

## CHAPTER 4

# The synchronisation of nutrient mineralisation and plant nutrient demand

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Natural grasslands and forests are generally believed to be nutritionally conservative in the sense that losses of nutrients are minimal (*see* Chapter 2). The small losses that do occur are balanced by small inputs from the weathering of soil parent materials, from atmospheric deposition or, in the case of nitrogen, from fixation. The disturbance of these systems by humans generally upsets this dynamic equilibrium. The removal of forests and the cultivation of forest and grassland frequently provides suitable conditions for the processes through which nutrients may be lost from the soil (Bormann and Likens, 1979; Ewel et al., 1981; Matson et al., 1987; Ramakrishnan, 1989). As described in Chapter 2, losses of potassium and magnesium are frequent. Among the biologically controlled elements, N is the outstanding example; it may be lost by leaching or by various gaseous products. However, in certain conditions, losses of sulphur and phosphorus may also be important, and in the case of leaching, the losses are accompanied by a loss of cations.

In the tropics there are large areas with inherent low soil fertility. Exploitation by humans in the humid tropics has resulted in the rapid loss of soil fertility, which is a constraint to crop production. Loss in yield cannot be corrected by the use of fertiliser in economies where cash flow is minimal. Consequently, farmers must suffer steadily reduced yields, and this often leads to land abandonment.

A farmer with limited cash flow cannot afford to change from a traditional system to one with high productivity through capital investment. Shifting cultivation, a traditional system in which productivity is maintained, is increasingly less available because of population growth. In the long term, population pressures dictate that efficient, high-input systems must be developed. In the short term, however, production systems must either conserve existing nutrient reserves (that is, losses must be reduced) and/or apply low-cost inputs. Productivity must also be increased in order to improve the cash flow to enable farmers to adopt more productive systems.

Current concerns about sustainability (*see* Chapter 1) have also focused attention on the need to conserve nutrients and other resources as agriculture intensifies. The 'synchrony' theme of the Tropical Soil Biology and Fertility Programme (TSBF) addresses this issue (*see* Appendix 1). Stated simply, this theme is that the supply of nutrients can be synchronised with plant growth demands. On

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the one hand, synchrony can be promoted by manipulating plant demand. This can be done in several ways (for example, by controlling planting date and duration of crop growth, selecting crops with different growth patterns, or using different multiple cropping systems). Alternatively, both the release of nutrients and the efficiency of nutrient availability to the plant can be manipulated by controlling the quantity and quality of organic inputs such as crop residues and manures, which sometimes facilitate the retention of added inorganic inputs, and the timing of their input.

The objectives of this chapter are to examine the synchrony theme and to establish whether its conceptual elegance may be applied within cropping systems in order to enhance the productivity and sustainability of tropical production systems. Where possible we draw on research work from the tropics and sub-tropics as examples. However, since much information already exists from research in temperate regions, and since the tropics have been relatively less intensively studied, we cite temperate experiences where relevant. We examine research done to arrest the decline and restore the fertility of soils. We also look at comparisons of cropping systems and pastures, as well as the natural systems from which they were derived. Where possible, we use examples from the TSBF programme.

The chapter opens with a description of a conceptual model of synchrony. It then examines the component processes that constitute this model. This is followed by an examination of ways in which the system can be manipulated, and a consideration of which management practices that incorporate the synchrony theme have a greater applicability. Finally, we assess the performance of the model in some natural and managed tropical systems, and attempt to answer the question 'Is synchrony a practical tool or just a good idea?'

## A CONCEPTUAL MODEL

### The concepts

The synchrony theme as used in the TSBF programme can be summarised thus: 'the release of nutrients from above-ground inputs and roots can be synchronised with plant growth demands' (Swift, 1984, 1985, 1987). The term 'synchrony' used in this sense thus implies that the rate of release of a nutrient into a plant-available form can be closely related to the rate at which it is needed by the plant. In the case of N, a temporal pattern of uptake exists that is closely related to the pattern of plant growth. There is also a time pattern of release of N from the soil and the decomposing organic residues. If the pattern of plant demand and that of release are similar, then a degree of synchrony exists. The location of released nutrients with respect to plant roots is also part of this concept.

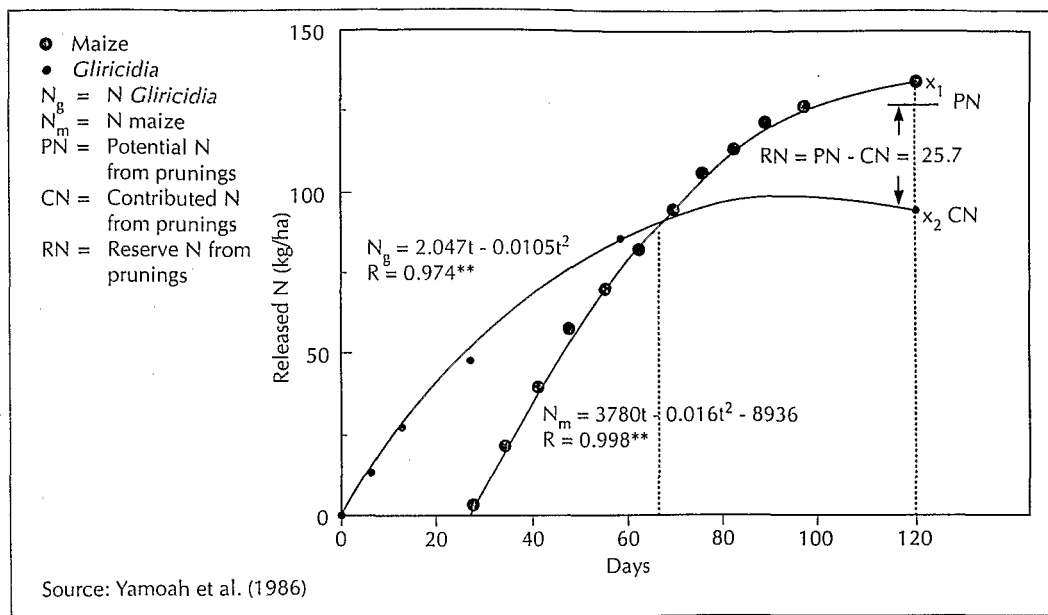
In any system, the pattern of the uptake of N into the vegetational component is closely related to the pattern of growth of the plants. There is a comparable concept of concurrence in space that has been termed 'synlocation' (R. Merckx, pers. comm.). In the TSBF programme, the two concepts are embedded together in concurrence of demand and availability in both time and space.

Synchrony applies mainly to nutrients for which biological cycling through soil organic matter is important, primarily N, P and S. Since cycling includes the processes of conversion of these nutrients into unavailable forms (immobilisation) and their release into plant-available forms (mineralisation), the possibility exists that management may either enhance or inhibit the supply of nutrients to plants.

Lack of synchrony (asynchrony) may occur when a nutrient is released or added to soil during periods of restricted plant demand, or when it is released at a rate exceeding the uptake or slower than the plant's needs. Combinations of these factors may exist during plant growth. For example, release exceeds demand at certain times but can be less than demand at other times. An example is given in

Figure 4.1 where supply exceeded demand for 65 days, but thereafter was less than demand. In such a situation, there would be no problem if losses did not occur or if immobilisation processes were operating during the times of excess.

Figure 4.1 Nitrogen release by prunings of *Gliricidia* and maize N uptake



In concept, a situation which lacks synchrony may be made more synchronous by applying a material that immobilises N during fallow or early crop growth, and then releases it later when crop demand is greater. Conversely, a nutrient-rich material could release N more rapidly than crop demand, and the situation may be less synchronous than desired.

What are the quality factors by which organic materials can modify the supply of nutrients? Three factors appear to be particularly important. These are the N, lignin and polyphenol concentrations in the materials. The capacity of these factors to influence synchrony is examined later in this chapter.

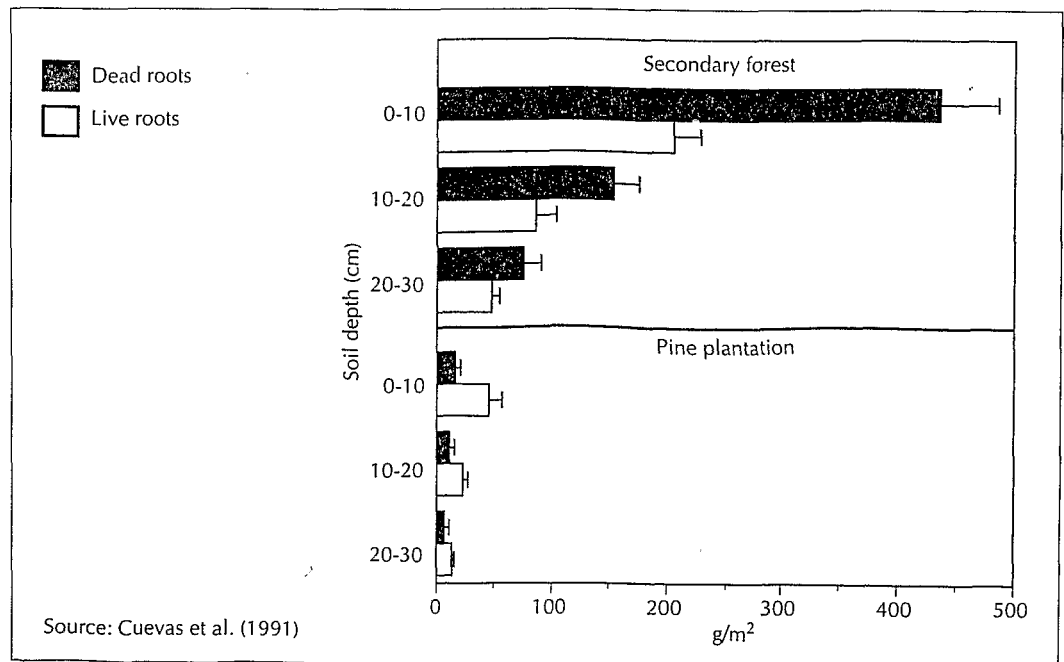
*The role of roots*

The interaction of the living root system with the soil is another key issue. Live roots can play an important role in determining net nutrient mineralisation. An example of this is seen in the work of Singh and Shekhar (1989a, b). They estimated that the microbial activity of decomposing root residues from previous crops in the soil accounted for 43-89% of total soil respiration. Peak activity coincided with the period of maximum root growth of the current crop and could be explained by the higher amount of rhizodeposits, either as exudates or sloughed cells, released when root growth was known to be greatest (Billes and Bottner, 1981). The result is the provision of an energy source for microbial

growth (Martens 1990). Singh and Shekhar (1989b) also found that roots from previous crops were providing nutrients for the current crop; in a sense, therefore, synchrony occurred between the demand of the current crop and the period of net mineralisation of the decomposing roots of the previous crops. Chotte et al. (1990), using  $^{15}\text{N}$ -labelled residues in the absence of growing plants, found that there was net immobilisation in the organic residues in the soil. However, when plants were grown in these soils, net mineralisation and uptake occurred, indicating a direct effect of live roots on microbial processes and nutrient availability in the soil system. When low-quality residues, either of exogenous origin, such as litter, or endogenous origin, such as roots, are left on the soil or incorporated into it, immobilisation occurs (Pieri, 1989). Once root exudates of high quality enter the soil system, mineralisation proceeds. Root exudation is strongly influenced by moisture stress (Martin, 1977), and thus the priming effect of rhizodeposits on residue mineralisation will depend upon soil water availability to the growing plant.

A synchronous system has to be able to exploit both above- and below-ground resources as these become available. Root distribution and density (length of roots per volume of soil) within the soil profile is primarily genetically determined, but it is also a response to soil type, moisture, nutrient availability, organic matter distribution and soil management. Asynchrony occurs when species with limited response plasticity are present in conditions where maximum response to the constraining factors is required. Environmental resources such as light, water and nutrients are the functional factors to which the plant will adapt and/or respond. At the TSBF site in Luquillo, where a 12-year-old secondary forest is established on clayey, acid soil with low P availability (Cuevas et al., 1991),

Figure 4.2 The relative standing stocks of fine roots in a secondary forest and a pine plantation, Luquillo, Puerto Rico



massive seasonal, secondary root production occurs (*see* Figure 4.2). This is interpreted as an adaptation that provides an increased root surface area which increases the capability for nutrient uptake in space and time. This is also considered to be a type of synchrony.

Organic inputs can produce a positive response in root development and crop yields. In a study which was conducted in Senegal, Cisse (1986) examined the effect of fertiliser and manure additions on the root mass of *Pennisetum* growing on sandy soils. The addition of manure increased rooting depth and root mass per unit area at all depths. In the plots which had been fertilised, the maximum root depth was 1.4 m, while in the fertiliser + manure plots, the maximum root depth reached 1.7 m. An increase of 21% of the total root mass per area was translated into a 100% increase in shoot allocation (shoot/root ratio of 7.2 in the fertilised plots, compared with 16.4 in those plots where manure was applied). Thus, an increase in the root surface area, brought about by organic additions in these sandy soils, results in a greater capacity of the plant to respond to increased nutrient availability.

Cisse (1986) also determined nutrient mobilisation and root absorption activity as influenced by additions of manure in a peanut crop (*see* Table 4.1). Root absorption activity is defined as the amount of nutrients absorbed per unit root dry weight per day. Manure additions increased N and P mobilisation and absorption fourfold compared with the fertilised plots, while K was increased twofold. These results indicate that organic residue additions can activate root function in crops grown on sandy soils, thus improving the synchrony of nutrient demand with nutrient availability. Research is needed to assess whether residue additions produce the same results in wetter climates and in soils with different clay content and mineralogies.

**Table 4.1** Manure effect on the daily nutrient mineralisation and uptake by peanuts in Senegal

	Soil solution (mg/l)			Mineralisation (kg/ha/day)			Uptake (mg/g root/day)		
	N	P	K	N	P	K	N	P	K
Fertiliser	13	—	13	0.85	0.09	0.5	3.6	0.4	2.1
Fertiliser + manure	36	—	22	3.8	0.5	1.3	14.1	1.8	4.8

Source: Cisse (1986)

#### *Time scales*

Time scale is an important factor. Synchrony can be considered on a short- or long-term basis. A short-term time scale is important in the case of annual crops where over a period of 90-150 days there are large changes in plant demand. In such systems, crop residues, which are important to nutrient cycling, enter the nutrient cycle as pulse inputs and can influence nutrient pool sizes relatively quickly. By contrast, in perennial forests, litter returns are continuous and exercise a relatively constant influence on nutrient supply. A longer-term time scale needs to be considered for such systems. The significance of the time scale is determined by the requirements for immediate plant response, or storage or immobilisation of nutrients for release at a later and more appropriate time, or for slow release for sustained plant response through time. These time considerations are of utmost importance when

attempting to enhance synchrony in agricultural systems which have different plant nutrient demand patterns and scales.

### *Spatial scales*

Spatial relationships are important in the synchrony concept. The location of plant residue, either on the soil surface or buried, has a large influence on its rate of breakdown and release of nutrients. The leaching of a nutrient into the subsoil may make it unavailable to a shallow-rooted crop but available to a deep-rooted crop.

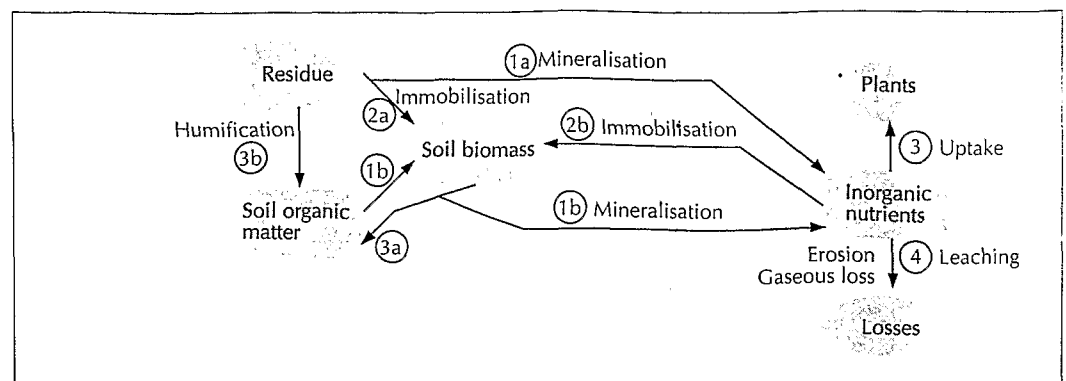
The spacing of plants can influence synchrony through modifying root distribution and the temporal pattern of plant demand. Increased plant densities result in competition for light which, in turn, reduces demand for nutrients. Situations should therefore exist where this leads to better synchrony of supply and demand.

A higher degree of synchrony is achievable in multiple cropping systems which provide crop demand patterns that bear a closer resemblance to the pattern of nutrient supply. Mixed cropping systems often have greater heterogeneity of root distribution that can better utilise the available nutrients.

### The pathways

A simplified model for synchrony regulation is presented in Figure 4.3. This conceptual model depicts the flow of C and nutrients between organic residues, soil organic and inorganic pools, and the plant. Pathways of loss are also included. Decomposition and mineralisation of plant residue is mediated by both soil faunal and microbial populations. Some of the C and associated nutrients are mineralised immediately (pathway 1a in the figure) or are immobilised in the soil microbial pool (pathway 2a), being transformed later into other soil organic pools by microbial by-products (pathway 3a). Recalcitrant plant material may enter the soil organic pools directly (pathway 3b). The C and nutrients held in the various soil organic matter pools are subsequently decomposed and assimilated by soil

Figure 4.3 Conceptual model of nutrient pathways



biomass, resulting in additional mineralisation (pathway 1b). The inorganic nutrients which are released by mineralisation may be assimilated by soil biota, a process referred to as immobilisation (pathway 2). Immobilisation occurs simultaneously with mineralisation and the rate at which nutrients are available for plant uptake depends upon the net balance between mineralisation (pathways 1a and 1b) and immobilisation (pathway 2). This is referred to as net mineralisation. The inorganic nutrients may also be taken up by plants (pathway 3), lost as a result of leaching or volatilisation (pathway 4) or remain in the soil. The size of the inorganic pool depends upon the balance of the various processes that add to the pool (mineralisation) and those that subtract from it (immobilisation, plant uptake and losses).

In natural systems there is a hierarchy of controls on the flux of nutrients between various pools. Environment, which includes climate and soil, is an overriding control which determines the rate of transfer between pools. However, these transfer rates will also vary depending upon the quality of the decomposing substrate or upon the types of organisms which are present within the systems (Swift et al., 1979). Management can lead to alterations in the natural processes. This leads us to the TSBF objectives within the synchrony theme, which are to understand the controls on the various fluxes and then to use this knowledge for managing inputs in order to alter the rates or directions of the nutrient fluxes.

#### The role of soil and climatic factors

Soil factors are important to the expression of synchrony in a number of ways. Properties of soils that affect drainage, including clay content and the presence of compacted layers, influence the stability of nitrate. Thus, freely draining soil in a high rainfall environment provides a greater risk of loss of productivity because of the lack of synchrony than does soil with a high water-holding capacity in a semi-arid environment. For P, soils with a high capacity to absorb P appear to offer greater benefits from controlled cycling through organic matter than soils with a lower adsorptive capacity.

Of the climatic components, rainfall has the greatest potential to influence the expression of synchrony. With mobile nutrients, the consequences of lack of synchrony may be negligible in a low rainfall environment where the nutrients remain within the root zone. However, in a high rainfall environment, mobile nutrients may be rapidly leached below the root zone, with significant results.

### THE COMPONENT PROCESSES

The N cycle and its component processes have been comprehensively reviewed in recent years by Stevenson (1982) and Wilson (1988). With respect to synchrony, the most important processes are mineralisation-immobilisation, denitrification, volatilisation and leaching. In the case of other nutrients, primarily P and S, the most important processes are mineralisation-immobilisation and leaching (Stewart and Sharpley, 1987). Here we briefly consider how these processes relate to synchrony.

#### Mineralisation-immobilisation

Mineral nutrients present in excess of plant needs are susceptible to various loss processes. Improved synchrony implies that there is less excess mineral nutrient and thus the opportunity for loss is reduced.

Net mineralisation needs therefore to be slow when plant needs are low, and rapid when plant demand is high. Whether a particular rate of release occurs depends largely upon the following factors: quality of the resource, quantity of the resource, moisture and temperature, and soil factors such as texture, mineralogy and acidity, biological activity and the presence of other nutrients. Water and temperature contribute strongly to synchrony since they both modify plant growth in much the same way as they modify mineralisation-immobilisation. For example, if either moisture or temperature are limiting, then little N mineralisation or plant growth will occur. By contrast, some factors may affect plant growth and nutrient release processes differentially. Thus, N mineralisation may proceed rapidly in acid soils but plant demand may be low if poorly adapted species or cultivars are sown (Leiwakabessy, 1989). Similarly, N mineralisation would continue in a waterlogged soil (Patrick, 1982) whereas the growth of most crop species would be inhibited. Fortunately, these are the exceptions; most modifying factors result in parallel plant and soil processes. The other major exception, one that will be discussed in detail later in this chapter, is the effect of exogenous organic materials, the decomposition of which may have little or no direct effect on the plant but a considerable effect on nutrient supply.

With respect to the presence or absence of the microorganisms required to mediate the processes, it is generally assumed that a varied suite of organisms is always present and that processes should not be limited by the absence of a particular organism. However, following the commencement of conditions suitable for a process, there may be a delay in end-products but an increase in specific microbial populations. Thereafter, if moisture and temperature conditions are suitable, N mineralisation proceeds at a rate dependent upon the quantity and quality of organic matter. Delays in mineralisation occur following the resumption of appropriate moisture or temperature conditions after prior conditions such as prolonged soil drying or extreme temperatures have resulted in a population decline. Similarly, when there is a change in substrate availability (for example, when organic materials are added), there may be a delay in microbial proliferation. If the nutrient content of the added material is low, but organisms are able to use the substrate as a C source, net immobilisation occurs.

There is some evidence that soil acidity may be a special case with respect to mineralisation-immobilisation and synchrony. There has been an assumption that soil pH affects mineralisation and immobilisation differently because immobilising organisms tend to utilise ammonia rather than nitrate (Alexander, 1961). If correct, this would have profound implications for the synchrony theme. However, it now appears likely that, in alkaline soils at least, immobilising organisms preferentially utilise nitrate (I.J. Rochester, pers. comm.). In such soils, synchrony may be enhanced by nitrate immobilisation-remineralisation. Since nitrification is, in many cases, slower in acid soils than in alkaline soils, some acid soils may be less prone to accumulation and loss of nitrate than non-acid soils.

### Denitrification

In a system lacking synchrony, mineral N may accumulate and, in all but very acid soils, this accumulation will be largely as nitrate. Under these conditions, the loss of N by denitrification becomes a potential consequence of lack of synchrony. The process of denitrification in soil has been reviewed in detail by several authors, including Firestone (1982) and Groffman et al. (1988). Loss through this process is facilitated by the presence of nitrate, the presence of decomposable organic matter to 'fuel' the process, suitable temperature and the absence of oxygen at the microsite where the process is taking place. The most likely occurrences of nitrate accumulation are in cultivated land when the land is in bare fallow, in land where nutrient-rich residues are returned to the soil, and in land where N fertiliser has been applied. Decomposable organic matter is thought to be a limiting factor in most field soils



(Firestone, 1982; Groffman et al., 1988), although this limitation is overcome when plant residues are returned to the soil. The process is seldom limited by temperature in the tropics, but in temperate and cool temperate regions low temperature may be a limiting factor during winter. Anaerobiosis occurs when oxygen is consumed faster than it can be replaced, and is therefore dependent upon the rate of aerobic activity, soil depth and the inter- and intra-aggregate oxygen diffusion rate (Smith, 1980). Sufficiently low oxygen diffusion rates that promote rapid denitrification are most likely under waterlogged conditions, as in rice paddies and in pasture systems with compacted soil.

In semi-arid regions, the moisture conditions conducive to denitrification are likely to be episodic, and not correlated with other necessary preconditions. In the humid tropics, suitable moisture conditions are more frequent and denitrification of accumulated inorganic nitrogen more likely. A major reason for seeking a more synchronous system is to reduce the risk of loss of N through denitrification.

#### **Volatilisation of ammonia**

When plant residues decompose on the soil surface, substantial amounts of ammonia may be lost to the atmosphere. Smaller losses occur when the residues are incorporated into the soil, particularly if the soil is acid rather than alkaline. Thus synchrony may be enhanced by achieving slower decomposition through surface placement, but this may have the undesirable side-effect of ammonia loss.

#### **Leaching of nutrients**

If soluble nutrients accumulate in soil, and water percolation occurs, then removal of some of these nutrients by leaching is likely. This is of most concern with nitrate, but can also be significant with S, K, Ca and Mg. Recent reviews by White (1988) and Nielsen et al. (1982) have examined this process in detail. The process depends upon the concentration of the particular ion, the degree to which the ion is adsorbed or exchanged with the solid phase, and the amount of water passing through the soil (Nielsen et al., 1982). The risk of loss is highest in soils of low water-holding capacity in the humid tropics, particularly those that receive additions of N fertiliser. However, nitrate can be leached below plant rooting depths even in semi-arid conditions (Catchpoole, 1992). A major aim of synchrony is to reduce the risk of nitrate leaching.

### **MANAGEMENT EFFECTS**

In this section we examine how synchrony may be influenced by management. The objective is to modify the relative rates of material flows so that there is minimal loss of nutrients and productivity is thus improved and sustained. First, we consider various options, including management of the plants, fertilisers and organic amendments, tillage and changes in general land use.

#### **Plant management**

This can be achieved in several ways: by manipulating plant husbandry to match nutrient supply, by growing the type of plant in which the demand for nutrients matches the temporal and spatial pattern

of availability in the soil, by growing plants that are more effective at recovering available nutrients, or by growing plants that can modify the pattern of nutrient release.

Optimisation of sowing date frequently includes a component of nutrient optimisation. In the tropics, the timing of sowing is generally based on a judgement that the rainy season has truly started and an awareness that early onset seasons are superior in terms of potential yield (Stewart, 1991). Sowing early after the start of rains has the additional purpose of enabling the crop to utilise the flush of nutrients that accompanies soil re-wetting. Delayed sowing in such early onset seasons therefore increases the risk of losing nutrients by leaching. Any decision-support tools that assist the farmer to identify correctly the onset of the season enhance the synchrony of the system.

However, it may also be necessary to grow the type of crop that can improve synchrony. For example, in environments where nitrate leaches rapidly, deep-rooting crops may be required. Wetselaar and Norman (1960) observed that nitrate leached beyond the effective depth of the root system of sorghum, but that pearl millet roots were capable of retrieving subsoil nitrate from as deep as 1.5 m. Vast areas of tropical lands have acid soils in which acid-sensitive crops perform poorly. An important component of this performance is poor root development. Better-adapted plants provide more effective root exploration, particularly with respect to depth of rooting. This may also be achieved by multiple cropping systems whereby two or more species growing together may provide better synchrony than a monocrop, or where the sequence of crops is such that at no time are there no crops (and no active root system). The choice of system, and of species and cultivars that are more tolerant of the growing conditions, may therefore lead to better root development and to a more effective synchrony.

An example of such a system is the mixed-species homegarden where the multistoreyed condition of the natural forest system is simulated through different perennial and annual crops with many different patterns of root distribution. This is the case in Javanese and Kandyan homegardens where deep-rooted crops such as cloves, nutmeg, jackfruit and breadfruit are cultivated with shallow-rooted ginger and palms.

Another method of managing the plant may be to graft improved cultivars onto more effective rootstocks. Some species that are amenable to grafting are rubber, mango, rambutan and avocado. Wild relatives growing in rainforests that are better adapted to organically mulched conditions may be a source of such rootstocks.

Plants themselves can modify the patterns of nutrient release from soil. Such plants include symbiotic N-fixing legumes and mycorrhizal plants, as well as less obvious examples of perennial plants in which litterfall and root-derived material modify nutrient cycling. Forest systems which have a continuous recycling of nutrients through litter and root turnover may achieve long-term synchrony. It will be argued later that some species achieve this to a greater extent than others because of the development of more appropriate types of root systems.

### Fertiliser management

Fertiliser is commonly applied to crops at or near the time of sowing. This is convenient for the farmer but it is a time when the crop's needs are small, and there is an opportunity for N losses to occur prior to increased crop demand. This problem has long concerned researchers who have sought the means to control the availability of N fertiliser following application. They have tried to achieve better synchrony by maintaining the N fertiliser in a form that is less susceptible to loss, and to have it released in a form available to the crop at a rate similar to the crop's needs. Ways in which this has been

attempted include the use of nitrification inhibitors, split application, banded or point placement, plastic or S-coated fertiliser, and mixed fertiliser and organic mulch.

These technologies have been described in detail by Meisinger (1980) and Engelstad (1985) and will not be elaborated upon here. In the case of coated fertiliser and inhibitors, to date the additional cost of the product has usually outweighed any advantage in yield. Such technology will not be adopted until the cost of the product is reduced and/or the benefit and the reliability of obtaining that benefit is improved. In general, under field conditions, band and point placement and split application have sometimes given modest improvement in use efficiency. Field examples of better synchrony resulting from the use of coated fertiliser or inhibitors are still rare, although S-coated urea produced higher rice yields than urea in intermittent flooding conditions but not in conditions of continuous flooding (TVA, 1979).

Management of fertilisers in the presence of crop residues, as occurs in reduced tillage systems, is not always easy. In the Australian sugar industry, conversion to a no-tillage and trash-retention system meant that 10-15 t/ha dry matter was left on the soil surface. It proved difficult to incorporate fertiliser through the litter layer, and so farmers broadcast urea onto the trash. As a result, massive losses of N by ammonia volatilisation occurred (Denmead et al., 1990), indicative of asynchrony compounded by a spatial component.

In systems where losses from applied fertilisers can be high, it is possible that other crop residues may help conserve applied nutrients. For this to provide economic benefits, the nutrients must first be immobilised and then later released for crop uptake. Although the processes concerned have been much studied, we find little evidence of serious attempts to develop this type of fertiliser management system. There is scope for experimentation in this area.

#### Management of organic amendments

The amendments discussed here include crop residues, green manure, animal manure, plant material brought from elsewhere, composted material, and waste products from processing plants. The materials are important both as sources of, and temporary sinks for, nutrients, particularly N.

#### *Quantifying plant residue quality*

In this section we introduce the concepts of low-quality and high-quality organic material. Material that releases nutrients slowly, or immobilises nutrients during the early stages of decomposition, is considered to be of low quality. For example, material that has a high C/N ratio and which immobilises N as it decomposes is of low quality. High-quality material releases nutrients rapidly during decomposition. Material with a low C/N ratio, as in the case of many legume residues, is of high quality. Green manures, animal manures, composts, some crop residues and some agricultural waste products such as sugarcane mill mud, palm oil mill effluent and rubber factory effluent are high-quality sources of nutrients. Cereal straws, woody materials from agroforestry systems and some other waste products (such as sugarcane bagasse) are low-quality materials. How can these resources be best managed in order to achieve better synchrony?

Decomposition of materials with N concentrations of less than 2% (or C/N > 25) lead initially to immobilisation of mineral N, whereas materials with higher than 2% N (or C/N < 25) release mineral N. During decomposition there is a partitioning of N first between mineral N and microbial N

(pathways 1a and 2a in Figure 4.3), then with turnover of microbial N, into mineral N, humic N (pathways 1a and 3a) and microbial N. The N-use efficiency of plant residues by a first crop is about 15% for legume residues and 5% for cereal straw residues, but there is much variation. This compares with up to 60% of N applied in inorganic fertiliser being utilised by the first crop. Some residues release less N than expected; examples are *Desmodium intortum* (Vallis and Jones, 1973) and *Leucaena leucocephala* (Read et al., 1985; Mulongoy and van der Meersch, 1988; Sandhu et al., 1990; Xu, 1991). Later we discuss a possible reason for this. In many cases, however, there is a consistent pattern to the partitioning of N between the mineral N and humic N pools (see Table 4.2). Thus Ladd et al. (1981), using  $^{15}\text{N}$ -labelled *Medicago littoralis* material in a study in a temperate environment, found that the first cereal crop recovered 11-17% of the residue N, whereas 72-78% went into soil organic matter. In a cool temperate environment, temperate legume residues contributed an average of 14% of their N to a cereal crop, with 21-40% remaining in the soil, presumably in the organic fraction (Janzen et al., 1990). In the tropics, sugarcane trash N was partitioned between plants (11-14%) and soil organic matter (73-84%) (Ng Kee Kwong et al., 1987). In Senegal, Feller et al. (1983) reported that, after adding  $^{15}\text{N}$ -labelled maize stover to a sandy soil, 25% of the  $^{15}\text{N}$  added in straw was found in the plant, with the remainder in the soil. There were no losses. Most of the  $^{15}\text{N}$  remaining in the soil was found in the  $> 50 \mu\text{m}$  particle size fraction. We can assume that such particulate N would be more readily mineralisable than the 'old' organic matter, and would therefore immediately enhance the soil's ability to mineralise N. Several authors, including Ng Kee Kwong et al. (1987) and Janzen et al. (1990), have concluded that the major contribution of N in crop residues, particularly low-quality gramineous residues, is through the soil organic matter (that is, through pathways 3a and 1b in Figure 4.3). The range of results obtained for different plant residues indicates that there is considerable variation in the partitioning of residue N between plants and soil organic matter. It should be possible to use knowledge of this variation to manage the release of plant-available N for better synchrony.

Table 4.2 Contribution of nitrogen added in plant residues to the subsequent crop and to soil organic matter

Crop (%)	Organic matter (%)	References
11-17	72-78	Ladd et al. (1981)
14	21-40	Janzen et al. (1990)
11-14	73-84	Ng Kee Kwong et al. (1989)

In order to achieve better synchrony, we need to be able to predict the outcome of residue management practices. Various authors have attempted to derive rules by which they might predict the performance of a given material. Frankenberger and Abdelmagid (1985) studied the mineralisation of four legumes (alfalfa, Egyptian clover, cowpea and soybean) divided into foliage, stems and roots. They found that 16-76% of the N was mineralised within 20 weeks and that N concentration and the C/N ratio were good predictors ( $R^2 = 0.8$ ). One material that did not conform was found to have a high lignin concentration. Mineralisation of N and S in some non-legume crop residues was strongly related to N concentration and S concentration of the residues, respectively (Janzen and Kucey, 1988). In a

field study in Sumatra, Sisworo et al. (1990) found that utilisation of N in crop residues by the succeeding crop could be explained largely by the N concentration in the residues and the rainfall received during the growth of the succeeding crop ( $R^2 = 0.69$ ).

It is clear that N concentration and C/N ratio are major determinants of the ability of plant residues to supply N. However, there are other modifying factors. For example, it has been demonstrated that the lignin concentration or the lignin/N ratio provides an effective index for N release patterns (Melillo et al., 1982; Melillo and Aber, 1984). Berg and McClaugherty (1987) have indeed suggested that N is not released from litter until decomposition of lignin commences. Feller (1979) proposed the ratio of neutral detergent fibre/cellular content (NDF/CC) as an index of potential N release. Gueye and Ganry (1978) applied the idea to results from a sandy soil in Senegal. Residues with high C/N and high NDF/CC contributed to the organo-mineral fractions of the soil, whereas a material with similar C/N but low NDF/CC resulted in a release of mineral N.

In many forest species and in some legume species, it has been recognised that nutrient-rich leaf materials may be slow to release N and that this is not associated with lignin concentration. Vallis and Jones (1973) observed that *D. intortum* was slow to release N. They suggested that this was related to the presence of polyphenols in the material. This is plausible since polyphenols are reactive compounds that can form stable polymers with many forms of N (Martin and Haider, 1980; Stevenson 1986).

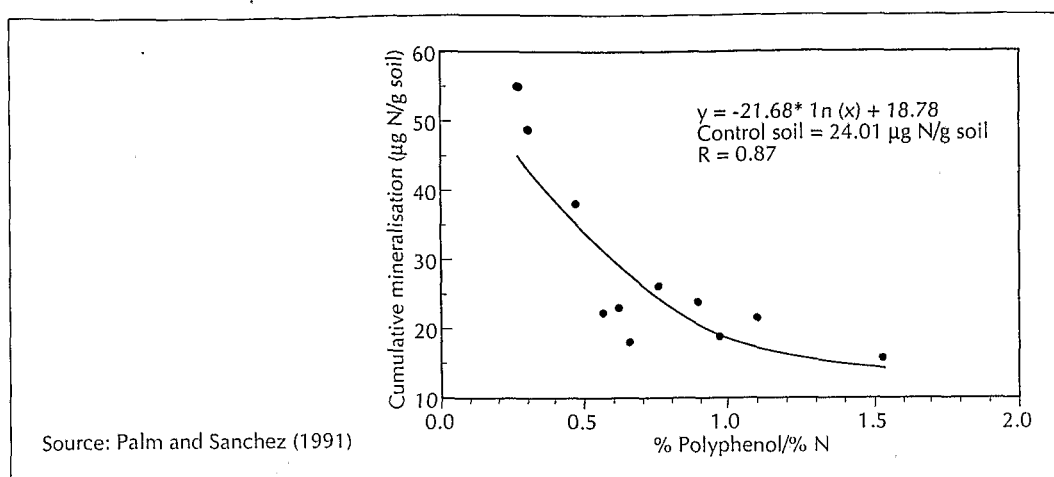
Perhaps through management of N, lignin and polyphenols, synchrony of N release with crop demand may be achieved. At Yurimaguas in Peru, Palm and Sanchez (1991) examined a range of plant leaf materials to determine the variation in their concentrations of N, lignin and polyphenols. As shown in Table 4.3, the 10 legumes ranged from 24 to 39 g/kg N, 63 to 163 g/kg lignin and 10 to 36 g/kg polyphenols. At the same time, N released after an 8-week incubation ranged from -20% (net immobilisation) to 46% of that applied. They found that regression against the polyphenol/N ratio could explain 76% of the variation in N release (see Figure 4.4 overleaf). Similar results indicating the

Table 4.3 Characteristics of organic additions and the net nitrogen mineralisation in 8 weeks

Treatment	N (g/kg)	Lignin (g/kg)	Polyphenols (g/kg)	8-week total (mg N/kg)
Control				24.0
<i>Gliricidia sepium</i>	37	78	10	54.0
<i>Erythrina</i> sp.	35	97	10	48.2
<i>Albizia saman</i>	32	63	15	40.7
<i>Inga edulis</i>	32	163	34	21.6
<i>Oryza sativa</i>	11	62	7	23.3
<i>Inga</i> sp.	30	179	16	22.2
<i>Leucaena leucocephala</i>	39	52	29	25.2
<i>Cassia reticulata</i>	25	108	22	23.5
<i>Cajanus cajan</i>	35	102	33	18.7
<i>Desmodium gyroides</i>	30	117	19	17.5
<i>Desmodium ovalifolium</i>	23	91	36	15.9

Source: Palm and Sanchez (1991)

**Figure 4.4** Relationship between nitrogen mineralised over an 8-week period and the polyphenol/N ratio of the plant material added



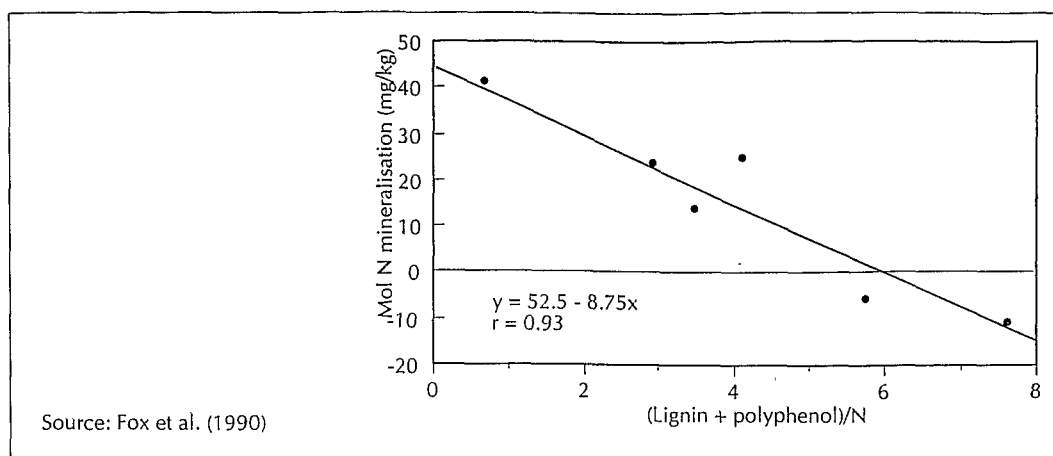
importance of polyphenol/N in controlling N mineralisation from legumes have been obtained by Oglesby and Fownes (1992). Fox et al. (1990) conducted a study using shoots of many tropical legumes. In these materials, lignin ranged from 42 to 111 g/kg, N from 18 to 47 g/kg and polyphenols from 19 to 82 g/kg (see Table 4.4). Net N released after a 12-week incubation varied from 11 to 47% of that applied. In this study the best predictor of N mineralisation was (lignin + polyphenol)/N (see Figure 4.5). These results are consistent with the idea that soil-incorporated plant lignins degrade to polyphenols, which, with other plant and microbial polyphenols, become the main constituents of recalcitrant, N-containing humic polymers (Haynes, 1986). Tian et al. (1992a, b), for a range of tropical woody and herbaceous residues, found that decomposition was strongly correlated with N, lignin and polyphenol concentrations. In turn, N mineralisation was directly related to decomposition rate, and the patterns of release of P, Ca and Mg were similar to that of N.

**Table 4.4** Concentrations of nitrogen, lignin and polyphenolics in selected legume shoots

Material	Total N (g/kg)	Lignin (L) (g/kg)	Polyphenols (PP) (g/kg)	(L + PP)/N
<i>Alfalfa</i>	47	42	27	1.48
<i>Cassia</i>	19	111	29	7.52
<i>Leucaena</i>	39	53	82	3.49
<i>Medic</i>	23	51	19	3.09
<i>Stylo</i>	18	67	35	5.82
<i>Vigna</i>	23	77	19	4.21

Source: Fox et al. (1990)

**Figure 4.5** Relationship between nitrogen mineralised over a 6-week period and the (lignin + polyphenol)/N ratio of the plant material added



One problem in research with polyphenols has been the use of different assays. Because polyphenols are a broad group of materials, the results obtained have varied greatly according to type and quantity of the extractant, the choice of standard and the method of assay. For example, an aqueous solution extracted 8-27 times more phenolic acids than an ethanolic extractant. A second problem is that the tannic acid used as a reference standard was a mixture of polyphenols and varied from sample to sample (McLeod, 1974). A further consideration is that within the polyphenols there are types that behave differently with respect to decomposition, N mineralisation and humification (Swain, 1979; Martin and Haider, 1980) and therefore have different influences on biological processes. Before further work in this area is attempted, careful attention should be paid to the methods for polyphenol analysis with a view towards developing a standard method.

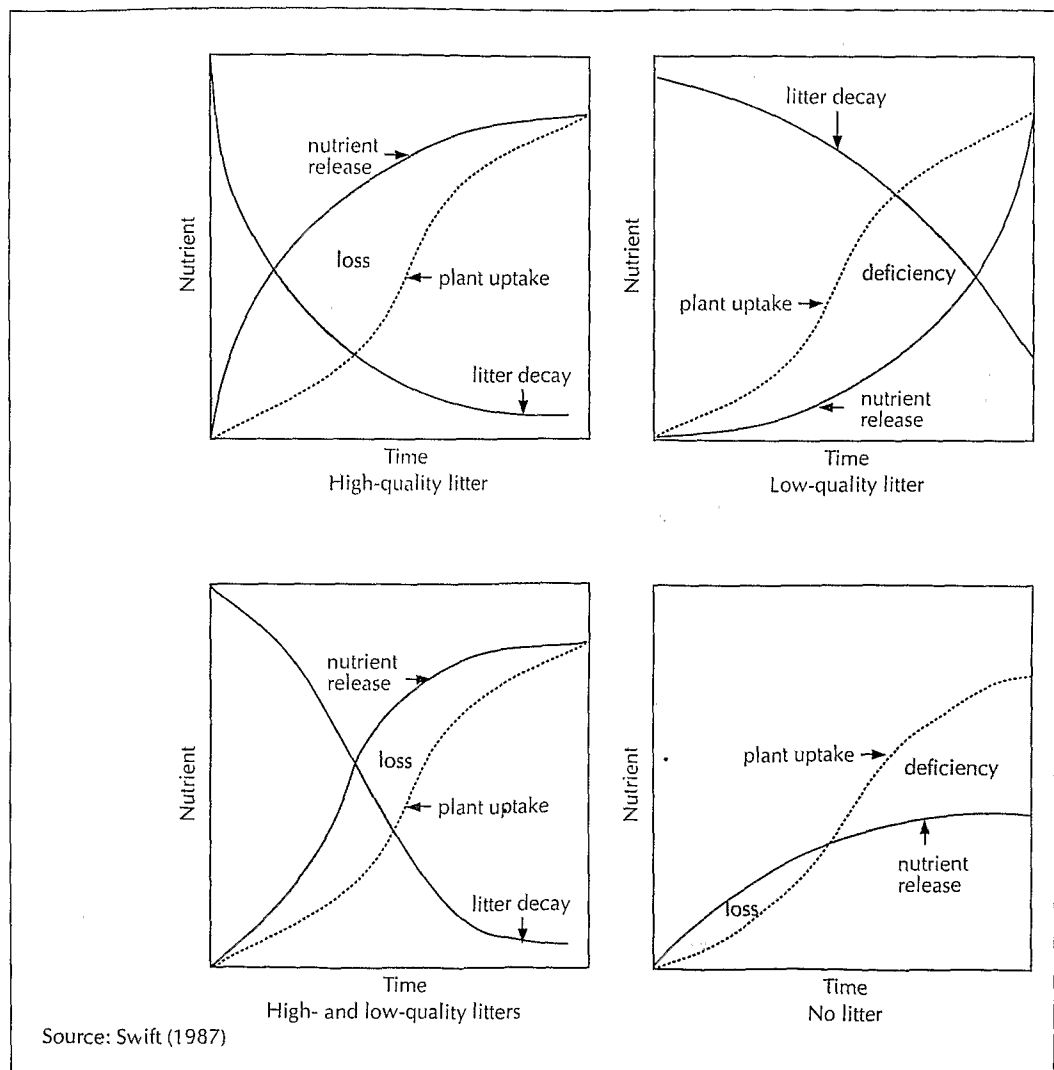
These studies, including two which were part of the TSBF programme (Fox et al., 1990; Palm and Sanchez, 1991), show that polyphenols play an important role in influencing N mineralisation patterns in leguminous material. Materials with high polyphenolic concentration, such as the *L. leucocephala* and *Cajanus cajan* materials used in these studies, and *D. intortum* in the study by Vallis and Jones (1973), despite high N concentrations, result in immobilisation, delaying the subsequent release of N by several weeks. According to the synchrony hypothesis, through species selection and the use of a combination of species, synchrony of N release and crop demand should be achievable.

#### *Can synchrony be enhanced through managing residue quality?*

An earlier statement of the synchrony theme proposed that by manipulating litter quality it should be possible to manage nutrient release to coincide with the time course of nutrient requirement of the crop (Swift, 1987). The hypothesis was that the presence of low-quality (low N and P, high lignin content or polyphenol content) litter inputs at the onset of rains extends the time period of availability of nutrients to the plant. Swift (1987) predicted some possible scenarios (see Figure 4.6). These scenarios were based on the assumption that low-quality litters resulted in immobilisation of nutrients, but that

these nutrients would later be released at a time of plant need. In the scenario with high-quality litter, nutrients were released rapidly, initially in excess of plant demand, and there was the risk of a nutrient such as N being lost through leaching or denitrification or a nutrient such as P becoming chemically unavailable (Anderson and Swift, 1983). In the scenario with low-quality litter, nutrient release was slow, leading to nutrient deficiency. However, a mixture of high- and low-quality material achieved better synchrony of supply and demand. This would result in increased yield and reduced nutrient losses. It was proposed that experiments be conducted to test this hypothesis.

Figure 4.6 Hypothetical patterns of nutrient availability in four treatments of an experiment to test the synchrony principle



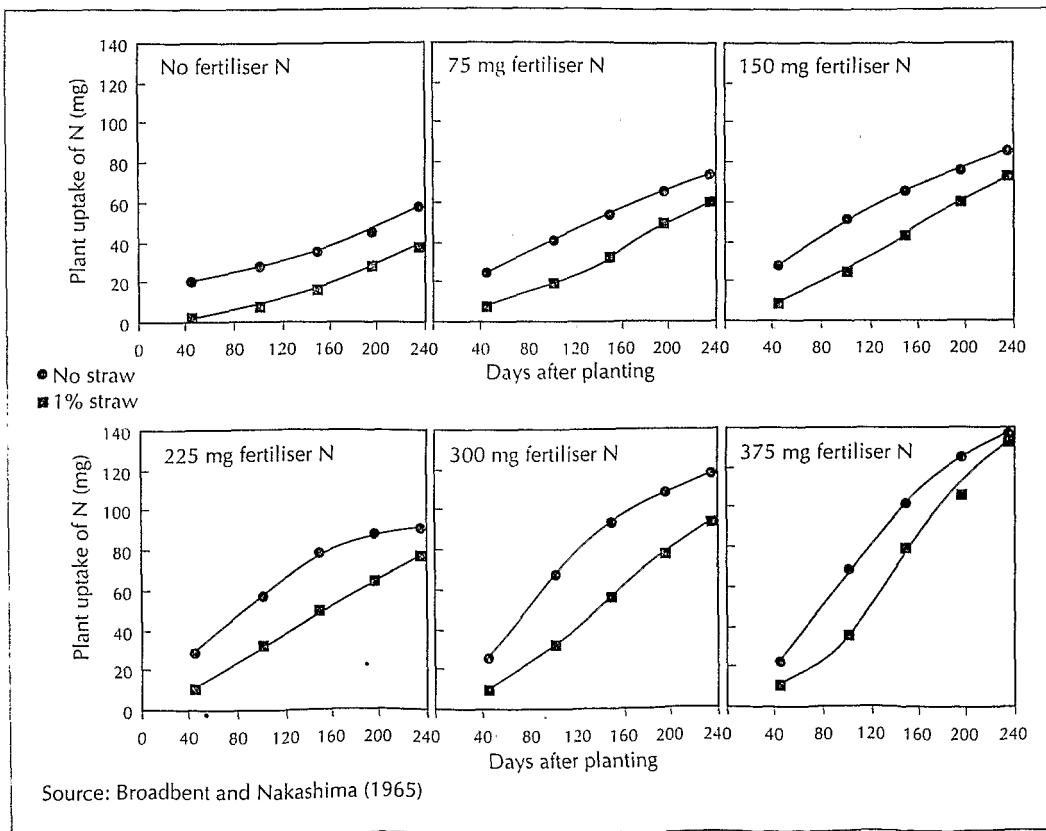


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Can evidence be found in the literature to support this hypothesis? The answer is a cautious yes. In a greenhouse study, Broadbent and Nakashima (1965) followed mineralisation and plant uptake of N immobilised by the addition of straw. Again, some of the results supported the synchrony concept. When N was added with the straw, there were indications that re-mineralisation of immobilised N was faster than mineralisation of N in unamended soils (*see* Figure 4.7). However, when no N was added with the straw the results did not support synchrony. Support for the synchrony concept is found in the results of a field experiment with flooded rice (Amarasiri and Wickramasinghe, 1988) in which rice receiving 60 kg N/ha fertiliser and straw yielded about the same as that receiving 90 kg N/ha as fertiliser alone. This role of straw may be interpreted as one of N recycling in a system where losses from the mineral N pool are potentially large, and as such is a type of synchrony.

Figure 4.7 Net nitrogen mineralisation (assessed by plant uptake) from a soil receiving different amounts of fertiliser N, in the presence and absence of straw

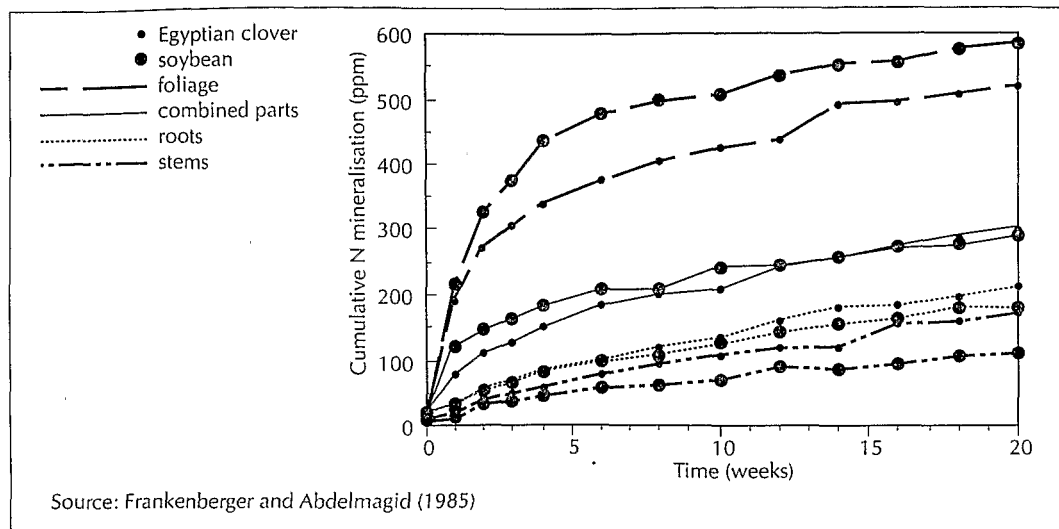


In a laboratory incubation experiment in the study by Frankenberger and Abdelmagid (1985) referred to earlier, the authors compared N release from material from four legume species (alfalfa, Egyptian clover, cowpea and soybean). In general, the different plant components released N in the

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order foliage > roots > stems. Between plant species there were no differences in the pattern of release when the initial rate of release was faster, and that trend then continued (see Figure 4.8). However, when mixtures of foliage, stems and roots were incubated with soil an interesting result was obtained. Soybean initially released N more rapidly than Egyptian clover in the first 3 weeks. After 3 weeks the rate of release was faster from the clover, such that after 14 weeks the amounts were equal. The N contents (6.4 mg vs 6.8 mg N added) and concentrations of these materials did not differ greatly, but the lignin concentration in the soybean roots was much higher than that in the Egyptian clover.

Figure 4.8 Pattern of nitrogen mineralisation of leguminous material incorporated into soil



Nnadi and Balasubramanian (1978) studied N mineralisation in a range of legume roots in 12-week laboratory incubations. Many of their results are inconclusive since some of the materials did not begin to release N until 8 weeks into the incubation period (see Figure 4.9). However, where lime was added and microbial activity was increased, there were indications that, had the incubation continued for a further few weeks, the amount of N mineralised from the material with the lower N concentration may have matched that from the material with the higher N concentration (see Figure 4.10). However, in a later study by Nnadi and Haque (1988) there was no evidence of N mineralisation from low-quality roots in a 70-day incubation.

Vallis (1983) studied N mineralisation and plant uptake from the leaves and stems of two tropical pasture legumes in the field. His results provided no evidence of any variation in the pattern of release of N other than the overall quality effect on rate of release.

Barrios et al. (1991), in a TSBF project at Mapire, Venezuela, provide anecdotal support for the notion of optimising synchrony through mixing the quality of inputs. As described in Chapter 2, in the Orinoco floodplains seasonal flooding deposits nutrient-rich sediments on agricultural land. Denitrification losses and nitrate leaching are potentially important processes that could reduce the value of these inputs. However, *Paspalum repens* grows during flooding and, as floodwaters recede, it senesces and provides a carpet of litter. It acts as a sink for nutrients during growth, as well as during

Figure 4.9 Net nitrogen mineralisation after the addition of legume roots to unlimed fallow soil

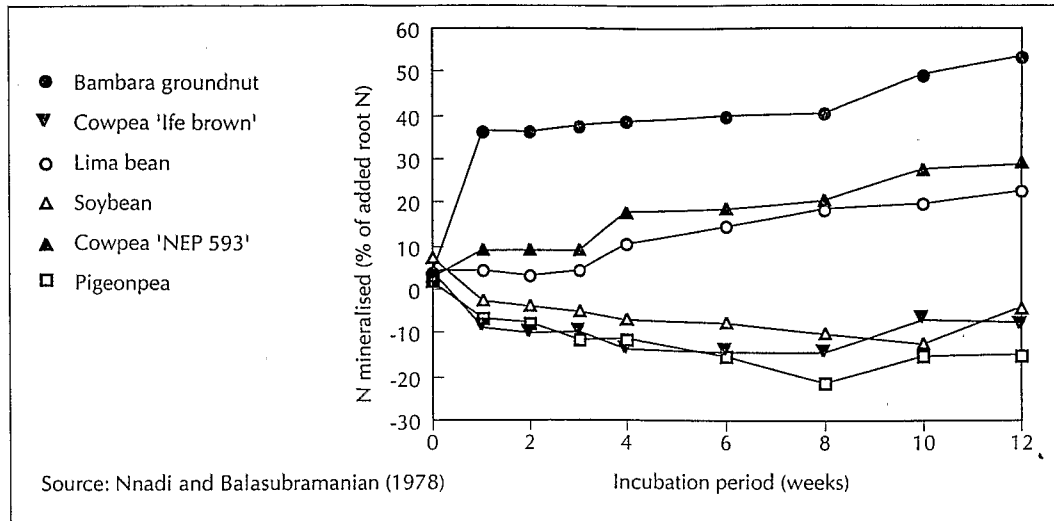
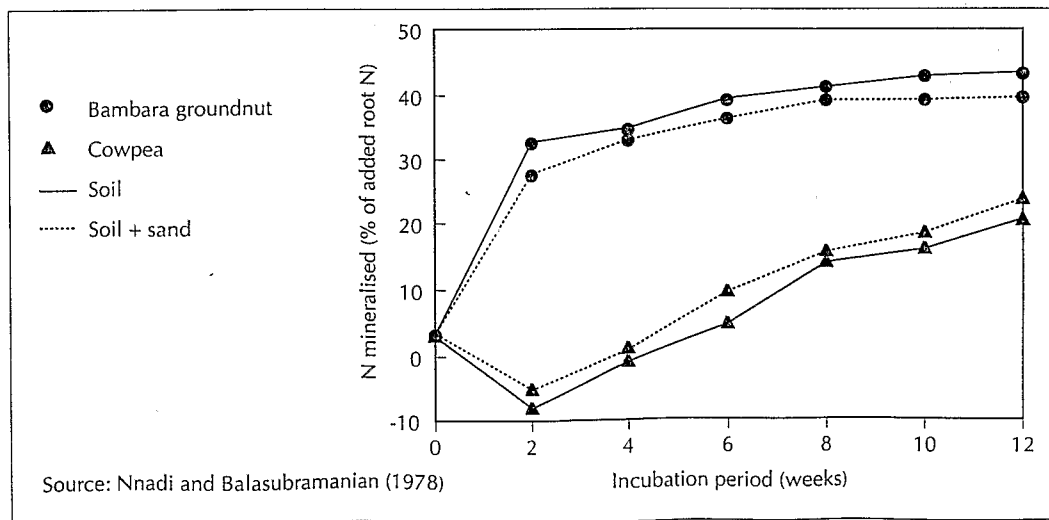


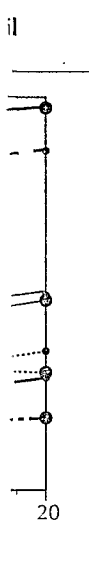
Figure 4.10 Net nitrogen mineralisation after the addition of legume roots to limed soil



the initial decomposition after senescence, but then through re-mineralisation it acts as a source of nutrients for the subsequent maize crop. *P. repens* therefore enhances the synchrony of a system that would otherwise have tremendous potential for a high degree of asynchrony.

Whereas legume residues may mineralise N rapidly and cereal residues mineralise N slowly or not at all, TSBF scientists have hypothesised that mixtures of residues of high and low N concentration

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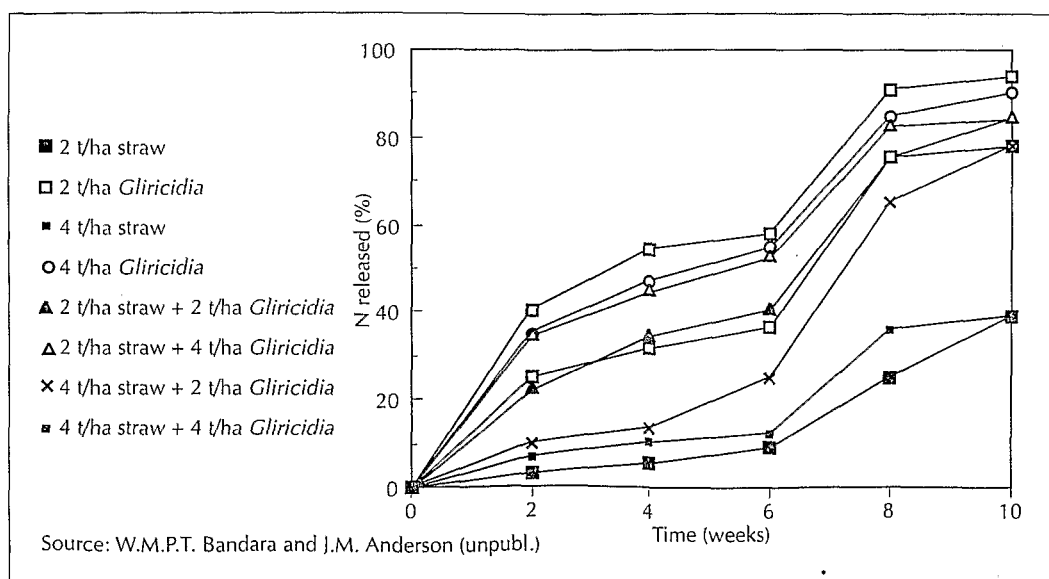
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may mineralise N slowly at first and then rapidly later (Swift, 1987). In a field experiment designed specifically to test this notion in an agroforestry system, W.M.P.T. Bandara and J.M. Anderson (unpubl.) compared N mineralisation from cereal straw, from a legume (*Gliricidia*) and from a mixture of the two. The results, summarised in Figure 4.11, show that the cereal straw mineralised the least N in the first 2-4 weeks, then mineralised N only very slowly. The *Gliricidia* material mineralised N rapidly for 4 weeks, after which there was only slow additional release. The mixture released mineral N at an intermediate rate, the rate gradually increasing during the 12-week experiment. The total amount mineralised was at that time greater than the amount mineralised from the *Gliricidia* material alone. The maximum growth demands of the maize crop occurred between weeks 6 and 10 when enhanced nutrient uptake was observed in the mixture treatment. Nitrogen mineralised during the crop maturation phase occurred when rainfall and the risks of nitrate leaching and denitrification were low. This is a clear demonstration of an important component of the synchrony theme.

Figure 4.11 Nitrogen release pattern of different mulches during decomposition



The conclusions from these studies are that there are instances where results do support the concept of using residue quality to achieve synchrony, but that there are other results that do not support it. Unless the mechanisms can be understood well enough to be manageable within the farmer's field, synchrony will remain an interesting concept but lack practical predictive value.

#### *Use of high-quality plant residues to achieve synchrony*

There are many examples of N being used inefficiently in the humid tropics. In a summary of a number of studies, uptake of fertiliser N in the humid tropics was frequently less than 25% of the applied N,

whereas in the semi-arid subtropics it was often 30-60%, although some examples of less than 25% were also cited (Myers, 1987). Over a range of soil types in the tropics, uptake of fertiliser N ranged between 12 and 45% (Chotte et al., 1990). Such observations demonstrate the risks of having supply (in this case, fertiliser application) and crop demand out of synchrony, since loss processes remove available N before uptake can occur. This is further exemplified by a study in the humid tropical environment of Sumatra (see Table 4.5), where the N in cowpea residues was more efficiently used by an upland rice crop than was the N applied as fertiliser (Sisworo et al., 1990). It is assumed that there was better synchrony of supply and demand in the case of the cowpea residues than with N fertiliser. As a result, it is assumed that substantial losses occurred from the N fertiliser, probably as nitrate leached below the root zone of the crop. It was observed that efficiency of utilisation of N fertiliser ranged from 9 to 18% for wet season upland rice (900-1300 mm rainfall during growth), whereas it was 32-40% for dry season maize (410-840 mm rainfall during growth).

Table 4.5 Utilisation efficiency of fertiliser and crop residue nitrogen in different seasons in the humid tropics

Crop	Rainfall (mm)	Utilisation efficiency (%)		Residue used
		fertiliser	residue	
Upland rice	900-1300	9-18	11-27	Cowpea
Maize/soybean	410-840	32-40	2-4	Rice
Cowpea	130-350	15-40	6-14	Maize/soybean

Source: Sisworo et al. (1990)

The use of *Azolla* as an alternative to N fertiliser in rice systems offers the potential of achieving better synchrony. Kulasooriya et al. (1988) compared urea and *Azolla* as sources of N. They found that *Azolla* was a better N source than urea and believed that this was because the *Azolla* released N more slowly than did urea, and that the pattern of release more closely approximated the demand of the plant. Both sources were more effective when applied at tillering stage rather than at transplanting stage. This experiment demonstrates two methods of achieving synchrony: delaying release of the available nutrient through its chemical form, and timing of application. Becking and Warwani (1989) report the results of a rice experiment in tropical soils amended with <sup>15</sup>N-labelled *Azolla* green manure. In controlled paddy conditions, using three different soils, 9-25% of the *Azolla*-N was recovered in plants. Under upland conditions using a different soil, 15-26% of *Azolla*-N was released. They considered that the decomposition of the *Azolla* biomass and the subsequent release of inorganic N proceeded more rapidly under upland than under lowland conditions.

One of the benefits perceived for alley cropping is improved quantity and efficiency of nutrients cycled. The efficiency of cycling depends upon synchrony between the nutrients made available from the tree prunings and crop plant demand. At Yurimaguas, Peru, prunings of three tree legumes species (*Inga edulis*, *C. cajan* and *Erythrina* sp.) were applied as mulch to upland rice in an alley cropping system (Palm, 1988). *Erythrina* prunings decomposed much faster than prunings of the other two species, consistent with the polyphenol contents of those species. However, these differences were not transferred into differences in rice yield, even after 4 years. One possible explanation is that perhaps

the *Erythrina* decomposed too fast and losses occurred from the soil mineral N pool while the rice plants were small.

Socioeconomic factors aside, green manures are capable of supplying N to crops and it is possible that the release pattern may indicate a degree of synchrony. In the Philippines, short-term green manures of mungbean and cowpea have been effective in supplying N to paddy rice (Morris et al., 1986a, b). Such green manures were as effective as equivalent quantities of N applied as fertiliser, with utilisation ranging between 33 and 41%. The response of rice to green manure was directly related to the quantity of N applied in green manure (Morris et al., 1989). Elsewhere it has been shown that much of the N fertiliser not utilised by the rice crop is lost to the atmosphere (Fillery et al., 1984) and that gaseous loss from incorporated green manure is relatively small (Nagarajah, 1988). The relatively high efficiency of green manure N utilisation achieved in these studies, and the expectation that much of the unutilised N would remain in the soil organic matter pool, indicates that synchrony was achieved.

#### *Does synchrony apply to nutrients other than N?*

Synchrony in relation to P can be important where P can be leached, as in high rainfall environments with sandy soils, or where available P can be converted to unavailable P, as is common in many tropical soils with high iron and aluminum oxide or allophane contents. Organic compounds appear able to displace adsorbed phosphate ions, making P more available. Despite the importance of P in tropical soils, there has been little research on the effect of organic inputs on P availability. McGill and Cole (1981) studied the principles of recycling P through organic matter. Net mineralisation of P from plant residue did not occur unless the C/P ratio of the residue was low (for example, 123/1 as observed by White and Ayoub, 1983). Other studies have reported the C/P ratio at which net P mineralisation occurs to be variable, ranging from 100 to 300. This may therefore not be a good index of quality; the N/P ratio has been suggested as a better indicator, with P mineralisation at N/P ratios of 10 (Vogt et al., 1986). The rate at which P is first transformed and then released from organic materials also depends upon the type and age of the specific plant part, maturity and type of crop residues (Fuller et al., 1956).

Mineralised P from plant material decomposing in soils can be directly assimilated by plants (Blair and Boland, 1978; Dalal, 1979; Ladd et al., 1981; McLaughlin and Alston, 1986). Thibaud et al. (1988) have quantified the use by ryegrass of N and P from plant residues added to the soil. The contribution of P derived from ryegrass residues to the nutrition of a second crop is similar to, and sometimes higher than, the contribution of P derived from inorganic fertiliser (see Table 4.6). The authors suggest that the protecting effect of the plant structure induces a slow release of phosphate ions into the soil. Much needs to be learned about the chemical characteristics of organic materials and how they affect P availability before progress can be made on management for P synchrony.

#### *Use of other organic materials to promote synchrony*

In the tropics, farmyard manure (cattle and buffalo), piggery effluent and poultry manure are potentially available for use as soil amendments. These materials are collected and stored before being applied to the soil. As a result of storage, changes take place which may lead to a loss of N and other changes in the quality of the resource. During 3-6 months storage in cool temperate conditions, 20% or more of the N may be lost from manure and the content of humic substances may increase (Kirchmann, 1985). Such losses can be reduced by the addition of energy-rich material, such as straw,

Table 4.6 Utilisation of phosphorus from ryegrass residues

Origin of P	Dry matter (g)	Total P (mg)	Utilisation efficiency (%)	
			residue	fertiliser
Control	5.2	20.5		
with aerial parts	7.4	41.1	31.9	
with roots	4.2	20.4	17.1	
Plus DAP	7.2	33.4		21.5
with aerial parts	7.5	54.1	21.7	11.4
with roots	5.6	29.9	18.1	17.8

Source: Thibaud et al. (1988)

to the manure before storage. The first crop grown on soil after amendment with manure generally utilises 15-35% of the manure N (Kirchmann, 1985). Lesser amounts are recovered in subsequent crops. Some of the variation between different manures is attributable to identifiable quality factors such as C/N ratio and content of available mineral N. Other nutrients such as P are readily available in animal manures (Maraikar and Amarasiri, 1989).

Mineralisation of N from animal manures varies considerably and this variation should be predictable if quality factors can be identified. Castellanos and Pratt (1981) examined a range of manures and found that an assay which released N with pepsin was a good predictor, but that most of the variation could be explained by multiple regression of respiration and N mineralised during a short incubation and the C/N ratio.

Composts from crop residues or from off-farm plant materials are important amendments to cropping systems in the tropics but there is little information regarding their value as promoters of synchrony. One experiment at the Eladuwa rubber plantation, Sri Lanka, carried out as part of the TSBF programme, investigated the possibility that coir dust (a waste product of coconut fibre production) could be used to improve fertiliser use by rubber trees (clone PB 86). Experiments were carried out in a 5-year-old plantation and were designed to test the hypothesis that N fertiliser (as ammonium sulphate) immobilisation by coir (C/N ratio 35/1) would lengthen the time course of N availability to the trees. Treatments included no fertiliser, fertiliser alone, coir mulch alone and fertiliser applied to coir mulch. The soil was a coarse-textured Ultisol with a ground-cover of *Pueraria phaseoloides*.

Nitrogen mineralisation in laboratory incubations (Anderson and Ingram, 1989) showed no differences between the topsoil in each treatment. However, mineralisation as ammonium N from the coir mulches was much higher than from soil but showed little effect of fertiliser. Unexpectedly, nitrification was completely suppressed in the coir material but the mechanism was not determined; it could be bacteriostatic agents or simply a pH effect.

It was concluded that the coir was ineffective in preventing leaching of fertiliser N and that the slow mineralisation rate of N from coir was more appropriate to the growth rate of the rubber trees. The clone PB 86 is known to be unresponsive to N fertilisation and hence the standard agronomic prescriptions of fertiliser to these plantations was a waste of a scarce commodity which was better replaced by the coir mulch. The key factor in these trials was that the slow N mineralisation rate from complex organic N showed closer synchrony under a very high rainfall regime.

During storage of manures or composting of plant materials, changes in the quality of the material occur. Composts are generally saved for use on a more important crop than the current one. If quality is reduced by a large loss of nutrients, then the value of saving is open to question. The quality change might, however, promote synchrony despite the loss of some nutrients. The range of interactions is obviously high and predictive generalisations are impossible at our currently limited level of understanding of the process.

Some plants processed in the tropics produce waste products that may be useful as soil amendments. These materials include bagasse and mill mud from sugar mills, dunder from distilleries, residues from rice milling and mill effluent from oil palm mills. Of these, only bagasse and rice husks have alternative uses, as fuel for sugar milling or as domestic fuel, but in some countries these products are under-utilised. Sugarcane mill mud and dunder are used as soil amendments and reduce the need for mineral fertilisers (L.S. Chapman and N.K. Greenwood, unpubl.). It is uncertain how much of the value of these products is due to the supply of nutrients and how much to improved nutrient cycling (that is, a higher degree of synchrony). Palm oil mill effluent is produced in relatively large quantities in some South-East Asian countries. In a pot experiment, it was shown to enhance crop growth (Shamshuddin et al., 1991). Abdullah et al. (1991) found that palm oil mill effluent resulted in a two- to fourfold yield increase of tobacco on an infertile sandy soil. It was not established how much of the benefit was due to improved nutrient supply and how much to complexing of soluble Al. Rubber factory effluents are available in several Asian countries. They have been demonstrated to promote the growth of young rubber plants and of flooded rice in pot experiments (Warnakula, 1989). However, the mechanism for this response was not evaluated, so this cannot be cited as an example of synchrony.

#### **Other management factors**

Tillage may influence synchrony. The rate of decomposition and the mineralisation of nutrients from organic amendments varies according to placement on the surface or incorporation into the soil. For example, under warm, humid conditions, Wilson and Hargrove (1986) found that with no tillage, surface-applied legume residue decomposed more slowly than incorporated residue during the first 4 weeks, but more rapidly during the following 12 weeks. If N release followed the same pattern, then it may promote synchrony. Sarrantonio and Scott (1988), however, obtained inconsistent results, with no-tillage legume residue resulting in greater maize yields and N uptake in one year and cultivated legume residues providing better results in the second year. They believed that an interaction with available water may have influenced these results.

#### **WHICH MANAGEMENT OPTIONS OFFER THE BEST PROSPECTS?**

Smallholder farmers in the tropics respond best to options that offer improved yield, reduced risk or reduced inputs of labour or cash.

#### **Some examples of synchrony and asynchrony**

Do arable cropping systems, as currently used in different parts of the world, provide examples of synchrony or asynchrony? To answer this we can use a simple simulation of crop growth and N



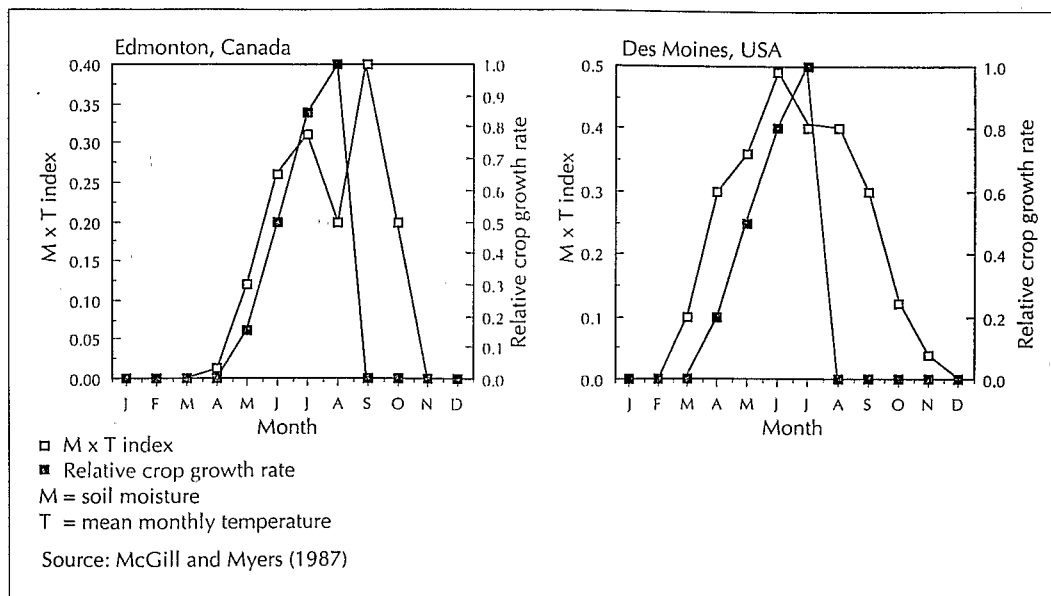
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mineralisation (McGill and Myers, 1987). In this simulation, an index of potential N mineralisation is estimated using a multiplicative index,  $M \times T$ , where T is an index based on mean monthly temperature and M is a soil moisture index derived from a water balance model. Known relationships between N mineralisation and temperature (Stanford et al., 1973; Myers, 1975) and moisture (Stanford and Epstein, 1974; Myers et al., 1982) were used in deriving these indices. Crop demand for N was estimated assuming sigmoidal growth curves. Crop growth and N release in cool temperate climates are more or less in synchrony (see Figure 4.12). However, in this example there is the opportunity for N mineralisation prior to crop growth and also after harvest, and it is known that these are times at which there is a risk of N loss from the system.

Figure 4.12 Potential nitrogen mineralisation (derived from a moisture-temperature index) in relation to relative crop growth rate for two temperate climate sites



In the tropics there are examples of synchrony and asynchrony (see Figure 4.13 overleaf). In the humid tropics, with rainfall most of the year and at least two cropping cycles, both crop growth and N mineralisation occur throughout the year with short opportunities for N loss between crops. In the semi-arid environment at Hyderabad, India, there is a substantial 'window' of risk for N loss prior to the growth of the rainy season crop. In the Australian sub-tropics, on Vertisols where either summer or winter crops are grown but the land remains fallow for half the year, there is substantial opportunity for losses of mineralised N, as shown for Narayen (see Figure 4.14 overleaf).

This method of analysis may be criticised for not considering the supply of organic resources. In cultivated systems, resource supply varies with time. Inputs of crop residues occur in pulses and prolonged drying of the soil temporarily increases the supply of mineralisable N. Fertiliser or manure inputs also result in pulses. All of these tend to reduce the degree of synchrony if crop growth is slow or absent when they are applied.

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Figure 4.13 Potential nitrogen mineralisation (derived from a moisture-temperature index) in relation to relative crop growth rate for two tropical climate sites

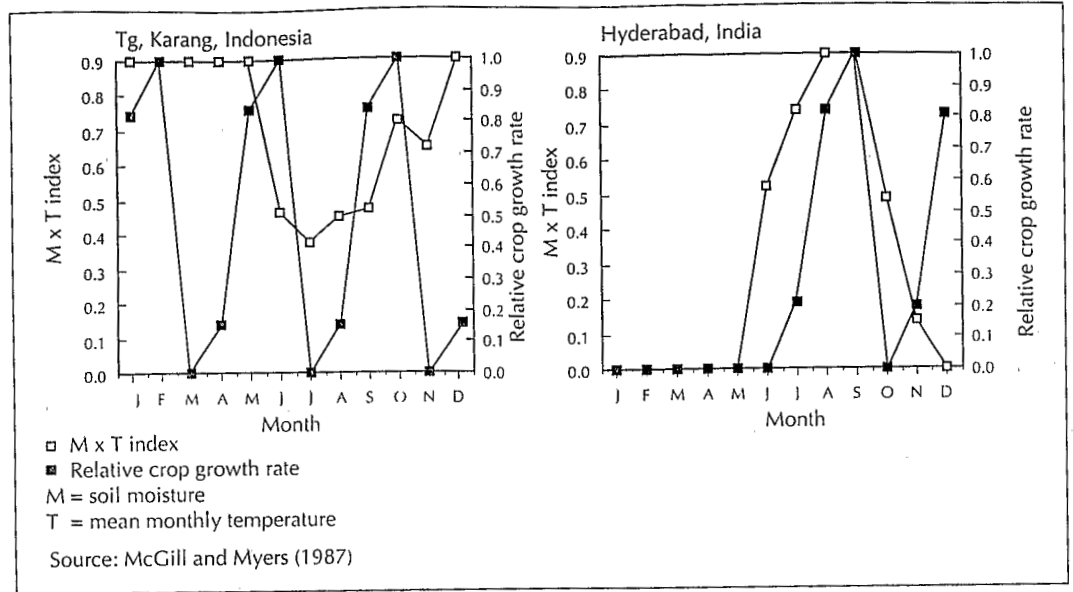
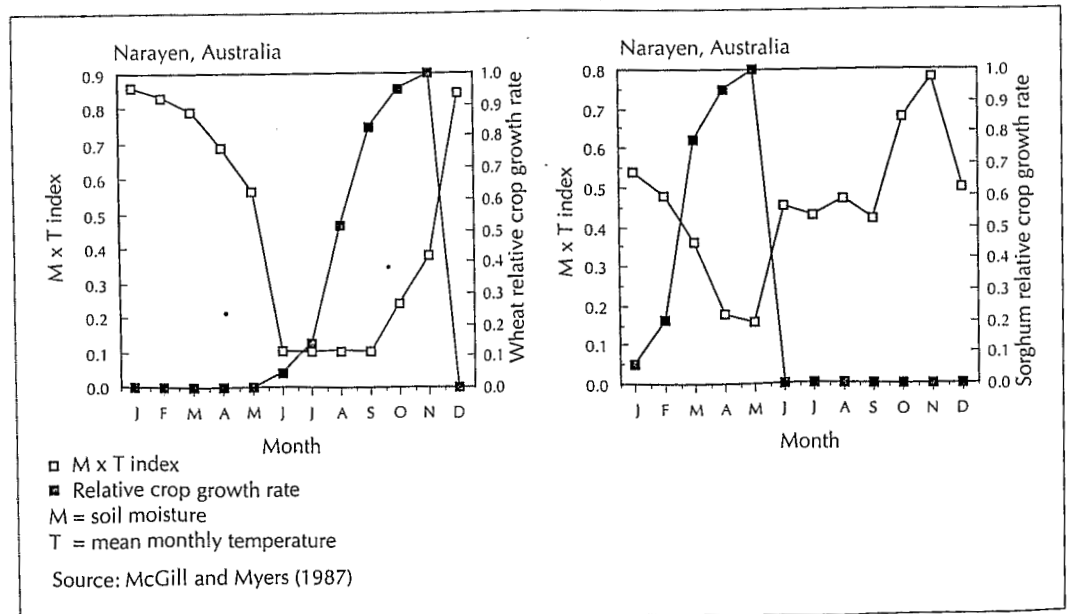
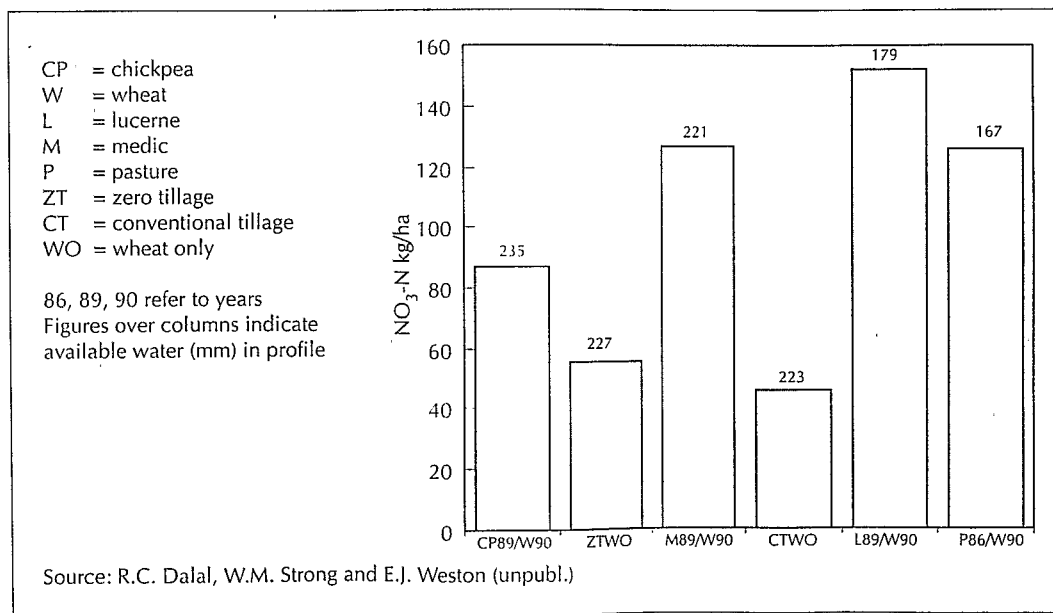


Figure 4.14 Potential nitrogen mineralisation (derived from a moisture-temperature index) in relation to relative crop growth rate for two crops grown in different seasons at a sub-tropical climate site



From their research at the TSBF Warra site in Australia, R.C. Dalal and colleagues (unpubl.) provide an example of this potential asynchrony (see Figure 4.15). The soil is under clean fallow for half the year at temperatures sufficient for the mineralisation of N. During that period, 40 kg N/ha mineral N accumulates in the profile under conventional tillage, and as much as 150 kg N/ha where lucerne is in the rotation. In the absence of conditions favourable to loss processes (that is, average or below-average rainfall), the cereal crop utilises this N effectively. When above-average rain occurs, N loss can be substantial (Catchpoole, 1992) and asynchrony is increased. The substantial benefits of treatments such as rotating legumes with cereals can therefore be lost in some years. In this semi-arid sub-tropical situation, asynchrony is not always a problem, but there is the risk of its reoccurrence. Better analysis of this risk is an important research need (Muchow and Bellamy, 1991).

Figure 4.15 Available soil nitrate (0-1.5 m) at sowing as affected by different crops and treatments, at the TSBF site at Warra, Australia

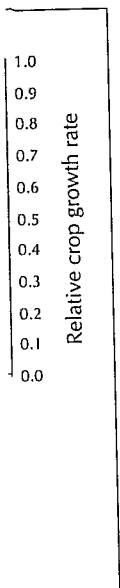


• Is synchrony better in natural systems than in derived systems? From the inception of the TSBF programme it has been part of the philosophy that productivity of natural systems is sustained by the tight integration of the vegetative system with the soil biological system in relation to nutrient cycling and organic matter. In contrast, many agricultural practices, particularly those involving tillage and fertilisers, tend to disrupt or bypass these regulatory biological processes. There has been the belief that principles learnt from natural systems could be used to improve the synchrony of agricultural systems.

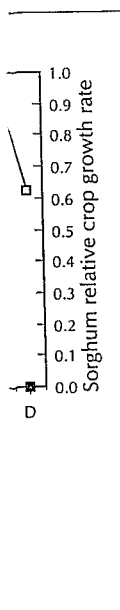
An overall view that is emerging from a variety of process-oriented and ecosystem-level studies is that the mature, steady-state forests of the humid tropics are generally in synchrony with respect to plant growth and availability of nutrients from litterfall, atmospheric inputs and mineral weathering. A variety of mechanisms or processes appear to contribute to this overall synchrony. For example, in

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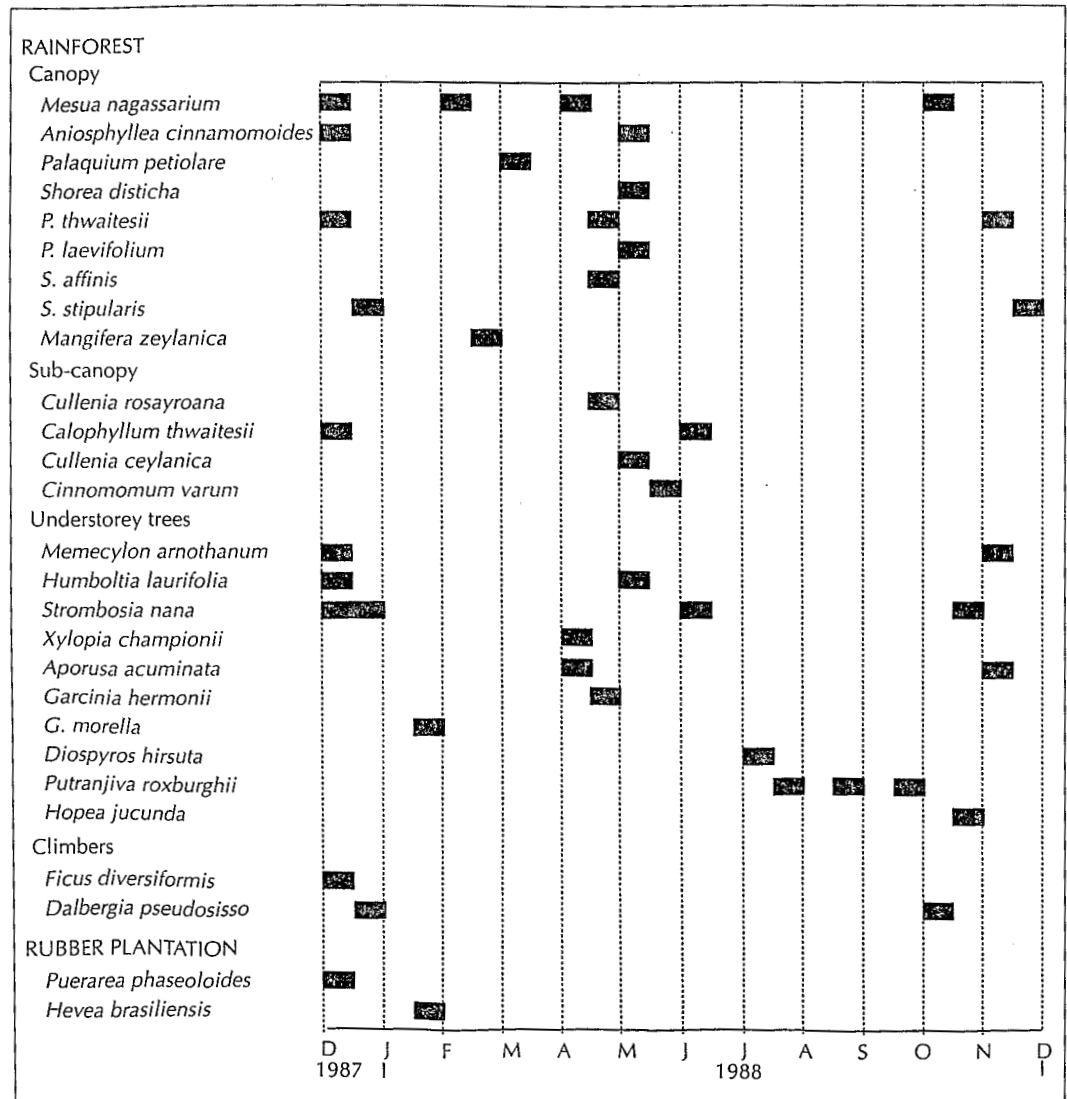


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many species-rich forests in the humid tropics, the fine litterfall is continuous, with peaks only during short dry periods (see Figure 4.16), and growth is continuous. Nutrient use is said to be efficient since relatively large amounts of organic matter are synthesised per unit of nutrient uptake (Vitousek and Sanford, 1986). Nutrient retranslocation from senescing plant parts and rapid uptake of nutrients by decomposers, mycorrhizas and roots contribute to the high productivity of these systems (Stark and Jordan, 1978). Although relatively large amounts of nutrients cycle between trees and soil, results from the few sites that have been studied intensively indicate that the nutrient losses from the system are

Figure 4.16 Peak leaf fall times for some rainforest species in a Sri Lankan forest and rubber plantation



relatively low. We must be cautious in generalising from these few studies. The extent to which these mechanisms and processes occur and result in synchrony will depend upon several factors, including climate, soil type and the nutrient in question. It has been proposed that the processes become more important as nutrients become limiting to production (Jordan and Herrera, 1981; Vitousek and Sanford, 1986), as in the major areas of soils in the tropics that are acid and infertile. Such soil systems should provide good case studies for evaluating synchrony.

In the humid lowland Ultisols of Sri Lanka, components of nutrient cycling were compared and contrasted in a TSBF study of a rainforest and a 5-year-old rubber plantation. Total annual litterfall was similar in both systems (*see* Figure 4.17 *overleaf*), but litter quality and decomposition rate differed. The species diversity of the mixed forest contributed to synchrony since the net effect of temporal variations in individual species' quantity and quality of litterfall tends towards a fairly constant supply of nutrients becoming available through litter decay. A similar situation may exist in mature phase, species-rich homegardens which derive a large part of system-level synchrony in nutrient input and uptake from partially overlapping vegetative and reproductive phenologies. In the less diverse *Hevea* rubber plantation (a deciduous tree monocrop with a legume or grass ground cover) litterfall showed a more or less overlapping peak with a relatively faster decomposition rate than in natural forest, due to the lower C/N ratio of the former (K.G.S. Jayawardana, I.U.N. Gunatilleke and J.M. Anderson, unpubl.), leading to annual pulses in nutrient release. Judging from the timing of the litterfall and the decomposition rate of rubber, legume or grass litter, the annual flushes of plant nutrients more or less coincide with the refoliation of the rubber tree, suggesting that the system is in a partially synchronous state. It has also been noted that in tropical rainforests there is high retranslocation of certain nutrients prior to litterfall (*see* Figure 4.17a). This reduces the quality of litter for microbial decomposition. Thus nutrients such as N and P are temporarily immobilised in microbial biomass, preventing their leaching from the system. Nutrient conservation mechanisms act as built-in synchrony controls or regulators. The level of retranslocation is reduced in hybrid clonal rubber trees and, as such, the litter decomposition rates are more rapid (*see* Figure 4.17b). Mineralised nutrients and inorganic fertiliser added at refoliation are more liable to be removed by leaching and denitrification. The nutrient conservation mechanisms of the tropical rainforest are less developed in monoculture tree crop plantations.

In two humid tropical systems of Central and South America, synchrony appears to occur whether the forest is mixed or monospecific (Cuevas et al., 1991). In Luquillo, Puerto Rico, mixed secondary forest and a *Pinus caribea* plantation have fairly even annual litterfall patterns, with only occasional spikes of litter production in short dry periods (Cuevas et al., 1991). In Ticoporo, Venezuela, semi-deciduous mixed forest and monospecific teak plantations have clear litterfall pulses (E. Cuevas, unpubl.) and the potential for asynchrony is high. However, in all four systems, synchrony is enhanced because of rapid responses in fine root production at times of nutrient supply. Carbon allocation to root growth and maintenance allows these systems to achieve a high degree of synchrony.

In a seasonally wet-dry grassland at Lamto in West Africa, nutrient cycling is considered to be tightly controlled through the soil fauna and microorganisms (*see* Chapter 6). There is no evidence of any substantial losses of nutrients, and in this sense synchrony is achieved.

The idea has also been examined for the clay soils of north-eastern Australia that originally had brigalow-belah (*Acacia harpophylla-Casuarina cristata*) dry woodland (Bligh, 1990). The woodland was cleared and sown to perennial bunchgrass pasture. A comparison was conducted 50-60 years after clearing, and the pasture site had been sown to green panic (*Panicum maximum* var. *trichoglume*) about 20 years previously. Litterfall, litter decomposition, soil N mineralisation and plant growth were examined. There was twice as much litterfall (containing four times as much N) in the woodland than in the pasture, while the C/N ratio of the woodland litter was 44 compared with 108 for the pasture litter.

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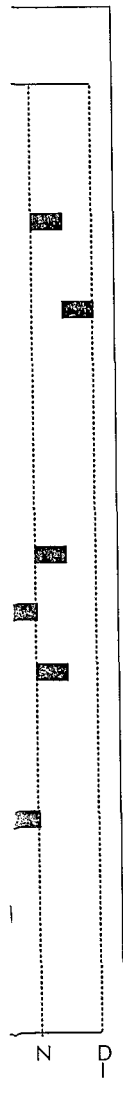
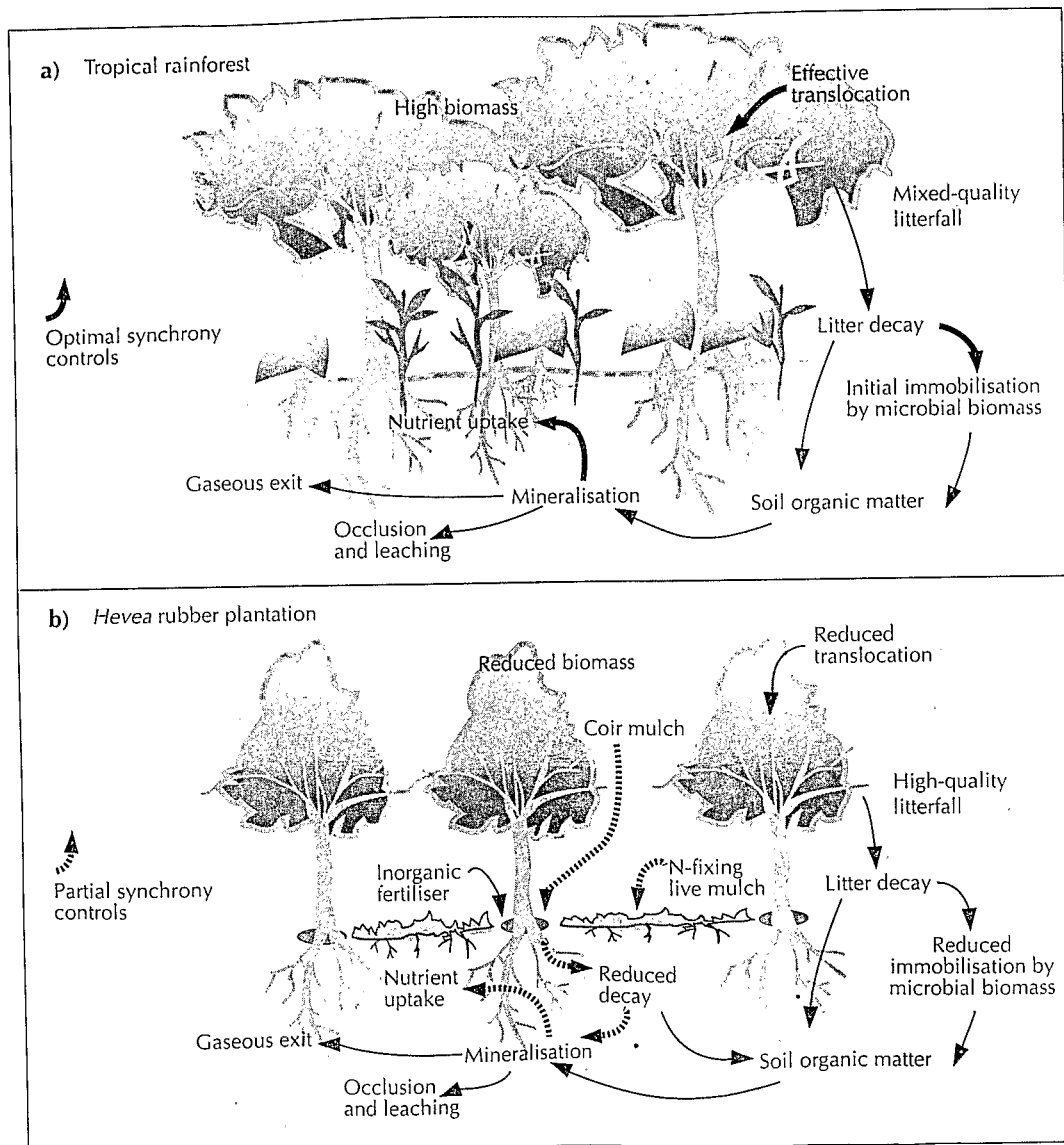


Figure 4.17 Diagrammatic representation of the synchrony controls operating in a tropical rainforest and a 5-year-old rubber plantation



The lignin/N ratio was the best predictor of litter decomposition rate. These characteristics of woodland litter resulted in rapid N mineralisation in the woodland, and soil-available N remained high throughout the year. Under woodland, the estimate of annual N mineralisation was 310 kg N/year. Under the pasture, the annual N mineralisation was 180 kg N/year, and available N was always low. The pasture, which was very deficient in N (Peake et al., 1990), was believed to lack synchrony because the continuous inputs and slow decomposition of low-quality litter maintained N in an unavailable

form. N was mineralised at a rate insufficient to meet plant demands. The woodland did not lack synchrony in the sense that N was always available in the soil. However, the large amounts of available N in the soil would be at risk if prolonged wet periods were to occur that favoured denitrification or leaching, and in this sense the system was not in synchrony. Because of this, we conclude that neither the woodland nor the pasture provide good examples of synchrony.

The same pasture system was compared and contrasted with an annual cropping system (Robertson, 1988). The pasture was N deficient whereas the unfertilised annual sorghum crops, on soil that had lost almost half of its original organic matter, were not deficient. There was almost twice as much microbial biomass N and C in the pasture soil than in the annual crop soil. The root mass of the pasture was also much greater than the seasonal root accumulation in the crop plots. Litter quality of both systems was low, but there was much more litter in the pasture system. As a result, more of the litter and root turnover in the pasture was stabilised into soil organic matter, accompanied by more of the associated soil mineral N. There is evidence of episodic leaching or denitrification losses from the cropped soil profile and that not all the soil N decline could be explained by removal in harvested product (Catchpoole, 1992). We conclude that neither system is especially well synchronised.

M.C. Scholes and R.J. Scholes (unpubl.) consider that the Nylsvley TSBF site in South Africa, a natural system in a semi-arid environment, is not a good example to support the synchrony hypothesis. Nutrient release is highly pulsed, with peaks following rainfall events. However, lack of synchrony is not an issue since losses of nutrients appear to be very small and available nutrients are stored in the system until utilised by plants.

It is significant that the Narayen and Nylsvley sites are amongst the driest TSBF sites (and the least tropical). Assuming that tropicality plays no major role in deciding whether a system is in synchrony or not (at least, no more than through temperature conferring a potential for activity throughout the year, which could add to the potential for asynchrony), moisture availability could be the most important factor. Perhaps in semi-arid tropical systems, the natural systems have developed such that they tend to optimise the use of water rather than synchronise nutrient demand and supply. Perhaps a degree of asynchrony is part of the optimisation strategy. Thus, available nutrients may be accumulated in the soil in advance of plant needs. This would help optimise plant growth when water is available, but also increases the risk of nutrient loss in the wet season. If conditions favouring loss are sufficiently infrequent, then this optimisation may be a better overall utilisation of resources than would occur with a high degree of synchrony. McNaughton (1979) in his studies of the Serengeti grassland in East Africa reached a similar conclusion. We hypothesise, therefore, that as natural systems become drier, efficient use of water becomes relatively more important than a high degree of synchrony of nutrient supply and demand. Within natural ecosystems, the humid regions have the greatest need of synchrony.

## CONCLUSION

Synchrony of the supply and demand of plant nutrients in managed systems of the tropics, particularly annual cropping systems, is important for efficient nutrient use and the minimisation of losses, and hence also for the sustainability of production in low-external-input agriculture in the tropics. This is true from the humid to the semi-arid regions. Many existing production systems in the tropics exhibit a low degree of synchrony. We believe that there is great potential to improve the productivity and profitability of these systems by use of management practices that improve synchrony, principally those in which nutrient cycling is managed through the use of organic residues. We consider that the synchrony theme is a practical tool of great potential value to tropical production systems.

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It is recognised that the intervention of humans has resulted in the creation of many systems where there is a substantial degree of asynchrony of nutrient release and demand. It is also clear that there are many outstanding examples of this in tropical areas where farmers' livelihoods are threatened by declining soil fertility. There is now a need to examine the opportunities that exist for achieving better synchrony in some of these systems. Greatest urgency appears to exist in tropical upland areas in all continents where arable annual cropping is practised, particularly in humid areas. It is in such areas where the penalties for lack of synchrony are most severe.

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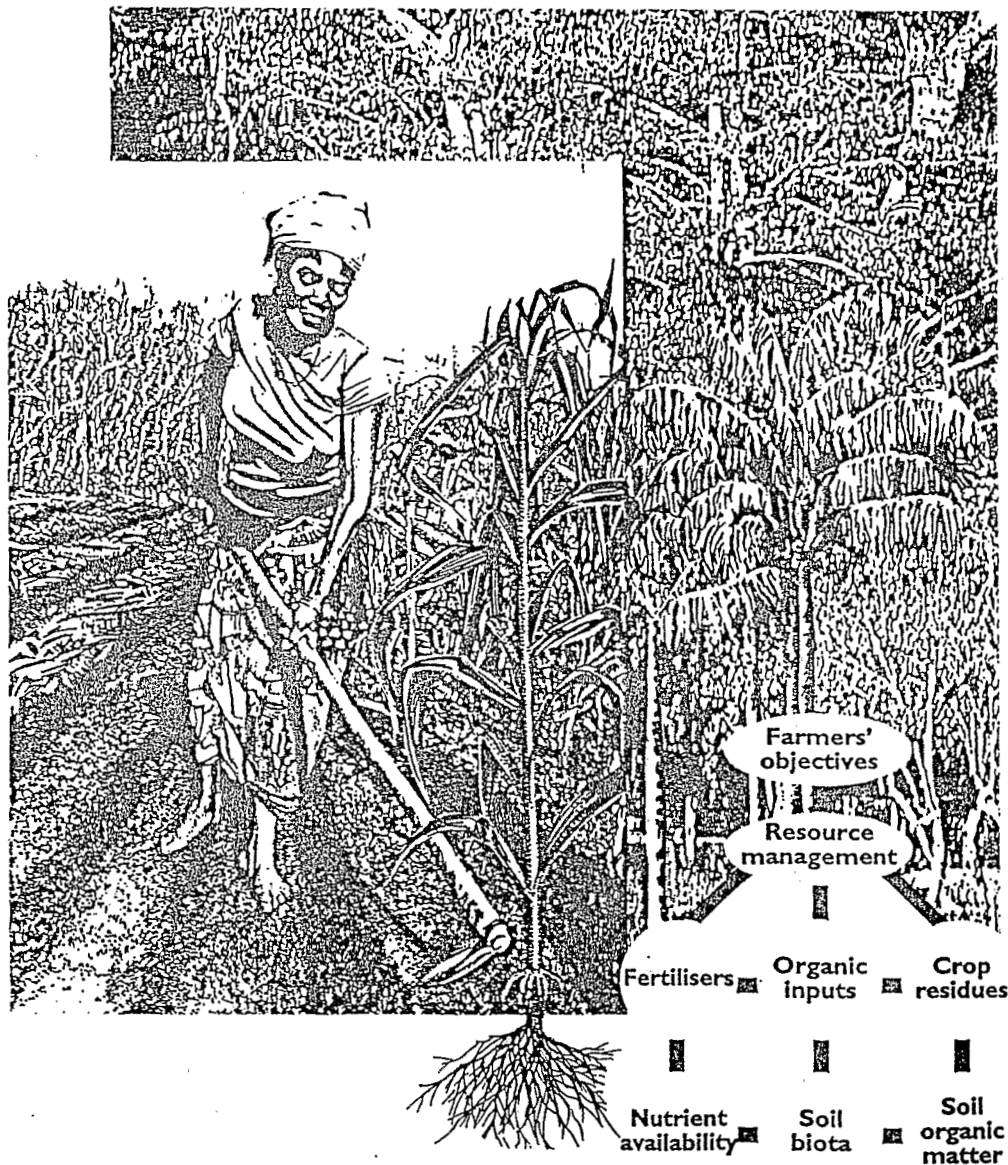
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# THE BIOLOGICAL MANAGEMENT OF TROPICAL SOIL FERTILITY

Edited by P.L. Woomer and M.J. Swift





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## Preface

The fertility status of many tropical soils, particularly those of smallholder farmers, is regulated by key biological processes and the organic resources available to farmers. Too often, these processes are not understood well enough by agriculturalists to be placed in the soil management context. Failure to understand the complexities of tropical soil fertility has resulted in the lack of well-integrated management strategies, and this has led to the recognition that agricultural systems must become more sustainable if the food requirements of future generations are to be met.

This book reports on the first five years of research by scientists of the Tropical Soil Biology and Fertility Programme (TSBF). TSBF is sponsored as a component project of the International Biological Sciences (IUBS) programme The Decade of the Tropics and of the Man and the Biosphere (MAB) programme of UNESCO, and is hosted by the UNESCO Regional Office for Science and Technology in Nairobi, Kenya. TSBF is a voluntary participatory international research programme whose members are committed to the concept that the fertility of tropical soils is controlled by biological processes and can be managed by the manipulation of these processes. Participating network scientists conduct field studies in Central and South America, sub-Saharan Africa, South Asia and Australia, and maintain close institutional links with researchers in Europe and North America. TSBF's main intention is to review the potential for the biological management of tropical soils, focusing on the programme's four main research themes: soil organic matter management; nutrient-use efficiencies; manipulation of the soil water regime; and the potential for the utilisation of soil fauna for soil fertility improvement. Each theme is discussed, together with accompanying chapters which set the context of the drive for sustainable agriculture, lay the foundations for an agroecological approach to soil and discuss the socio-economic implications of TSBF research.

The book contains nine multi-author chapters but it has been prepared as a continuous discursive text. The authors have all worked together at workshops and in the field and share a common philosophy of research and soil management. The book is thus intended as a basic text for research in sustainable soil management. It is aimed primarily at young, post-graduate scientists in the disciplines of soil science, agronomy, forestry or ecology, as well as senior scientists and decision-makers concerned with the sustainable development of agriculture and other land uses in the tropical regions.

The publication of this book would not have been possible without the generous financial support from several organisations. Direct funding for the initial meeting of the authors was received from the Rockefeller Foundation, ORSTOM and the United Nations Environment Programme (UNEP). The editors' salaries were provided by the Natural Environment Research Council (NREC, UK) through the Institute of Terrestrial Ecology (ITE), the Overseas Development Administration (ODA, UK) through the International Centre for Research in Agroforestry (ICRAF) and the International Institute of Tropical Agriculture (IITA). Financial support for TSBF Headquarters in Nairobi, Kenya was also provided by the United Nations Scientific, Cultural and Educational Organisation (UNESCO) through the Man and Biosphere Programme (MAB) and the Regional Office for Science and Technology for Africa (ROSTA). We gratefully acknowledge the involvement by, and the financial contributions from, all of the above organisations.

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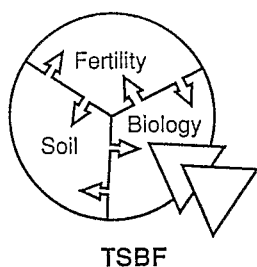


## Tropical Soil Biology and Fertility Programme (TSBF)

TSBF was established in 1984 under the patronage of the Man and Biosphere programme of Unesco and the Decade of the Tropics initiative of the International Union of Biological Sciences (IUBS). The objective of the programme is to develop appropriate and innovative approaches for sustaining tropical soil fertility through the management of biological processes and organic resources. To achieve this objective, TSBF aspires to:

- make available to farmers and other land managers in the tropics methods for soil management which will improve agricultural productivity but conserve the soil resource
- contribute to increasing the carbon storage equilibrium in tropical soils in the face of global changes in land use and climate
- improve understanding of the role of biological resources in soil fertility and the sustainability of tropical land-use systems
- improve the research and training capacity of national institutions in the tropics in the fields of soil biology and management of tropical ecosystems

TSBF is a voluntary participatory international research programme whose members are committed to the concept that the fertility of tropical soils is controlled by biological processes and can be managed by the manipulation of these processes. Research is conducted at both the ecosystem level and the process level on the basis of two principles: that the capacity to manage soil fertility depends on a mechanistic understanding of the biological processes regulating nutrient flux, organic matter dynamics and soil physical structure maintenance, and that successful management for sustainable soil fertility must be implemented at the ecosystem level by integrating soil biological processes with those of human decision making in relation to all components of the ecosystem.



International Union  
of Biological Sciences



Man and Biosphere  
programme of Unesco