is market demand available for products?	Yes		1
	No		

Is there potential resource conflict with cattle?	Yes		-1
	No	✓	0
Is the use of fire a potential threat?	Yes	✗	-2
	No	✓	0
Climatic considerations:			
Is rainfall mostly:	Unimodal?		0
	Bimodal?		1
	High?	✓	1
	Low?	✗	-2
Is temperature mostly	High?		-1
	Moderate?		1
	Low?		0
Soil considerations:			
Is soil *p*H generally:	Neutral?	✓	1
	Other?		-1
Is soil texture generally:	Sandy?		-1
	Loamy?		1
	Clayey?		1
Is sub-soil fertility	High	✓	1
	Low		-1
Is the landscape:	Hilly?	✓	2
	Flat?	✗	-2
Biomass considerations:			
Is biomass quality:	High?	✓	2
	Moderate?	✗	0
	Low?	✗	-2
Is biomass quantity:	High?	✓	2
	Moderate?		1
	Low?	✗	-1

Key: ✓ = need for positive evaluation; ✗ = killer factor
Scoring system: N = no; Y = yes; -2 = severe constraint; -1 = constraint; 0 = not important; 1 = some requirement; 2 = large requirement

It is also worth remembering that any new technique could have substantial negative impacts and it is always important to consider under what circumstances this is likely to happen, and to consider the option of not using the technique. Of particular concern is the fact that impacts of any new technology are likely to be unevenly felt within the household, with major benefits often going to the men of the household and added burdens or negative effects being felt by the female members of the household. Technologies are rarely gender neutral, either in adoptability or effect. Girls, for example, may be withdrawn from school to supply labour for the technology, particularly if it produces a cash income. Resources may be diverted from subsistence crops, often farmed by women, to cash crops often farmed by men. The effects of technologies should not be considered simply within the context of whole household, but also according to impacts within the household. We believe therefore that a further major need is to ask how the technology will impact within the household. Do women, who often grow the bulk of the subsistence crops have access to the technology. How will the technology affect the internal distribution of household resources, particularly capital and labour?

8.4 Heterogeneity in forest/agriculture interface systems

8.4.1 Heterogeneity at the systems level

In carrying out this review, the high degree of heterogeneity between and within forest/agriculture interface production systems was brought home. Although the FAI systems in the four focus countries of Bolivia, Brazil, Ghana and Nepal are all characterised by interactions between crops, trees and possibly livestock, they are all very different systems with specific problems. In Bolivia and Brazil, the system is driven by economic forces fuelled by government support for colonisation of forest frontier regions. In Ghana, population pressure is forcing intensification on traditional shifting cultivation systems. In Nepal, the agricultural system is already relatively settled, and forests and agriculture coexist with farmers using the forest as a source of fodder, nutrients, and other products. Although all of these systems have both temporal and spatial characteristics, we have classified those in Bolivia, Brazil and Ghana as predominantly temporal in nature, and that in Ghana as predominantly spatial (see Section 1.1.1), largely depending on population density and land scarcity.

Similarly, within any country, biophysical and socio-economic conditions may vary greatly within relatively small areas. Of particular importance are climate (temperature, rainfall, solar radiation, seasonality) and soils (*p*H, texture). Socio-economic heterogeneity includes variable access to resources (land, labour, capital) and markets. Where tenure is insecure, techniques such as agroforestry, multi-purpose trees, and fruit trees, for example, are unlikely to be grown where access to their benefits cannot be guaranteed. Similarly, where markets are non-existent or too distant, cash-generating enterprises are not likely to be practised. For example, fast-growing timber trees are unlikely to be grown where local timber values are extremely low, or contractors are only interested in buying timber in quantities that farmers cannot supply. Also, as with any human society, variation exists in the aspirations of individuals within local populations and in their solutions to their livelihood problems. Thus, whilst one farmer may perceive that greater productivity is required from the farm, another may decide that stability is more important. Others may decide that agriculture is a supplement to their livelihood strategy, rather than the lynch pin, and moderate their inputs accordingly. All these factors can influence the applicability of the techniques that have been developed thus far at the FAI.

Thus, technologies are not introduced into a void, but into a situation where certain processes are already operating. Both temporal and spatial FAIs can potentially provide stable systems, although the appearance of each will be very different. Whereas spatial systems tend to produce FAIs that are sharply defined, temporal systems produce a broader and more uncertain interface. Thus, further analysis of the systemic characteristics of FAI variants could be used as one possible way of screening potential interventions, by matching the dynamics of the system with those of any prospective technique. Thus, for example, where spatial dynamics are already in evidence, it is likely that biomass transfer, and intercropping techniques are likely to be the most suitable options. On the other hand, where a temporal dynamics predominate, it may be most useful to consider the use of rotational legumes or improved fallow techniques.

Even on a single farm, both spatial and temporal processes are likely to operate. For example, fields near a homestead are often intensively farmed, and spatial techniques such as biomass transfer, legume intercrops, or multipurpose tree species may be appropriate interventions. At the same time, fields further way from the homestead may be managed in a more temporal way – i.e. through alternate cropping and following. In this case, rotations and improved fallow systems may be more appropriate.

8.4.2 Heterogeneity amongst farmers

As already mentioned, heterogeneity amongst farmers is another aspect of the FAI, along with most agricultural systems. The usual tendency is to talk about 'farmers' as if they are a homogenous group, but clearly there is a range of capacities with any one group. This range may be due to any number of reasons, including age and experience in farming, access to resources, educational level, proportion of time devoted to farming compared to other activities, etc. Some farmers may be already practising relatively effective techniques for their particular biophysical and socio-economic environment, and may not be able to improve their effectiveness much further without raising their access to resources to a new level (e.g. the use of mineral fertilisers). Other farmers, however, may not be using the resources they have available to them in the most effective way, and it is perhaps these that should be targeted, with the aim of bringing them closer to the technically proficient farmers, thereby increasing the average and narrowing the range of efficiencies (Figure 8.5).

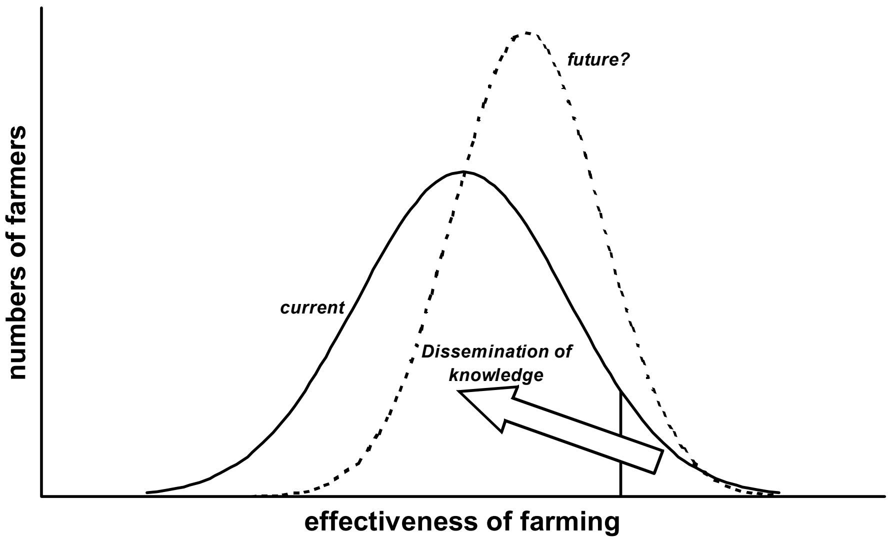

Figure 8.5: Schematic diagram showing possible distribution of farmer effectiveness and direction of movement of knowledge from the upper fraction to the remaining farmers. Solid line represents current distribution, dotted line represents distribution after dissemination of knowledge has occurred.

Progress could be made by identifying the most effective techniques currently being used, and introducing them to less effective farmers, rather than trying to continuously develop 'new' techniques. There may, in fact, be little need for further technical research until a significant proportion of farmers are using these more effective techniques. The focus shifts to one of identification of effective existing techniques and dissemination of these to farmers not practising them. Of course, this process may reveal further technical problems that do not affect adoption by resource-rich farmers, but may be sufficient to affect adoption by resource-poor farmers. Such factors may or may not be solvable by further adaptive research.

8.4.3 Patch heterogeneity

As already mentioned, there is small-scale spatial heterogeneity in most FAI farms or 'patches', although in much of the analysis of farming systems, this is ignored and the fertility of a farm is thought of as being constant across all fields or parts of the farm. There may, however, be possibilities of improving livelihoods by purposely exploiting, or even creating, variation in soil fertility in a farm. For example, by concentrating nutrients on one patch at the expense of the rest (say by grazing of livestock over a wider area and collecting manure on a smaller area), it may become possible to grow a high value crop which will offset the decline in yield on the rest of the farm.

A simple model can help demonstrate this. Let us assume that there are two crops, A and B (Figure 8.6), the first of which (A) is a relatively low-value crop, but can grow such that it produces a return even at very low fertility levels. The second crop (B) is a relatively high-value crop, but requires a certain level of soil fertility before any return is produced at all. As the soil fertility increases beyond this critical level, the return increases rapidly to eventually give a much higher return than A. Crop A may be a crop such as maize, while Crop B may be bananas.

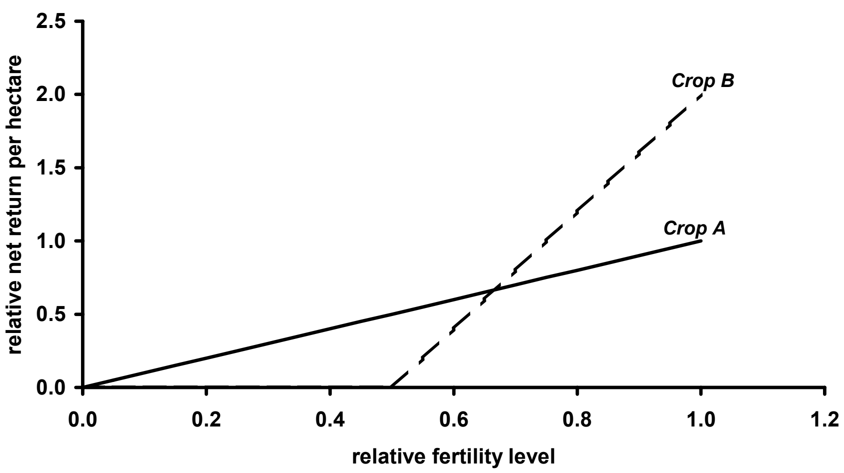

Figure 8.6: Schematic diagram showing relationship between net return per hectare and soil fertility level for two hypothetical crops. Crop A is a relatively low-value crop, but produces some return even at very low fertility levels. Crop B is a relatively high-value crop, but requires a certain level of fertility before any return is produced. Thereafter, the return increases rapidly as soil fertility increases to eventually produce more return than crop A.

Let us also assume that we have a farm with two fields, or patches, of equal area that these two crops can potentially be grown on, and that initially, the soil fertility of these two fields is equal (i.e. they have a relative fertility level of 0.5 in Figure 8.6). In this case, B would not produce any return at all, and a farmer would be better to plant all of his/her farm in A. If, however, the farm is made more heterogeneous by transferring some of the fertility from one patch to the other, then A will give a lower return, but B starts to be able to produce some return. At a certain level of heterogeneity, the total income from the two patches becomes more than from the farm with completely uniform patches, and the livelihood of the farmer can increase (Figure 8.7). It may be that some of this extra income can be spent in buying in inorganic fertiliser to apply to the patch with depleted fertility, so that the overall fertility of the farm can increase, and possibly become more stable. For this to happen, however, the farmer would need to have access to markets.

Of course, in the very simple example we have given, the rational outcome is for the farmer to concentrate as much of his soil fertility in one place as possible at the expense of the rest of the farm, and plant as much of his/her farm in the high-value crop as possible. There are, however, many reasons in practice why this may not be the best strategy, or even possible. Firstly, he/she may need or want a certain level of the low-value crop, which is likely to be a subsistence crop such as maize or millet, for consumption by the household, not wanting to rely on buying this in from a market. Secondly, there may be some risk associated with growing the high-value crop, and the farmer may want to spread this risk by growing a number of crops, even if they do differ in value. Thirdly, there may be a limit to the amount of soil fertility that can be transferred from one patch to another, so that the ratio of fertilities of Patch A/Patch B in Figure 8.7 can never reach zero.

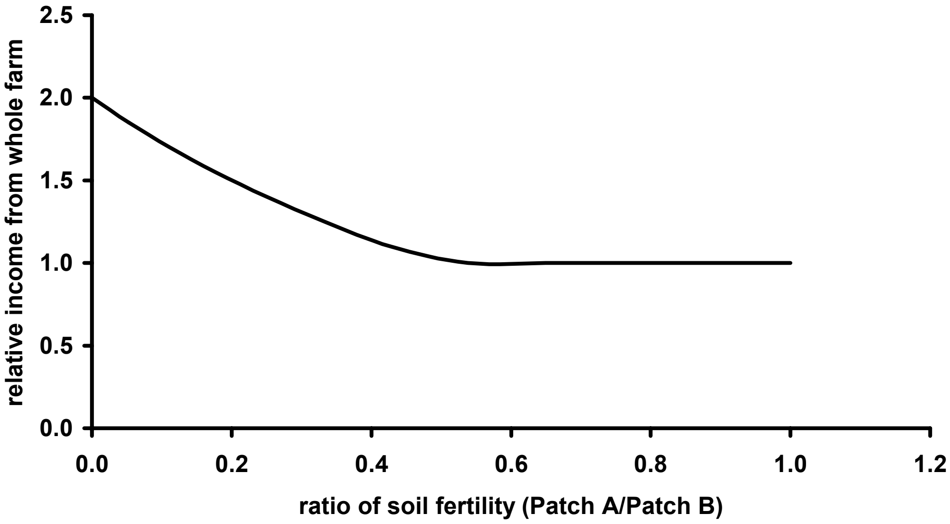

Figure 8.7: Predicted response in total income from the two patches to changes in the ratio of the soil fertility levels of the two patches. A ratio of 1.0 indicates that the two fertility levels are equal, while a ratio of 0.0 indicates all of the soil fertility of Patch A has been transferred to Patch B.

Nevertheless, the example does show that by manipulating the soil fertility of a farm, it is possible that the livelihood of the household can be improved, and that the overall fertility of the farm could even be increased, if some of this increased income could be used to buy fertiliser from outside. In theory at least, it is not inevitable, therefore, that the soil fertility of a forest/agriculture interface farming system needs to decline, forcing farmers to clear more forest to maintain their livelihoods.

Of course, this is not a new idea. Farmers have been practising variations on the theme for a long time. In Nepal, for example, the fertility built up in forested areas over long periods of time is transferred gradually to nearby farms through collection of fodder for animals and biomass for enhancing on-farm soil fertility. In many countries, the soil fertility of small areas used as home gardens is enhanced by incorporating household waste containing nutrients gathered from a wider area, both from other parts of the farm through consumption of crops harvested there, and from off-farm sources such as food bought in a market. Higher-value crops such as vegetables or fruit are often grown in such patches, where they wouldn't grow well elsewhere on the farm. Briggs & Twomlow (2001), for example, note that considerable organic material is transferred for mulch from annual crops grown some distance from the homestead to banana plantations close by, but warn that the system may not be sustainable as eventually crop yields, and hence supply of mulch, will decline.

Clearly, the system is complex, and there are questions regarding overall sustainability, but with the advent of new crops, new markets, and better infrastructure in many regions of the forest/agriculture interface, it may be worthwhile to re-examine these traditional systems of nutrient redistribution carefully to see if there are any possibilities of enhancing livelihoods that farmers have not yet discovered. Household systems modelling is a useful tool that can help to analyse various options in this regard.

9 Conclusion

In this review, we have examined a number of low-input organic techniques being evaluated in NRSP-funded projects in Brazil, Bolivia, Ghana and Nepal, and analysed them in terms of their fundamental biophysical and socio-economic characteristics in relation to the likelihood of their uptake. These techniques included alley-cropping, biomass transfer, cover crops, multi-purpose tree species, animal manure, *Tithonia diversifolia*, improved and enriched fallows, and legume intercrops.

In the case of techniques that have aimed at maintaining or improving soil fertility, the nutrient content and the quantity of biomass that can be produced within the resources available to such farmers (i.e. in terms of land and labour) is insufficient to meet the requirements of most crops, certainly at a reasonable yield level. However, the techniques may have a useful role to play as part of an integrated nutrient management strategy. Inorganic fertilisers have the advantage that nutrient concentrations in them are much higher than in organic materials, making it easier for farmers to handle and apply for the same quantities of nutrients. In contrast, organic materials add carbon to the soil, which inorganic fertilisers do not, and therefore can potentially help to improve soil physical properties. However, it is questionable as to whether the addition of organic materials in the quantities that FAI farmers are likely to have available, can make an appreciable difference to overall soil organic matter levels, as most is lost back to the atmosphere as CO_2 when it decays. Nevertheless, a combination of biological N fixation, applications of mineral P fertilisers, enhanced P cycling using species such as *Tithonia*, use of trees to maximise nutrient cycling, the return of crop residues, soil erosion prevention, improved crop management practices, and improved availability and timeliness of supply of fertilisers, may help to maintain soil fertility more than any one technique alone.

Weed control by low-input techniques in the projects reviewed seemed to have little effect on crop yields, although weed populations were reduced in most cases. There was some evidence that integrated strategies involving cover crops, herbicides and burning, were able to control *Imperata contracta* in banana plantations after 2-3 years, and reports from other countries (e.g. Honduras) indicate that cover crops alone can be successful in reducing weed populations and increasing crop yields.

Thus, it seems that most of the techniques by themselves are unlikely to be able to contribute significantly to improving farmers' livelihoods at the forest agriculture interface, and that they are unlikely to be able to provide the impetus to lift FAI farmers out of poverty. Future research in forest/agriculture interface production systems need, therefore, to focus more on developing interventions to meet farmer perspectives, such as increased food security, improved cash generation, reduced risk, and enhanced quality of life, rather than researchers' perspectives of improved soil fertility or weed control. This may necessitate consideration of a broader range of interventions than just natural resource management options. This fits in with one school of thought in development thinking that suggests stabilisation of cultivation systems at the forest/agriculture interface can be achieved by developing means of improving the livelihoods of the people involved, so that there is less need for them to move on and clear new forested areas. However, this is not an argument for 'holistic' versus 'reductionist' approaches - we maintain that both approaches are necessary and valuable. The starting point should be from a holistic viewpoint, the analysis of problems in the system and development of solutions should be reductionist, and any successful solutions to the problems should be evaluated holistically again. However, care does need to be taken that the reductionist analysis does not restrict thinking to either the biophysical or the socio-economic processes of the system alone, as has been the tendency in the past, but that both are taken into account.

There is, therefore, a clear need to take a systems approach when considering options for stabilising forest/agriculture interface systems. The Sustainable Livelihoods Framework offers a way in which this can be achieved. However, many of the processes, both biophysical and socio-economic and their interactions, are poorly understood, and it is essential that future research addresses this. This lack of knowledge is compounded by the large degree of heterogeneity of FAI systems, both at the system level with different cultivation systems in the different countries, and also at the individual farm level with between-farm variability in terms of farmer aspirations and attitudes, and within-farm variability in resources. Bio-economic and multi-agent simulation modelling at the household and community level is proposed as a way of integrating these processes to provide a means to evaluate different pathways of transition to more settled systems of agriculture.

Finally, we suggest that current understandings of 'uptake pathways' and processes relating to farmer adoption at the FAI has been impaired by the imprecise use of 'technology' within the scientific and development community. We have therefore proposed the use of more specific terminology to differentiate between knowledge, technology, technique, and practice, all of which are generated and disseminated in quite different ways. Work currently being carried out by Reece & Sumburg, amongst others, on uptake pathways is, we feel, likely to provide further valuable understanding and clarification in this key area. This, in turn, will enable us to explore more critically the concern that there has been a low uptake of low-input organic techniques at the FAI.

10 Appendix

10.1 Data tools

The following text and tables could provide the basis for paper based tools aimed for example at extention workers and researchers using low input organic techniques at the FAI. This is only a model of what could potentially be done and we would suggest further development of such tools.

10.1.1 Soil organic matter

The need to build up SOM as a basis to soil fertility has been shown. There appears to be no substitute for the role that organic matter plays in the development of the soil physical structure, WHC and CEC, and this is in contrast to nutrient supply and weed suppression, where alternative methods can be employed. In order to develop these important characteristics in the soil, it is necessary to maintain a certain minimum level of SOM. The 'ideal' level for plant growth is considered by some researchers to be about 5% (Brady, 1990), although the minimum levels required to have an impact on soil degradation may be around 2%. Both plant biomass and animal manure may be used to achieve these objectives.

Soil organic matter will tend to accumulate most easily in cool conditions, with high soil moisture levels and in clayey, acidic soils. These conditions favour the accumulation of organic matter, mainly because they reduce the rate of mineralisation. Where biophysical conditions favour high rates of mineralisation and socio-economic conditions favour low rates of input, the accumulation of organic matter to adequate levels may be difficult.

In some respects, there may be a fundamental contradiction at the heart of using organic matter techniques to build up SOM and simultaneously to supply N, P and other nutrients. The ideal conditions for SOM accumulation do not favour the decomposition and release of organic sources of N and P. Low temperatures favour the development of SOM because mineralisation is reduced. But the release of nutrients will also be reduced. Additionally, it appears that the development of SOM may be better served with the use of medium or low quality organic matter, than with high quality organic matter. As has been shown before, the release of nutrients from medium or low level organic matter will be slow and there may also be net immobilisation of N or P.

Because there is no substitute for the use of organic matter technologies must be capable at least of supplying adequate quantities of organic matter to improve soil physical conditions and to prevent physical degradation of the soil. The required quantity will largely depend on the biophysical conditions of the area and in particular on rainfall, soil texture and the rate of mineralisation. Where large quantities of land exist and labour is scarce, farmers may be unlikely to expend any energy on organic matter amelioration, as traditional techniques, in the form of forest fallow and bush fallow, is well suited to the task. The practicality of using new techniques must quite evidently be set against the existing techniques of the farmers. As population pressure increases, farmers may be willing to accept the introduction of techniques that increase SOM, although they will generally do so on the basis of demonstrable and substantial impacts on crop yields. Most importantly they must feel that the opportunity cost of developing SOM is not excessively high.

As population densities increase above the level that can be supported by forest fallow and bush fallow systems, the use of temporal technologies may become less relevant. Farmers may increasingly have to rely on the spatial dynamics of their environment. SOM technologies may shift from long term fallow technologies through to short fallow technologies perhaps through to a variety of other techniques more typical of land scarce areas such as biomass transfer, intercropping and multi-cropping with grain legumes. This progression is a response to the problem of supplying food at different population densities.

The table below attempts to summarise the limitations for organic matter technologies when organic matter is provided through rotation technologies, biomass transfer technologies, intercropping technologies and animal manure. As such it provides a framework that can indicate whether organic matter technologies can be successfully incorporated into existing farming systems using key biophysical and socio-economic variables. We suggest however that the table needs further thought. The intention here is to present it as a possible framework for further refinement and as a means of starting to highlight important considerations. Our intention here is primarily to try and provoke ideas about the way in which large amounts of information can be summarised into useful tools. We have grouped the technologies according to their major dynamics - whether they are spatial, temporal or transfer based, although we recognise that this is only one way of looking at them and that others groupings may prove to be more useful.

Table 10.1. Key biophysical and socio-economic considerations for soil physical improvement with organic matter technologies.

	Problem	**Poor Soil Physical Characteristics**			
	Objective	**Improved soil structure, CEC, WHC.**			
Technologies		**Plant biomass transfer technologies (agroforestry, biomass banks)**	**Plant rotation technologies (leguminous herbacious and perrenial fallows)**	**Plant intercropping technologies (alley cropping, legume cover intercrops)**	**Animal manure technologies (stall fed animals)**
Biophysical limitations					
Quality of biomass	Low				
	Moderate	✗	✗	✗	✗
	High	✗✗	✗✗	✗✗	✗✗
Quantity of biomass	Low	✗✗	✗✗	✗✗	✗✗
	Moderate	✗	✗	✗	✗
	High				
Temperature	Low				
	Moderate				
	High	✗	✗	✗	
Rainfall	Low	✗✗	✗✗	✗✗	
	Moderate				
	High				
Soil texture	Clay				
	Loam				
	Sand	✗✗	✗✗	✗✗	
Soil pH	Acid				

	Neutral	✗	✗	✗	
	Alkaline				
Associated pests or diseases	Yes	✗	✗	✗	✗
	No				
Socio-economic limitations					
Land area availability	Low		✗✗✗		
	Moderate	✗	✗	✗✗	✗
	High	✗✗		✗✗✗	✗✗✗
Labour availability	Low	✗✗✗		✗✗✗	✗✗
	Moderate	✗✗		✗✗	
	High				
Capital availability	Low	✗✗	✗✗	✗✗	✗✗
	Moderate				
	High				
Distance to market	Near				
	Far	✗		✗✗	✗✗
Infrastructure	Poor	✗	✗	✗✗	✗✗
	Moderate				
	Good				
Time for benefit	Short				
	Medium	✗		✗	✗
	Long	✗✗	✗	✗✗✗	✗✗
Distance to farm land	Near				
	Far	✗✗✗	✗	✗	✗✗✗

Key

✗	**Limiting**
✗✗	**Very limiting**
✗✗✗	**Killler factor**

Score	Adoptability	Comment
3 ✗ 's or more	The technique is likely to be limited by insignificant benefits as a result of limiting bio-physical and socio-economic factors	Choose a different technique or see if some of the limitations can be reduced or removed altogether. This may at least allow the technique to have a niche role.
0 to 2 ✗ 's	The technique may have a niche role to play in the farming system, either spatially (close to the house, on a specific crop, in a small area) or temporally (the technique may server a certain use at a certain time, which may be cyclical or one off).	Develop the niche role of the technique. Successful functioning of the technique in a niche role may lead to broader use of the technique in modified and innovative ways. Note that the technique may still fail to function more effectively than current practice.
0 ✗ 's	There should be no biophysical or socio-economic limitations affecting the use of this technique, in a niche or even more generally. Failure to use the technique may depend on inertia or very specific cultural, biophysical and personal factors (such as the increase in snakes caused by cover crops, preference for particular colours)	The technique is not faced with severe limitations that will undermine it. However, it may fail to function more effectively than the farmer's current technique to any practically significant degree. Provide the farmer with the necessary support to adopt the technique if they wish (training, exposure, on-farm research). The technique may still have an important (niche) role to play.

One ✗ indicates a minor limitation, two ✗'s a severe limitation and three ✗'s, a "killer factor" that will prevent the successful use of organic matter technologies for SOM development. Clearly, where technologies have between 0-2 crosses, there are certain limitations to the use of the technique, although it may have a niche role to play, either in a temporal or in a spatial context. Where there are no crosses, there should be no reason why the technique could not be adopted. However, it is worth bearing in mind that there may be other limiting factors that are difficult to define generically, for example cultural preference for certain colours or for "modern" aspirations. The logic underpinning the table is noted (Table 10.2. Rational for the classification of limitations for Soil Organic Matter technologies).

Table 10.2. Rational for the classification of limitations for Soil Organic Matter technologies.

Biophysical limitations	
Quality of biomass	The technique should supply biomass of a standard that can be directly used or corrected within farmer limitations. Although the quantity of organic matter may not need to be especially high for the objectives outlined above, the application of low quality organic matter will affect nutrient availability in the soil. Plant biomass and animal manure applied should be of moderate or high quality to ensure that net N and P immobilisation does not occur at a time that can affect crop growth and yield. For organic matter low in N or P or both, but also low in lignin and polyphenol, integrated use of fertiliser at farmer "friendly" levels may be considered or pre-mineralisation of the organic matter in compost.
Quantity of biomass	The amount of plant biomass or animal manure that needs to be applied in order to build up soil organic matter is large, often several tons per hectare. An organic level of about 5% (2.9% C) is considered to be ideal for plants and as a general rule of thumb about 10 t ha^{-1} fresh biomass may be adequate for tropical areas. The quantity of biomass is particularly important for soil organic matter functions. High quantities of plant and animal biomass need to be applied to have an impact on soil structure, CEC and WHC. Moderate levels may only be sufficient to allow a niche role in a limited area of the farming system.
Temperature	The accumulation of soil organic matter is higher where temperatures are low to moderate. High temperatures result in rapid mineralisation of organic matter, necessitating very large inputs of plant biomass. Raising soil organic matter to a level that is practically significant in high temperature areas may be difficult.
Rainfall	The amount of soil moisture also influences soil organic matter build up. Areas with low rainfall generally have lower levels of organic matter in the soil, whereas areas where soil moisture is high also tend to show higher levels of soil organic matter build up. The corollary to this is that mineralisation rates may be lower, with less available for plant growth and development.
Soil texture	Evidence suggests that the accumulation of organic matter tends to be most rapid in soils with a loamy to clayey texture. The build up of organic matter in sandy soils may be very difficult requiring very large levels of organic matter input.
Soil pH	Low soil pH tends to favour the accumulation of soil organic matter. Some evidence also suggest that highly alkaline soils may favour the build up of soil organic matter. Ironically, the pH that is suitable for the growth of plants tends to be least suitable for the accumulation of soil organic matter.
Associated pests or diseases	The use of organic matter technologies may cause an increase in pests or diseases that either directly affect people, or the plants they are trying to grow. If pests, such as snakes, scorpions or weeds have been kept under control with traditional technologies, the association of pests with certain technologies may prove to be a disincentive to many farmers.
Socio-economic limitations	
Land area availability	For many resource poor farmers at the forest agriculture interface, land area is a major constraint to the successful use of soil organic matter technologies. Supplying adequate quantities of plant biomass may require several times the amount of land that can be usefully improved by the incorporation of organic matter and resource poor farmers with little land will have to find off-farm supplies of biomass. This may be either for animal feed or for direct incorporation into the soil.
Labour availability	For most resource poor farmers, household labour may be the only source of labour for agricultural activity. The management, harvesting, transport and incorporation of biomass for soil organic matter improvement may require more labour than can be supplied by the household.
Capital availability	The perceived advantage of most soil organic matter technologies is that they offer the farmer a cheap way of improving soil organic matter using locally available resources. However, this may be the case only where the farmer has access to adequate quantities of land and labour. Where land or labour is lacking, capital can act as a substitute, for example by buying in labour for the harvesting, and transport of organic matter in the soil, or by buying off farm biomass. Lack of capital may therefore hinder the successful use of organic matter technologies.
Distance to market	Evidence suggests organic matter technologies are more likely to be adopted where there is a market within reach of the farmer's land, which guarantees an outlet for the produce. The farmer may feel that it is worth investing extra resources in organic matter technologies if this gives rise to greater income.
Infrastructure	Infrastructure such as roads and processing facilities may also encourage farmers to invest in technologies where they perceive that the efforts of investment in that technique has a chance of being rewarded. Good infrastructure and local processing facilities may act as spurs to agricultural intensification, with the use of organic matter technologies although this is not always a foregone conclusion.
Time for benefit	Farmers are most likely to use a technique where the use of that technique results in immediately obvious benefits. The effects of soil organic matter improvement may often be too long-term for the farmer, particularly when the increased labour or land or capital requirements of that technique are taken into consideration.
Distance to land	Resource poor farmers may often have several fields in different areas of the farm. Fields that are far

away from the house are often less intensively cultivated than fields that are close by. As many technologies are relatively labour intensive they are more likely to be used near to the house. For example, stall-produced manure is more likely to be applied to land that is close to the stall than on land that is far away.

10.1.2 Nitrogen

As noted previously, N is one of the major limiting nutrients for resource poor farmers and much attention has justifiably focussed on ways of supplying it to crops. The most important feature of N is that it is the only nutrient that can be generated *in situ* with the use of N fixing plants. As such this represent a net increase of N in the landscape, rather than a transfer from one location to another. Nitrogen may also be supplied through biomass transfer technologies, such as forest litter or animal manure. The practicality of supplying the full quantity of N is however questionable given the amounts of biomass required to supply this and the fact that resource poor farmers are often limited by labour and/or access to sufficient areas of land to procure the biomass.

The rotation of a grain legume within the cropping system may tempt the farmer to use legume technologies, but much of the fixed N will be removed in the harvest. The use of a leguminous cover crop in a temporal niche may fix N for the following crop. However, it is unlikely that the amount of N fixed will replace what the crop extracts and lead to long term sustainability.

The amount of N fixed by legumes reduced in an intercropping situation, as there is proportionally less land under the legume. Evidence suggests that in difficult conditions, legume competition can actually decrease main crop yields. This situation may be even worse where perrenials are used in spatial agroforestry systems. The more difficult the biophysical conditions, the more difficult it may be for farmers to supply N with organic matter techniques. Nitrogen fixation will be reduced by extremes of temperature and soil moisture. In general, evidence suggests that factors that are conducive to optimal plant growth are also conducive to N fixation.

The quality of organic matter supplied to the land is important. Where low quality organic matter is used, N and P may be immobilised and even added mineral N and P can be immobilised in some cases. The situation is not however, completely straight-forward. There may be some advantage to be gained from immobilising N for a short period of time, particularly in very high rainfall or very high temperature areas where leaching and volatilisation are high, whilst short term N is supplied by mineral N. However, the practicality of doing this may make management so complex that the farmer will find such techniques unsuitable.

However, the value of N fixing technologies lies in their ability to supply at least some N to the farming system and clearly there are a variety of different technologies that are capable of supplying N to the crop. Given suitable biophysical conditions for N fixation, the most appropriate technique will depend on the relative availability of land, labour and capital. Organic matter techniques cannot be expected to supply the entire N requirements of a farm and clearly, there may be some merit to taking advantage of the complexity of farming systems in the tropics and finding niche roles for techniques in both time and in space. This may even involve the option of using various N technologies on different parts of the farm simultaneously.

It is worth noting that the fixation of N is greatest when the soil is already low in N. Where soil N is already high, evidence suggests that most legume N requirement will come from the soil. This has implications for the use of legumes both spatially and temporally. In spatial terms it will be important to use the legume on soils low in N and to transfer the biomass to the crop as a green manure. In temporal terms it may be important to perhaps grow a (grain) legume towards the end of a rotation so that full advantage is made of the N fixing capability of the legume for the last productive crop in the rotation. Growing a legume after the clearing of fallow land for example may have lower N benefit, as N levels will already be relatively high.

Where populations are low, it may be possible to integrate legumes in a rotation, either with annual cover crops if rainfall regimes permit or with perrenial plants if prolonged dry periods are usual. As population pressure increases, it will be increasingly necessary to shift to short rotation fallows and eventually to intercropping technologies. As crop N requirements will in general only be supplemented by such techniques, it will be necessay to use additional N, either in the form of organic matter or with mineral N, to attain reasonable and sustainable yields. As before, it is worth bearing in mind that N technologies need to provide a substantial improvement over exising techniques to have a realistic chance of adoption by farmers.

Importing biomass in biomass transfer techniques may also provide some of the needs of the farmer where N cannot be supplied from on-farm sources. Many farmers already deploy such techniques, in particular by transferring N from the forest to agricultural land, as in Nepal. Nitrogen can also be supplied with animal manure. However, up to two thirds of N excreted by cattle is lost in the urine. Techniques to reduce excretery N losses in urine may be important and N applications could be greatly increased by developing techniques to reduced losses through volatilisation or leaching of stored manure and urine.

It is worth noting that the advantage of supplying N through manure or urine is that the rumen provides good biophysical conditions for physical breackdown of organic matter, largely irrespective of external conditions. This may for example be important in hill areas where release of plant N is reduced by cold conditions.

Table 10.3. Biophysical and socio-economic limitations of Nitrogen technologies with reference to key factors limiting Nitrogen technologies at the FAI.

	Problem	**Nitrogen**			
	Objective	**Improved N status**			
Technologies		**Plant biomass transfer technoloiges (agroforestry, biomass banks)**	**Plant rotation technologies (leguminous herbacious and perrenial fallows)**	**Plant intercropping technologies (alley cropping, legume cover intercrops)**	**Animal manure technologies (stall fed animals assuming adequate nutrition)**
Biophysical limitations					
Quality of biomass	Low	✗✗✗	✗✗✗	✗✗✗	✗✗✗
	Moderate	✗✗	✗✗	✗✗	✗✗
	High				
Quantity of biomass	Low	✗✗	✗	✗✗	✗✗
	Moderate	✗		✗	✗
	High			✗✗	
Temperature	Low	✗✗	✗✗	✗✗	
	Moderate				

	High	✘✘	✘✘	✘✘	
Rainfall	Low	✘✘	✘✘	✘✘	
	Moderate				
	High	✘✘	✘✘	✘✘	
Soil texture	Clay				
	Loam				
	Sand	✘✘	✘✘	✘✘	
Soil pH	Acid	✘✘	✘✘	✘✘	
	Neutral				
	Alkaline				
Associated pests or diseases	Yes	✘	✘	✘	✘
	No				
Socio-economic limitations					
Land area availability	Low		✘✘✘		
	Moderate	✘	✘	✘✘	✘
	High	✘✘		✘✘✘	✘✘✘
Labour availability	Low	✘✘✘		✘✘✘	✘✘
	Moderate	✘✘		✘✘	
	High				
Capital availability	Low	✘✘	✘✘	✘✘	✘✘
	Moderate				
	High				
Distance to market	Near				
	Far	✘		✘✘	✘✘
Infrastructure	Poor	✘	✘	✘✘	✘✘
	Moderate				
	Good				
Time for benefit	Short				
	Medium	✘		✘	✘
	Long	✘✘	✘	✘✘✘	✘✘
Distance to farm land	Near				
	Far	✘✘✘	✘	✘	✘✘✘

Table 10.4. Rational for the classification of limitations for nitrogen technologies.

Biophysical limitations	
Quality of biomass	Nitrogen percentage in the applied organic matter should be at least 2.5% to prevent net immobilisation of mineral N. The application of low quality organic matter will affect nutrient availability in the soil. Plant biomass and animal manure applied should be of moderate or high quality to ensure that net N and P immobilisation does not occur at a time that can affect crop growth and yield. For organic matter low in N or P or both, but also low in lignin and polyphenol, integrated use of fertiliser at farmer "friendly" levels should be considered or pre-mineralisation of the organic matter in compost.
Quantity of biomass	The quantity of biomass that is required for sufficient N supply may be several tons per hectare. It appears that recovery rates of N applied in organic matter are about 25%. A crop removing 100 kg ha^{-1} of N may need to have 400 kg N ha^{-1} applied inorder to meet the requirement. Supplying adequate levels of organic N through animal manure may be even more difficult if sufficient effort is not made to catch the urine where most of the N is excreted. Clearly, large amounts of biomass are required to satisfy crop N requirements. If these are not available, farmers will not perceive the benefits of the technique. A niche role in a limited area should therfore be considered.
Temperature	*Rhizobial* activity is inhibited in very high or very low temperatures. Where these temperatures predominate, the fixation of N will be reduced as will the growth of the legume. Low growth of plants reflects low rates of N fixation and total N quantities. The final quantity of N fixed may well be insufficient to maintain crop requirements during the growing season.
Rainfall	Areas of low rainfall result in low rates of plant growth and N fixation. There may also be a cost associated with N fixation that increases the amount of water needed by legumes. In high areas of rainfall, legumes may grow well, but the amount of N in the soil can be rapidly leached away. Both these processes may greatly reduced the effectiveness of organic N or increases the quantities of organic matter required to supply N.

Soil texture	Evidence suggests that the accumulation of organic N tends to be most rapid in soils with a loamy to clayey texture. In such soils, the N may be tightly bound in organo-mineral complexes and less likely to be lost through volatilsation or leaching.
Soil pH	Low pH has been shown to reduce the abilty of *Rhizobia* to fix N. Rhizobia populations are also reduced. The process of nitrification may also be reduced as it is carried out by micro-organisms that may be sensitive to low pH.
Associated pests or diseases	The use of N fixing technologies may increase the population of certain pests to a degree that local farmers find unacceptable or dangerous. If N technologies are believed by farmers to be provinding habitats for dangerous animals they may discontinue use.
Socio-economic limitations	
Land area availability	For many resource poor farmers at the forest agriculture interface, land area is a major constraint to the successful use of N technologies. In an annual rotation, quantities of N are unlikely to supply sufficient N to prevent long term decline. A longer rotation may provide the answer. However, where land is scarce this may not be possible. Biomass transfer from common land may be required from common land. The use of intercropping technologies will supply at best a partial solution.
Labour availability	For most resource poor farmers, household labour may be the only source of labour for agricultural activity. The management, harvesting, transport and incorporation of biomass for N improvement may require more labour than can be supplied by the household.
Capital availability	It is likely that the use of leguminous technologies can supply only a part of the N requirements of the farm. If capital is lacking, the organic matter might best be used on a smaller area of land. If some capital is available, mineral N may be used to supplement the organic N.
Distance to market	Evidence suggests N fixing technologies are more likely to be adopted where there is a market within reach of the farmer's land, which guarantees an outlet for the produce. The farmer may feel that it is worth investing extra resources in organic matter technologies if this gives rise to greater income.
Infrastructure	Infrastructure such as roads and processing facilities may also encourage farmers to invest in technologies where they perceive that the efforts of investment in that technique has a chance of being rewarded. Good infrastructure and local processing facilities may act as spurs to agricultural intensification, and encourage the use of N technologies.
Time for benefit	Where there are no immediate benefits to the use of N fixing technologies, the farmer is unlikely to continue to use the technique. It is unlikely that there will be a long term cumulative effect, especially because N is so mobile and the farmer may be supplying insufficient N to the system.
Distance to land	Fields that are far away from the house are often less intensively cultivated than fields that are close by. It may be possible to use in situ N fixing technologies such as legume fallows or grain rotations on such fields as they are less intensively farmed. Clearly the use of biomass transfer technologies is unlikely unless the source and the destination for the organic matter happen to be close. For example, stall-produced manure is more likely to be applied on land that is close to the stall than on land that is far away.

10.1.3 Phosphorus

Many soils in tropical countries suffer from a deficiency of P. Much attention has recently been focussed on the possibility of supplying P to crops with green manure crops such as *Tithonia diversifolia*, which appear to extract relatively high levels of P from the soil. As noted, animal manure can also be used to supply P. Whereas N is very mobile, P is relatively immobile. It rapidly becomes adsorbed by soil particles and it is difficult for plants to use this. Through the process of ageing, the immobility of P may increase, as adsorbed P moves towards the interior of the soil particles. Labile P may therefore be a relatively small amount of the total P in the soil and may do little to enhance the status of soluble P. Thus, although there may be large amounts of P in the soil, it is unavailable to plants.

The constraints encountered with supplying P through organic matter technologies are generic and similar to the constraints noted thus far, for the use of organic matter techniques in SOM and N development. Indeed, the constraints may be even more acute, as even larger amounts of biomass may be required to supply useful quantities of P to the plant than are required for satisfactory SOM or N supply. Additionally, P cannot be generated *in situ*. Any net on-farm increases in P must essentially occur by moving P to the farm with biomass transfer technologies. Where *Tithonia* is used as a fallow or a rotation, this merely mobilises and recycles P that already exists in the soil.

Clearly the use of organic matter techniques to supply P can provide only a partial fix to the solution, unless P deficiencies are relatively slight. Organic matter techniques may be useful in recycling P from depths below the level of the crop roots or mobilising and transferring P from one area to another. However, in conditions of great P deficiency, they are unlikely to provide a total solution and P will have to be supplied through mineral sources if reasonable and sustained yields are required. Where P is to be supplied entirely through organic matter techniques, on P deficient soils, and where sufficient biomass is unavailable, the organic matter may best be used in a niche context on a limited area of land, perhaps with high value crops.

Table 10.5. Biophysical and socio-economic limitations of phosphorus technologies with reference to key factors limiting organic matter technologies at the FAI.

	Problem	**Phosphorus**			
	Objective	**Improved P status**			
Technologies		**Plant biomass transfer technoloiges (agroforestry, biomass banks)**	**Plant rotation technologies (leguminous herbacious and perrenial fallows)**	**Plant intercropping technologies (alley cropping, legume intercrops)**	**Animal manure technologies (stall fed cattle)**
Biophysical limitations					
Quality of biomass	Low (<0.1%)	✗✗✗	✗✗✗	✗✗✗	✗✗✗
	Moderate	✗✗	✗✗	✗✗	✗✗
	High				
Quantity of biomass	Low (<5 t ha^{-1})	✗✗✗	✗✗✗	✗✗✗	✗✗✗
	Moderate (5 - 10 t ha^{-1})	✗✗	✗✗	✗✗	✗✗
	High (> 10 t ha^{-1})				
Temperature	Low	✗✗	✗✗	✗✗	
	Moderate				
	High				
Rainfall	Low	✗✗	✗✗	✗✗	✗✗
	Moderate				
	High				
Soil texture	Clay				
	Loam				
	Sand	✗✗	✗✗	✗✗	✗✗
Soil pH	Acid	✗	✗	✗	✗
	Neutral				
	Alkaline	✗	✗	✗	✗
Associated pests or diseases	Yes	✗	✗✗	✗	✗
	No				
Socio-economic limitations					
Land area availability	Low		✗✗✗		
	Moderate	✗	✗	✗✗	✗
	High	✗✗		✗✗✗	✗✗✗
Labour availability	Low	✗✗✗		✗✗✗	✗✗
	Moderate	✗✗		✗✗	
	High				
Capital availability	Low	✗✗	✗✗	✗✗	✗✗
	Moderate				
	High				

Distance to market	Near				
	Far	✗		✗✗	✗✗
Infrastructure	Poor	✗	✗	✗✗	✗✗
	Moderate				
	Good				
Time for benefit	Short				
	Medium	✗		✗	✗
	Long	✗✗	✗	✗✗✗	✗✗
Distance to farm land	Near				
	Far	✗✗✗		✗✗✗	✗✗✗

Table 10.6. Rational for the classification of limitations for Phosphorus technologies.

Biophysical limitations	
Quality of biomass	Phosphorus percentage in the applied organic matter should be at least 0.25% to prevent net immobilisation of added P. The application of low quality organic matter will affect nutrient availability in the soil. Plant biomass and animal manure applied should be of moderate or high quality to ensure that net N and P immobilisation does not occur at a time that can affect crop growth and yield. For organic matter low in N or P or both, but also low in lignin and polyphenol, integrated use of fertiliser at farmer "friendly" levels should be considered or pre-mineralisation of the organic matter in compost. **See main report:**
Quantity of biomass	The quantity of biomass that is required for sufficient P supply may be several tons per hectare. Crop recovery rates of added P can vary widely. Assuming a recovery rate of about 25%, a crop removing 10 kg P ha^{-1} may need to have 40 kg N ha^{-1} applied inorder to meet the requirement. Supplying adequate levels of organic P through animal manure does not pose extra problems as almost all P is excreted in the feaces. Clearly, large amounts of biomass are required to satisfy crop P requirements. If these are not available, farmers will not perceive the benefits of the technique. A niche role in a limited area should therefore be considered.
Temperature	Temperature is important is so far as it affects crop growth and organic matter mineralisation. Where temperatures are very high, common P plants such as Tithonia may not grow. Minerlisation may also be reduced due to reduced bacterial activity. Where temperatures are low, plant growth will also be low and mineralisation of P reduced. Clearly, optimal temperatures are required for the successful use of P technologies.
Rainfall	Areas of high rainfall may encourage good growth of plant biomass. However, there may be problems in leaching of soluble P, particularly in sandy soils. Areas with very low rainfalls regimes may not be capable of producing adequate quantities of biomass and clearly mineralisation rates will be low.
Soil texture	Adsorbtion by clayey or loamy soils may be relatively high. In sandy soils, P is less tightly bound and more labile. Thus P management may be easier in sandy soils. This is contrast to N where organic matter and fine textured soils may act to reduce losses by volatilsation and leaching.
Soil pH	Low and high pH has been shown to reduce the availability of P. Where the pH is between about 6 -7, P is relatively available. In acid soils, P forms compunds with calcium that are relatively insoluble and liming appears to be the best solution.
Associated pests or diseases	The use of P technologies may increase the population of certain pests to a degree that local farmers find unacceptable or dangerous. If P technologies are believed by farmers to be provinding habitats for dangerous animals or pests they may discontinue use.
Socio-economic limitations	
Land area availability	For many resource poor farmers at the forest agriculture interface, land area is a major constraint to the successful use of P technologies. In an annual rotation, quantities of P are unlikely to supply sufficient P to prevent long term decline. A longer rotation may provide the answer. Biomass transfer from off-farm areas will be required. The use of intercropping technologies, for example alley cropping, hedges, will supply at best a partial solution.
Labour availability	For most resource poor farmers, household labour may be the only source of labour for agricultural activity. The management, harvesting, transport and incorporation of biomass for P improvement may require more labour than can be supplied by the household.
Capital availability	It is likely that the use of P technologies can supply only a part of the P requirements of the farm. If capital is lacking, the organic matter might best be used on a smaller area of land. If some capital is available, mineral N may be used to supplement the organic N.
Distance to market	Evidence suggests P technologies are more likely to be adopted where there is a market within reach of the farmer's land, which guarantees an outlet for the produce. The farmer may feel that it is worth investing extra resources in organic matter technologies if this gives rise to greater income.

Infrastructure	Infrastructure such as roads and processing facilities may also encourage farmers to invest in technologies where they perceive that the efforts of investment in that technique has a chance of being rewarded. Good infrastructure and local processing facilities may act as spurs to agricultural intensification, and encourage the use of P technologies.
Time for benefit	Where there are no immediate benefits to the use of P technologies, the farmer is unlikely to continue to use the technique. It is also unlikely that there will be a long-term cumulative effect that might persuade the farmer to expend effort on P technologies for long-term future use.
Distance to land	Fields that are far away from the house are often less intensively cultivated than fields that are close by. Clearly the use of biomass transfer technologies is unlikely unless the source and the destination of the organic matter are close. For example, *Tithonia* or stall-produced manure is more likely to be applied on land that is close to the *Tithonia* biomass bank or stall than on land that is far away.

10.1.4 Weeds

As previously noted weeds are one of the major reasons for limiting the length of the cropping period. Evidence suggests that it is often the development of weeds rather than the reduction of soil fertility that causes farmers to return land to fallow. The development of weeds is also a major constraint to the development of "stable" agricultural systems. Forest and bush fallow techniques in a labour scarce, capital poor, land abundant context may provide the most useful solution to the development of weeds on agricultural land.

In all probability and in the absence of chemical weed control, which is expensive, organic matter weed suppressing technologies will have to be used in conjunction with other technical solutions. For example the option of using cover crops may have to be considered in conjunction with improved methods and timeliness of mechanical or hand weeding, increased density of crop, improved placement of fertiliser, so that weeds are not fed, levelling to prevent waterlogging, and crop rotations (Euroconsult, 1989).

Table 10.7. Biophysical and socio-economic limitations of weed suppressing organic mater technologies with reference to key factors limiting organic matter technologies at the FAI.

	Problem	**Weeds**	
	Objective	**Improved Weed Control**	
	Technologies	**Plant rotation technologies (leguminous cover crops)**	**Plant intercropping technologies (cover crops)**
Biophysical limitations			
Quality of biomass	Low	✗✗	✗✗
	Moderate		
	High		
Growth of cover crop	Low	✗✗	
	Moderate	✗	✗
	High		✗✗
Competition for resources	Low		
	Moderate		✗✗
	High		✗✗✗
Temperature	Low	✗	✗
	Moderate		
	High	✗	✗

Rainfall	Low	✗	✗
	Moderate		
	High	✗	✗
Soil texture	Clay		
	Loam		
	Sand		
Soil pH	Acid	✗	✗
	Neutral		
	Alkaline		
Associated pests or diseases	Yes	✗✗	✗✗
	No		
Socio-economic limitations			
Land area availability	Low	✗✗	✗
	Moderate	✗	
	High		
Labour availability	Low	✗	✗✗
	Moderate		✗
	High		
Capital availability	Low	✗	✗
	Moderate		
	High		
Distance to market	Near		
	Far	✗	✗
Infrastructure	Poor	✗	✗
	Moderate		
	Good		
Time for benefit	Short		
	Medium	✗✗	✗✗
	Long	✗✗✗	✗✗✗
Distance to farm land	Near		
	Far		✗✗

Table 10.8. Rational for the classification of limitations for weed suppressing technologies.

Biophysical limitations	
Quality of biomass	Although the quality of biomass is not directly related to the function of the cover crop as a weed suppressing technique, the cover crop is normally used as a green manure at some point, in which case the normal rules regarding quality of organic matter become important.
Growth rate of weed suppressing techniques	The quantity of biomass produced by the weed supressing technique is important, particularly in rotations, where weed suppression depends on the ability of the cover crop to outstrip the weeds. In intercropping systems, high cover crop growth may smother the main crop, particularly if they have a verticle rather than a horizontal growth habit. In effect, the cover crop becomes the weed itself. However, it is unlikely that a slower growing, less competitive cover crop will be able to outcompete the crop, without being more aggressive than the weed. Moderate growth rates may suppress weed development to some extent, but perhaps not sufficiently to make a practical difference.
Competition for resources	Where a window exists for the intergration of a cover crop during an existing fallow, there is unlikely to be competition with the main crop. In an intercropping situation, weed-suppressing technologies may compete excessively with the main crop for nutrients, light and water.
Temperature	Temperature affects the speed with which cover crops grow, and where temperatures are either very high or low, their ability to suppress weeds may be reduced. However as growth rates of weeds are also likely to be lower the net difference may be insignificant.
Rainfall	Rainfall affects the speed with which cover crops grow, and where soil moisture is either very high or low, their ability to suppress weeds may be reduced. However as growth rates of weeds may also be lower in these conditions, the net difference may be insignificant.
Phenology	In rotations, it is extremely important that weed suppressing technologies should grow for as long as possible to prevent the development of weeds before the growth of the main crop. In both cases, it is important for the cover crop to be able to seed so that stores can be made for the next season.

Associated pests or diseases	Where weed-suppressing technologies increases the incidence of pests and diseases, they may be rejected as a result.
Socio-economic limitations	
Security of tenure	Tenure ought to be secure for at least a couple of years to make the effects of weed suppressing technologies relevant to the farmer.
Land area availability	In general, weed suppressing technologies should be relatively land neutral. In rotations, the cover crop will normally fit into an existing window in the cropping calander. Where intercropping and relay intercropping are intergrated, there should be no extra requirement for land, unless the cover crop suppresses main crop yields, in which case the farmers is likely to discontinue use.
Labour availability	The establishment and management of weed suppressing technologies will increase the workload on farmers, the extent to which this is problematic depends on whether the labour occurs at a peak periof and wherther the technique reduces labour expended on physical weed control measures.
Capital availability	Generally, small amounts of capital are required to suppress weeds with cover crops.
Distance to market	Locality of markets may encourage the farmer to invest in weed suppressing technologies
Infrastructure	The availability of infrastructure may convince farmers that using cover crop technologies to extend cropping periods may be worth a go. Evidence however suggests that weed suppressing technologies may not in themselves provide the solution to weed problems for reasons mentioned above.
Time for benefit	Short term benefits are required from weed suppressing technologies as the farmer is unlikely to continue use even if in the long term weed suppressing technologies reduce weed seed carryover.
Distance to land	As there is no need to transport large anounts of biomass, distance to land should not be an issue. However, where cover crops require large labour inputs, there may be a need to localise activities close to the homestead.

10.2 The FAI website

The FAI web site has been developed to allow access to some of the information in the FAI report in an easy to read format. It should however be noted that not everything in the report is available on the web site and, that the report has been modified in the months since the web site was started. Due to the large amount of time that is required to redevelop web pages, we have not been able to keep up with the development of the report. However, we feel that there is still plenty of useful material available on the web pages, and hope that users will be able to see it as a reference tool that can inform them of possible issues regarding the use of organic matter technologies. We also suggest that presenting information in this format may provide a possible way of making research more easily accessible for everyone. Such electronic information tools we believe can be extremely valuable as well as straight-forward to use.

The following is a quick guide to the web site:

- General Introduction — This provides a brief background to the project.
- The Forest Agriculture Interface — This provides an introduction to the FAI
- The technologies — This provides a brief introduction to organic matter technologies
- Soil organic matter — This examines the use of organic matter technologies for soil physical improvement
- Nitrogen — This examines the use of organic matter technologies for increasing nitrogen supplies to the crop

•	Phosphorus	This examines the use of organic matter technologies for increasing phosphorus supplies to the crop
•	Weeds	This examines the use of organic matter technologies for controlling weed development
•	Socio-economics	This examines socio-economic considerations in the use of organic matter technologies
•	Synthesis	This provides a 'holistic' assessment of the circumstances leading adoption or organic matter technologies by farmers and a tabular summary of the positive features, negative features, 'requirements' and possible niches of the organic matter technologies

In recognition of the fact that many areas of the world do not have good access to the Internet, we suggest that the web pages be used off-line with the use of a web browser. The files in the accompanying floppy have been zipped. They can be unzipped into a folder (directory) of the user's choice (with WinZip[1] Version 6.3 or later).

1. Open the file 'fai.zip' in WinZip.
2. Press the 'Extract' command.
3. In the window that appears, select 'All Files' and 'Use Folder Names' and select the folder into which the files will go in the 'Extract to' box.
4. In the same window, press the 'Extract' button.
5. The files should be unzipped in the directory of your choice, but with the original folder structure.
6. Open '....\fai\fai.htm' in your web browser.

10.3 The FAI database tool

The FAI database has been developed to see how existing data can be used to estimate the requirements for biomass, labour and land in the use of organic matter technologies. This is done by taking the data in the ORD (Gachengo *et al.*, 1998) on N and P concentrations in various plants to give an approximation of biomass, land and labour requirements for the use of that biomass. Because the FAI database relies so heavily on ORD, we request that any citation of the FAI database should cite the underlying role of the ORD (Gachengo *et al.*, 1998).

An approximation of possible uses of the biomass, given its quality, are also given along the lines suggested by the ORD (Gachengo *et al.*, 1998) and by (Mafongoya *et al.*, 1997b). To use the database, users will have to supply some of the input data themselves, and this is indicated where necessary.

The database can be unzipped into a folder (directory) of the user's choice (with WinZip Version 6.3 or later).

1. Open the file 'faidb.zip' in WinZip.
2. Press the 'Extract' command.

[1] WinZip 6.3 can be downloaded free from the Internet if the user does not have a copy. The web site address is: http://www.winzip.com/

3. In the window that appears, select ‘All Files’ and ‘Use Folder Names’ and select the folder into which the files will go in the ‘Extract to’ box.
4. In the same pop up window, press the ‘Extract’ button.
5. The file should be unzipped into the directory of your choice.
6. Open Access (Access 97 or later) and find ‘...\faidb.mdb’.

11 Personal communications

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12 Abbreviations

The following abbreviations were used in this review:

ADP	Adenosine diphosphate
ATP	Adenosine triphosphate
BNF	Biological nitrogen fixation
CARDER	Centre d'Action Regional pour le Developpement Rural
CARE	Co-operative for Assistance & Relief Everywhere
CEC	Cation exchange capacity
MPa	MegaPascal
DAS	Days after sowing
DFID	Department for International Development
DM	Dry matter
DNA	Deoxyribonucleic acid
EPS	Extra-cellular polysaccharides
FAI	Forest Agriculture Interface
FW	Fresh weight
ICRAF	International Centre for Research in Agroforestry
IIED	International Institure for Environment and Development
INRAB	Insitute National de la Recherche Agricole du Benin
IWE	Integrated Weed Management
LDC	Less developed country
MoFA	Ministry of Food and Agriculture
MPa	MegaPascal
NPV	Net present value
NRSP	Natural Resources Systems Programme
OM	Organic Matter
ORD	Organic Resource Database
PPB	Participatory plant breeding
PVS	Participatory varietal selection
RAMR	Recherche Appliquee en Milieu Reel
RNA	Ribonucleic acid
SL	Sustainable Livelihoods
SOM	Soil Organic Matter
spp.	Species
TSBF	Tropical Soil Biology and Fertility Programme
WHC	Water holding capacity

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