



How Trees Affect Soils

**A report for the
Rural Industries Research and Development
Corporation
by
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**March 1998
RIRDC Publication No 98/16
RIRDC Project No CSL-3A**

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ISBN 0 642 54035 7
ISSN 1321 2656

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Foreword

Extensive clearing of native vegetation in Australia has resulted in a general decline in the condition of our natural resources.

Replacement of trees in the landscape is seen by many as a way to slow or perhaps even reverse the degradation. This report reviews some of the evidence to support both the positive and negative effects of trees on the chemical and physical properties of soils.

The review was funded by the Joint Venture Agroforestry Program which is funded by the Rural Industries R&D Corporation, Land and Water Resources R&D Corporation and the Forest and Wood Product R&D Corporation.

Peter Core

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Acknowledgments

We would like to express our appreciation to the Joint Venture Agroforestry Program which is funded by Rural Industry Research and Development Corporation (RIRDC), Land and Water Resources Research and Development Corporation (LWRRDC) and the Forest and Wood Products Research and Development Corporation (FWPRDC) for giving us the opportunity to undertake this review. We are also grateful to the many people who offered advice and suggestions in putting together this report, in particular Dr Lloyd Anderson of the Institute of Terrestrial Ecology, Bangor Research Unit, UK, and Dr Roslyn Prinsley of the RIRDC.

Executive Summary

Extensive clearing of native vegetation in Australia to establish pastures and European based agricultural production systems has resulted in a general decline in the condition of our natural resources which includes the development of dryland salinity, soil acidification, soil erosion, soil degradation and a loss of biodiversity. The manuscript reviews some of the evidence to support both the positive and negative effects of trees on soil chemical and physical properties. They are as follows:

1. In discussing agroforestry as a land use system, a clear understanding of the theoretical objectives of such a system are required. In general, it can be described as a land use system that increases productivity and provides multiple products with the objective of conserving a resource base. Such a system reduces a producer's vulnerability to economic and environmental fluctuations and emphasises the sustainability and maintenance of a finite resource base.
2. The parent material from which soils are derived effectively sets the upper limit of nutrient supply by a soil. Contrasting this vegetation component of the ecosystem acts as a means by which mineral nutrients are sequestered, and carbon and/or nitrogen is fixed, and subsequently added to the soil through litter fall and the decomposition of organic matter.
3. The maintenance of soil organic matter is a fundamental component in efficient nutrient cycling and the sustainability of agroforestry production systems. Trees have the ability to maintain soil organic matter through the supply of litter and root residues and in certain species enhance the nitrogen status of the soil. Their extensive root system and association with mycorrhiza give them the capability of efficiently recycling nutrients.
4. Research has shown that many agroforestry systems with a cropping component resulted in a decline in soil fertility; this was most evident on soils with a low inherent fertility. Nutrients added in organic mulches are often inadequate to completely meet the total nutrient demands of a moderate crop. For the long-term sustainability of agroforestry systems the addition of inorganic or organic fertilisers is required to cropping systems particularly on acid, infertile soils. In addition, the maintenance of soil organic matter is essential although extremely difficult where soil disturbance takes place.
5. Plant residue, particularly legume residue acts as a source of nitrogen for subsequent crops. The contribution of nitrogen from this source is a function of the pattern and rate of mineralisation in relation to crop demand. Between 4 and 20 % of nitrogen applied to the soil

surface as prunings is reported to be recovered in the immediate succeeding crop. Significantly higher recoveries have been observed where inorganic nitrogen is applied. However, compared to inorganic sources of fertiliser, organic materials have a greater residual effect on soil fertility due to their slow-release characteristics.

6. Phosphorus appears to be the major limiting element in many soils for the production of crops under alley-cropping systems. The addition of leguminous plant materials as prunings can provide adequate amounts of nitrogen for the crop but not sufficient concentrations of phosphorus. This implies that the maintenance of fertility will require external sources of inorganic or organic amendments. Mycorrhizal associations and the development of proteoid roots in selected species can result in an enhanced ability of a species to sequester adequate levels of phosphorus.

7. In viewing the maintenance of resources in an agroecosystem, by invoking a system in which there is a continued replenishment of nutrients exported from site, the long-term impact of an agroforestry system on nutrient accretion would probably be very low if nutrients exported from site are replaced. An agroforestry system will not balance nutrient export if there are no inputs to replace exports. These inputs could be N through N-fixation by legumes the application of inorganic or organic fertiliser sources, and the addition of soil conditioners (ie. lime).

8. Under plantation systems, the establishment of monocultures of *Eucalyptus* spp. and *Pinus* spp. have been shown to be able to recycle their own nutrients and maintain a high fertility status on soils that are inherently rich. However, on relatively infertile soils such plantings can have a negative impact on site nutrition and result in a general decline in site fertility. Additions of inorganic or organic fertilisers are required to maintain productivity. Of importance in the long-term sustainability of a site is the maintenance of soil organic matter through the retention of slash and through limiting site disturbance to a minimum.

9. If plantation rotations are shortened to optimise biological productivity, then regular fertilisation at rates similar to that used in annual cropping systems may be necessary to sustain high productivity, especially if the degree of utilisation is concomitantly increased.

10. There is a general perception that tree plantations can be relegated to sites unsuited to agricultural production. Although this may be the case in certain instances (ie. waterlogged soils), in reality plantation productivity is a function of site quality. Consequently, there is the potential for direct competition between agricultural and timber enterprises. However, if

timber production is viewed as an integral component of a farming enterprise it is doubtful whether this will be a major obstacle in adoption.

11. In low input agricultural systems where inorganic fertilisers are avoided, the introduction of selected tree species may be the only practical manner in which the nitrogen status of the soil is increased and the recycling of nutrients from depth ('biological' pumping) are achieved. However, based on ecological theory and limited data on tree-root profiles there is growing agreement that competition between trees and crops is likely to outweigh the positive benefits of mulching especially on highly acidic and low-moisture soils. The current strategy of introducing nitrogen fixing and fast growing trees to alley-cropping systems may be counterproductive since their extensive root system may be too aggressively competitive with the alley crop. It has been suggested that it would be more worthwhile to select trees with non-aggressive rooting habits from climax vegetation. In this respect species such as *Grevillea robusta* and *Markhamia lutea* may be of use.

12. Trees growing at low densities in arid and semi-arid pastoral ecosystems (ie. the savannas of Africa, Australia and the 'dehesa' system in Spain) have often been found to improve their understory environment. Trees improve site conditions in these savanna ecosystems by adding organic matter and nutrients through leaf-fall, by reducing soil temperatures and water loss due to evapotranspiration and by attracting birds and large mammals that add nutrients to the soil in their droppings. Of potential use in Mediterranean environments of southern Australia is the dehasa system.

13. Trees have been successfully used in the reclamation of saline/sodic soils. There is evidence to show that significant decreases in soil pH and electrical conductivity and increases in soil organic matter has been effected through the establishment of trees. However, the long-term viability of vegetation-based strategies alone for the reclamation of salt affected soils, reuse of saline drainage water and/or industrial and domestic effluent disposal is questionable. Without adequate leaching fractions to reduce the salt concentration within the root zone, even the most tolerant of plant species will eventually succumb.

14. Of concern in the implementation programs to establish trees on farms, and in particular the establishment of pure stands, is the lack of information on the best species and provenances for specific sites, market prospects for products, risk analyses and long-term effects of trees on soil and catchments. Along with economic uncertainty and up-front costs, this results in a lack of confidence by primary producers in the prospects for growing trees on farms. Key areas of concern regarding the current status and perceived gaps in our knowledge on the growing of trees on farms are identified in the Summary of Workshop

Proceedings. It is the opinions of the authors that our understanding of site / species / provenance interactions with respect to Eucalypts is severely lacking and the basic infrastructure for the implementation of an ambitious planting program is lacking. In addition, it is doubtful whether seed stocks of desirable provenances (if defined) are available for projected planting programs and therefore the establishment of clonal nurseries would be required to provide desirable planting material. This in itself is a major undertaking judging by the problems experienced in Brazil and South Africa. It is suggested that comprehensive studies be undertaken of the forestry industries in the aforementioned countries in order to avoid the pitfalls that are associated with plantation forestry.

15. From 16 identified research and development priorities identified, the participants of the workshop were asked to rank the top three priorities which covered the issues and constraints identified. These were as follows:

1. The need for a fundamental understanding of the root architecture of tree and crop components is vital in our ability to reduce competition and create facilitation between these two components. Tree rooting patterns are central in the concept of 'nutrient pumping', whereby tree roots are able to extract nutrients from depth that are not available to the crop, and subsequently make them available through biomass decomposition and nutrient release.
2. Influence of agroforestry systems on soil physical, chemical and biological properties.
3. There is a need for information on the best species combination for sodic soils, acidic soils, mineral soils, soils with structural and physical problems and water use. The information would be used in a tree soil type database.

Terms of Reference

1. A review of the literature and other information regarding the role of trees in maintaining and improving soil fertility for both tropical and temperate climates, and for both fertile and degraded soils. Information regarding negative effects of trees on soils should also be collected. Where possible beneficial and detrimental tree species should be identified. The following processes by which trees affect soils should be investigated:

- i. increases in soil organic matter
- ii. increase in nutrients at various soil horizons
- iii. improved physical structure
- iv. reduced erosion and runoff
- v. improved moisture status

2. A comprehensive discussion of the role of trees in soil improvement in Australian agricultural systems on the basis of the findings in (1). Particular reference should be made to trees in windbreaks and their effects within 1.5 tree heights and to alley-farming for both temperate and tropical zones. However, recommendations for other agroforestry systems where trees can have both a significant benefit to soils as well as fit into a profitable agricultural system should also be made. Where possible, benefits should be quantified so that some judgement can be made concerning the relative benefits of trees as soil improvers as opposed to other benefits of trees.

3. An outline of key gaps in our understanding of the influence of farm trees on nutrient cycling and local hydrology and proposed research strategies to address these gaps.

1. Agroforestry Systems

1.1. Definition

Agroforestry systems, as well as many natural tree based ecosystems, are perceived to improve or maintain soil fertility and productivity, to promote soil conservation, reduce soil degradation and achieve sustainable production. These positive effects are often attributed to the tree component of the system. Before discussing evidence to support or discredit these concepts it is pertinent to define what is meant by the term agroforestry and how this relates to the impact of trees on soils. In general terms agroforestry has been defined as 'a system combining agricultural and tree crops of varying longevity (ranging from annual through biannual and perennial plants), arranged either temporally (crop rotation) or spatially (intercropping), to maximise and sustain agricultural yield (Vergara, 1982). Put more simply, agroforestry could be viewed as an amalgamation in space or time, of forestry and agriculture into a collection of land use practices (Anderson & Bell, 1995). In evaluating the influence of trees on soils we have not restricted ourselves to the aforementioned definition, but have drawn on examples from pure tree systems such as plantation forestry to emphasise the positive and negative effects of trees on soil properties.

1.2. Ecological basis for agroforestry

The adaptation of plant communities to nutrient-poor soils is observed throughout the world. For example, in the wet tropics highly weathered and leached soils with very low levels of exchangeable cations and available phosphorus typically support rainforests of massive structure, productivity and diversity of species (Procter, 1983). This results from tight nutrient cycling between vegetation and soil, and efficient production per unit of limiting nutrient (Vitousek, 1984). In an effort to emulate the efficient nutrient cycling characteristics of these ecosystems under cropping systems, various agroforestry systems have been tested with mixed success.

The concept of mixtures of species to create diversity is appropriately extended by growing woody and herbaceous perennials in association with seasonal annuals. Such mixed systems have been extensively studied in the humid tropics and sub-tropics. Suitable combinations of species of perennials and annuals and appropriate cultural practices for their management are different for different soils and environments. Agroforestry systems are postulated to be capable of improving soil physical properties, maintaining soil organic matter and increasing nutrient cycling (Pinto *et al.*, 1994). Until recently, agroforestry research has revolved around a phenomenological approach. It is now generally agreed that emphasis should be placed on mechanistic approaches, understanding the interactions that occur

between the tree and crop components and the specific processes involved (Anderson & Bell, 1995).

1.3 . Socioeconomic basis for agroforestry

In a rural context, economically poor farmers, which are prevalent in developing countries, would view agroforestry as a means to : (1) increase total productivity; (2) widen the range of products and thereby spreading risk; and (3) preserve their livelihood and survival by conserving a resource base (Conway, 1987). The same criteria would apply to farmers in Australia undertaking agroforestry as a farming practice this being a means to reducing vulnerability to fluctuations in the environment and market place by introducing diversification into their production systems. In addition, trees and shrubs may reduce the negative effects of land degradation (ie. soil salinity and rising watertables) occurring in particular areas of Australia.

1.4. Types of agroforestry systems

Different types of agroforestry widely used in the humid tropics include rotational agroforestry and intercropping systems. Traditional shifting cultivation is a form of rotational agroforestry in which cultivated annuals (1-3 yrs) are rotated with woody species of natural regeneration (5-40 yrs). In comparison, intercropping involves the continuous presence of both annuals and perennials on the same site at the same time. These have been termed 'sequential' and 'simultaneous', respectively (Sanchez, 1995), or 'rotational' and 'spatial' (Young, 1989).

Other possible methods by which food crop annuals can be intercropped with woody shrubs and perennials include: (1) trees grown at random, or scattered within the field as is the case with traditional farming (ie. the 'dehasa' system of southern Spain and Portugal), or regularly spaced; (2) trees grown on the field boundaries at wide spacings as windbreaks and living fences; (3) a row of trees grown on the contour or on terrace walls; (4) trees grown in strips with alternate strips of trees and food crops; and (5) food crops grown in between the rows of young trees during the initial 2 to 3 years of tree crop establishment. The last system, known as Taungya, is also known as the Shamba system in East Africa (Lal, 1989a). Alley cropping is an agroforestry system in which food crops are grown in alleys 2-5m apart formed by contour hedgerows of trees or shrubs (Kang *et al.*, 1981), and has received attention as a possible sustainable cropping system for the humid tropics. The hedgerows are preferably established from native trees or perennial shrubs. These trees are periodically pruned to prevent shading of the food crops.

1.5. The effects of agroforestry on soils and crop yield

The effects of agroforestry systems on soil properties and the yields of annual food crops, depend on a number of factors including:

- the type of agroforestry system
- the proportion of land area allocated to food crops versus tree crops
- ecological compatibility of different species used
- soil and crop management systems used for food crop production
- antecedent soil properties and the prevailing climate (Lal, 1989a).

While some food crops perform satisfactorily in one system for a specific soil and climate, they may not do so for another soil, climate and management system (Lal, 1989a). Studies of soil changes under agroforestry have been outlined in the 23 papers presented at an ICRAF symposium (Mongi & Huxley, 1979) and in a review of soil aspects on agroforestry (Nair, 1984). Unfortunately, studies of nutrient cycling and the monitoring of changes in soil chemical and physical properties are rarely considered in the experimental designs of agroforestry studies and therefore it is often difficult to ascertain the impacts of these systems on the soil. Several references to anecdotal evidence of the positive effects of trees on soil properties can be found in the literature. It is questionable whether these observations would stand up to rigorous scientific scrutiny. There is, however, substantial literature on the influence of monocultures of planted trees on soil properties which can be useful in assessing the impacts of trees on soils.

2. Mechanisms by Which Trees can Affect Soils

2.1. Effects on soil chemistry

2.1.1. Background

The ability of soils to supply nutrients to plants is determined by parent material, climate, topography, age and vegetation. Parent material invariably sets the upper limit on nutrient supply through pedogenesis. The effect of vegetation is more complex. It involves nutrient release through litter fall and organic matter decomposition, acidification through the secretion of acids by roots to compensate cation uptake, organic acid additions from decomposing litter, depletion of nutrients through uptake by the plant, and addition of nitrogen through fixation (Anderson & Bell, 1995). The soil also has a significant influence on the availability of nutrients. For example, the affinity of soil minerals for phosphorus is so great that concentrations maintained in the soil solution are extremely low and consequently losses from leaching are small. In contrast to phosphorus, nitrogen is more labile in soils. It is present mainly in organic forms that are in various stages of mineralisation to ammonium and nitrate forms. Both these forms can be taken up by plants or microbes and metabolised (Fitter, 1986). Ammonium produced during the ammonification stage of mineralisation is retained on cation exchange sites of the clay minerals. Nitrate produced through nitrification is a highly mobile ion which if the anion exchange capacity of the soil is small will result in extensive leaching, resulting in a net accumulation of protons. Nitrate may also be lost by denitrification to gaseous oxides or N_2 .

One of the reasons for an enhanced interest in agroforestry, in particular for adoption by resource poor farmers, is the belief that inclusion of compatible and desirable species of woody perennials in arable land use systems would lead to improvements in soil fertility. Agroforestry may enhance soil fertility in the following ways (Nair, 1987):

- (i) An increase in organic matter content of soil through addition of leaf litter, prunings and other biomass, could have significant effects on soil chemical and physical properties.
- (ii) Efficient nutrient cycling within the system.
- (iii) Biological nitrogen fixation by leguminous shrubs and woody perennials,
- (iv) Possible complementary interactions among associated species due to differences in canopy structure, root systems and active zones of water and nutrient absorption.

Data supporting these contentions, are however, scarce (Sanchez, 1979, 1987). In addition, those systems most often quoted as examples of successful agroforestry are invariably found in areas dominated by base-rich naturally fertile soils such as Alfisols and Andosols. These systems include the homegardens of Asia and Africa (Michon *et al.*, 1986; Fernandes *et al.*, 1984), coffee and cacao production systems in South America (Russo & Budowski, 1986), and alley cropping (Kang *et al.*, 1990).

2.1.2. Organic matter accumulation and breakdown

Soil organic matter is a fundamental component in the plant-soil nutrient cycle of ecosystems. Its maintenance or increase, in some cases, is a prerequisite in the long-term improvement and sustainability of these ecosystems. In recent years, soil organic matter has received additional attention because of its potential to sequester carbon emanating from atmospheric CO₂ (Rasmussen & Collins, 1991; Fisher *et al.*, 1994). Indirect evidence for the ability of agroforestry systems to maintain soil organic matter is the fact that under natural forest ecosystems soil organic matter tends to accumulate. It also accumulates under permanent pasture. In contrast, repeated tillage of the soil results in a steady decline in soil organic matter. Additional evidence of the ability of soils to increase their soil organic matter pool can be found where degraded agriculture lands are left fallow for a period after intensive cultivation.

The potential accumulation of organic matter in different climatic zones is summarised in Table 1 of net primary production of above ground dry matter from Young *et al.*(1987).

Table 1. Relationship between climatic region and annual above ground biomass production. (Adapted from Young *et al.*, 1987)

Climatic region	Above ground biomass (kg ha ⁻¹ .yr ⁻¹)
Humid tropics (no dry season)	> 20000
Humid tropics (short dry season)	20000
Subhumid tropics (moist)	10000
Subhumid tropics (dry)	5000
Semi- arid zones	2500

In addition, roots contribute approximately 20-25% of the total living biomass of trees, although this varies under different environmental conditions (Armson, 1977). Roots make a continuous contribution to soil organic matter through decay and their annual contribution to the organic pool can be as high as that from above-ground litter (Nadelhoffer *et al.*, 1985).

In natural forest ecosystems the major portion of nutrients falling to the soil surface and litter layer are recycled in combination with photosynthetically-fixed carbon (Attiwill & Adams, 1993). These nutrients are returned to the soil and made available for plant uptake through the processes of decomposition and mineralisation. This nutrient cycle plays a key part in regulating the productivity of an ecosystem. In general terms decomposition is the oxidation of carbon and mineralisation is the rate at which organically bound nutrients are converted to ionic forms (Attiwill & Adams, 1993). The first stage of the decomposition process is undertaken by an array of soil macrofauna which ingest, oxidise and excrete carbon, thereby lowering the C/N and C/P ratio and increasing the surface area to volume of

organic particles (Swift *et al.*, 1979). The second stage in the decomposition process is mediated by microorganisms resulting in the mineralisation and release of nutrients. Faunal activity in the first stages of decomposition enhances the patterns of nutrient release effected by microorganisms (Morgan *et al.*, 1989).

2.1.3. Factors affecting nutrient release from organic matter

The effectiveness of organic amendments (litter, prunings, manures, soil organic matter) in modifying soil properties under agroforestry systems depends critically on the factors governing decomposition and nutrient release. These include:

- (i) Climate (effective precipitation and temperature).
- (ii) Chemical composition of the material.
- (iii) Quantity and placement of the organic matter (Szott & Kass, 1993).

Decomposition of organic materials occurs at a fast rate under humid and warm conditions (Anderson & Swift, 1983). It is more rapid in sandy soils than clay soils (Amato *et al.*, 1987) and when incorporated into the soil rather than left on the surface (Holland & Coleman, 1987). In general, leguminous plant materials are high in N and have a low C:N ratio. Thus it is frequently assumed that decomposition of these materials will rapidly release large quantities of N. For this reason leguminous perennials are often included in alley cropping systems so that mineralisation of prunings will supply N to the accompanying crop. In short-term studies nitrogen mineralisation and residue decomposition have been shown to be related to total nitrogen, negatively correlated with C:N ratio, lignin content, total nitrogen to lignin ratio, the polyphenol concentration and polyphenolic:N ratio of the initial material (Witkamp, 1966; Aber & Melillo, 1982; Bosatta & Staaf, 1982; Melillo *et al.*, 1982; Aber *et al.* 1990; Fox, *et al.*, 1990; O'Connell, 1988; Palm & Sanchez, 1990, 1991). Palm and Sanchez (1991) have suggested that the polyphenolic:N ratio of leguminous materials may serve as a useful index of litter quality.

Although short-term rates of decomposition differ between different organic materials, Aber *et al.* (1990) suggest that in the long-term decomposition of different materials may be similar due to similarities in carbon chemistries of the material remaining after initial decomposition. Due to the variable nature of litter and the numerous soil and environmental constraints governing the rate of decomposition and release of nutrients, it is extremely difficult to predict the availability of individual ionic species for uptake. It is of note that high lignin and polyphenol concentrations in the leaves of certain plant species inhibit grazing by herbivores, and this would directly influence the rate of turnover of such material in an ecosystem. There may be a negative correlation between ease of nutrient release from such leaf litter and anti-herbivore defences. From a quality perspective the rate of breakdown of litter can be significantly influenced by the presence of phytotoxic accumulations of ionic species. For example, soil organic carbon tends to accumulate under

plant communities adapted to growing on serpentine soils. This is assumed to be due to the accumulation of chromium (Cr) in the litter which acts as a biocide for decomposing microorganisms.

The quality of organic matter can significantly influence the rate of release of nutrients other than N. For example, the mineralisation of P, K, Ca and Mg was faster from high quality *Erythrina* leaves than from low quality *Inga edulis* or *Cajanus cajan* leaves (Palm & Sanchez, 1991). Similarly including twigs with the leaf litter of *Calliandra calothyrsus* and *Gliricidia sepium* reduced the short-term net N mineralisation and release of available N from decomposing green manure (Constantinides & Fownes, 1993). This effect would explain the complex patterns of N mineralisation and immobilisation in leaf and twig mixtures previously observed (Oglesby & Fownes, 1992).

2.1.4. The direct effects of organic compounds on soil development

While the decomposition of organic matter releases plant nutrients, it may also release organic compounds which affect soil chemistry. Organic compounds emanating from the mat of litter decomposing on the surface of forest soils can play a key role in pedochemical weathering. Iron and aluminium (Al) bound into the structures of soil minerals are susceptible to complexing by soluble organic compounds which have the ability to mobilise these minerals, thereby creating the characteristic podzol (Bloomfield, 1953). Stands and individual trees of mor-forming (acid) species such as Kauri (*Agathis australis* Salisb.) produce localised podsolization. The egg cup shaped podsols that form under Kauris demonstrates the powerful effect of organic matter on soil development. Likewise the development of podsols often observed beneath alpine scrub and snow grass in New Zealand are indicators of previous presence of mountain beech (*Nothofagus solandri* var *cliffortioides*) (Molloy *et al.*, 1962). In contrast, non-podsolized mull (non-acidic) soils are characteristically found under broadleaved stands and some mixed forests.

2.1.5. Chemical properties of soil organic matter

Soil organic matter exerts its major influence on chemical properties of soils through direct and indirect effects on nutrient supply. The composition of soil organic matter and specifically the contents of carbon (C), nitrogen (N), phosphorus (P), and sulphur (S) have been studied extensively (Jenkinson, 1988). The ratio of organic C to organic N (C:N ratio) is relatively constant in most soils, ranging from 10 to 14. A similar constancy of organic C to organic S ratios (7 to 8) has commonly been reported. There is strong evidence to suggest that soil organic C is less closely linked with soil organic P than with organic N or organic S. In addition, it appears organic P is less readily mineralised to plant available forms than are organic N or S, probably because a substantial proportion of soil organic P occurs as inositol phosphates which are relatively stable (Tate, 1987).

Rapid intake of inorganic P from soil or fertiliser by microbes and its incorporation in organic matter may be an advantage in acid soils with high rates of P fixation. Such soils are invariably P deficient due to their high P fixing capacity (Tiessen, *et al.*, 1992). The slow release of plant-available P by mineralisation would allow plant roots to compete for it against the process of fixation (Syers & Craswell, 1995).

Indirect effects of soil organic matter on nutrient supply include its role in enhancing cation exchange capacity (CEC). This is particularly important in sandy soils where organic matter is the most important contributor to soil CEC. The metal complexing ability of soil organic matter is well established and the ability of organic matter to lower exchangeable Al in soils has been demonstrated by Hargrove and Thomas (1981).

2.1.6. Influence of roots in mobilising nutrients

The acquisition of nutrients by plants is influenced by the volume of soil exploited, coupled with the extent of root surfaces in that volume and the rate of ion movement in the soil towards those surfaces (Clarkson & Hanson, 1980). Plants can also directly alter the availability of nutrients in the rhizosphere by (1) altering pH through secreting protons or HCO_3^- in exchange for cations or anions, (2) secreting oxygen into anaerobic soils, which reduces iron and alters P availability at the root surface (3) secreting organic acids which solubilize labile P (4) hydrolysing organic P with root phosphatases, (5) fixing N, (6) stimulating decomposition of soil organic matter in the rhizosphere through exudation of soluble organic compounds from roots, which act as substrates for micro-organisms (Chapin, 1980). Micro-organisms increase the availability of nutrients by direct effects on solubilising soil minerals, or by the release of chelates which increase the concentrations of cations in the soil solution (Brown, 1978).

Growing roots of plants release considerable amounts of organic carbon into the rhizosphere. Three major components have been suggested: low-molecular-weight organic compounds, high-molecular-weight gelatinous materials and sloughed-off cells (Marschner *et al.*, 1986). Low-molecular weight root exudates may enhance mobilisation of mineral nutrients in the rhizosphere as well as protect the root from phytotoxic elements such as Al (Delhaize *et al.*, 1993). Roots of Fe-deficient grasses release phytosiderophores which dissolve inorganic iron compounds by chelation of Fe^{3+} . Citric and malic acids released by P-deficient white lupin (*Lupinus albus* L.) and rape (*Brassica napus*) mobilise sparingly soluble P (Marschner *et al.*, 1986; Hedley *et al.*, 1983). Some species form cluster or proteoid roots with high specific surface area under low nutrient conditions. In white lupin it is these structures which excrete citric acid under low P conditions (Gardner *et al.*, 1981).

Proteoid roots are also known to form in woodlands on coastal sands supporting *Banksia* and may form a continuous mat on the mineral soil surface, incorporating the lower litter layer (Attiwill & Adams, 1993). In this respect Grierson (1992) analysing leachates

from these proteoid roots found they contained large amounts of low-molecular-weight organic acids including citric acid (50% of the total), malic acid (18%) and aconitic acid (17%). Likewise a large number of simple low molecular weight organic acids, have been extracted from forest soils in the south eastern United States. These are thought to originate from both micro-organisms and plants (Fox & Comerford, 1990). Mulette *et al.* (1974) suggested an interaction between root exudates (e.g. citrate), micro-organisms, aluminium ions and root uptake mechanisms to account for the ability of *Eucalyptus gummifera* to grow on impoverished soils.

Recent research has presented some fascinating insights into the ways plants influence the soil chemistry in the rhizosphere. However, our understanding is fragmentary and many questions at both the descriptive and mechanistic levels remain to be answered. In a recent review Attiwill & Adams (1993) conclude that the significance of root exudates to nutrient cycling has yet to be quantified.

2.1.7. Extraction of nutrients from depth in the soil

One of the postulated benefits of agroforestry is that trees are able to exploit nutrient reserves at depth in the soil profile because they have deep root systems. *Acacia*, *Prosopis* and *Eucalyptus* species have substantial and vigorous tap root systems which are able to reach depths of > 20 m (Dye, 1996). Fagg (1991) has reported roots to a depth of 35 m for the Tenere tree growing in the Sahel. *Leucaena leucocephala*, a species commonly grown in alley cropping systems, has a strong tap root and there is evidence to suggest that this species exploits water reserves from deeper soil horizons than the associated crop (Lawson & Kang, 1990). However, *Leucaena* despite its strong tap root can also have a well developed superficial root system which will compete for soil moisture with any crop inter planted. Studies in Nigeria indicate that *Gliricidia* can be deep rooted. However, in Sumatra the same species had roots which extended for more than 6 m from the plant just beneath the soil surface and there was little tap root penetration (van Noordwijk & Dommergues, 1990).

There are few detailed studies of the rooting behaviour of trees in the humid tropics. Niche differentiation on the basis of root architecture has been examined in alley cropping experiments (Hairiah & van Noordwijk, 1986; van Noordwijk, 1989) that included a number of tree species traditionally used in agroforestry systems (*Leucaena leucocephala*, *Gliricidia sepium* and *Acioa barteri*). An optimal spatial distribution was considered to combine deep root development for 'nutrient pumping' with limited horizontal development in order to reduce competition with crop roots for nutrients and water. Studies of fine root distribution using *Cassia siamea*, *Eucalyptus camaldulensis*, *E. tereticornis*, *L. leucocephala* and *Prosopis chilensis* have indicated that vertical root distribution of these species was similar to maize (*Zea mays*) suggestion that there was intense competition between tree and crop (Jonsson *et al.*, 1988). In temperate silvopastoral systems there is an increase in biomass

allocation to roots in *Prunus avium*, and the vertical distribution of roots in *Fraxinus excelsior* to be downwards under competition from grass swards (Tomlinson & Eason, 1990; Campbell & Dawson, 1991). Such changes in rooting patterns are indicative of a response to reduced soil water and nutrient availability as a result of competition by the sward.

2.1.8. Mycorrhiza associations

The role of mycorrhizal associations with trees in increasing the uptake of P from infertile soils is well recognised. For a comprehensive discussion on this topic the reader is referred to a number of excellent texts (Allen, 1991; Brundrett, 1991; Newman, 1988). Mycorrhizas in forests are almost universal in vascular plants and occur in most soils (Bolan, 1991). The general consensus suggests that mycorrhizal plants exploit similar sources of soil phosphorus as do non-mycorrhizal plants but have a greater effective absorbing surface area (Bolan, 1991). The hyphae of both ectotrophic and endotrophic mycorrhizas extend from the root surface to much greater distances through the soil than root hairs, and act as a secondary root system that facilitates the uptake of certain nutrients (phosphorus, zinc and possibly sulphur) by the host. There are three main types of endotrophic mycorrhiza, including the vesicular-arbuscular (VA) endomycorrhizas that infect the great majority of terrestrial plant species (Harley & Smith, 1983).

All mycorrhizas can improve plant growth by enhancing the uptake of P, and in P-deficient soils mycorrhizal plants grow markedly better than non-mycorrhizal ones (conversely in nutrient-rich soils plants tend to have very low levels of infection) because the hyphae can explore soil inaccessible to the plant roots and enable plants to overcome limitations to diffusion. There is also evidence of direct uptake of P from litter via mycorrhiza, such that the soil pathway is bypassed and an entirely closed cycle exists (Herrera *et al.*, 1978). VA mycorrhizal fungi tend not to exhibit a high degree of host specificity, and their hyphal links can unite plants of the same and different species. In contrast, ectomycorrhizas do exhibit some specificity (Newman, 1988). Such direct links offer possible routes for partially closed cycling of nutrients and assimilates between plants (Finlay & Read, 1986).

Ectomycorrhiza are adapted to systems in which nitrogen is limiting, and all nutrients and water taken up by the plant go through the ectomycorrhizal fungus. Conversely VA mycorrhiza are found in systems where P is the most limiting nutrient and are primarily concerned with the uptake of this ion. Mycorrhizal associations have been related to ecosystem characteristic, such that ectomycorrhizas are concentrated in the organic layer, and VA mycorrhiza in the mineral layer (Finlay & Read, 1986). Such spatial separation leads to the possibility of combining ectomycorrhizal trees with VA mycorrhizal crops thereby achieving resource partitioning (Anderson & Bell, 1995).

In addition to the large surface area produced by mycorrhizas there are reports that they excrete organic acids which may have a direct influence in the mobilisation of nutrients. Malajczuk and Cromack (1982) have reported the accumulation of calcium oxalate in the mantle of mycorrhizal roots of *Pinus radiata* and *Eucalyptus marginata* and increases in the phosphatase activity may occur at the surface of mycorrhiza (Dighton, 1983).

2.1.9. Soil micro-organisms

Differences in vegetation type and soil factors such as structure, organic matter content, total nitrogen and mineral nitrogen can influence the microbial populations that occur under trees (Theodorou, 1984). In a comparison of microbial populations under pasture, native eucalypt woodland and *Pinus radiata*, Theodorou (1984) observed greater numbers of bacteria in the soil under pasture than under the trees and ascribe this to the pasture having four times the root biomass of the trees. The rooting system of the pasture could provide more exudates and additional energy substrates for microbial growth through decomposing roots (Bowen, 1973; Martin, 1977). *Pinus radiata* caused an increase in the fungal population compared to that of the pasture or eucalypt woodland soil, this increase being ascribed to the accumulation of litter on the forest floor. Nitrification rates were greater in soil under pasture than under eucalypt woodland or pines suggesting that nitrifying populations may be low under the latter two systems. Such low populations may be due to the high C/N ratio of forest soils (Heilman, 1974), low pH (Thoe bald & Smith, 1974) or inhibitory substances produced by pine roots and litter (Boquel & Suavin, 1972). It is known that mycorrhizal pine roots readily use ammonium nitrogen (Bowen & Smith, 1981) and the lack of nitrification is likely to be a benefit especially in sandy soils which are often used for plantations of *P. radiata* (Theodorou, 1984).

2.1.10. Allelopathy

The role of allelopathy in inhibiting nitrification is still widely debated without a clear consensus on the matter. The bulk of the evidence comes from studies undertaken on forest ecosystems where allelochemicals such as tannins, phenols and volatile terpenoids are known to inhibit nitrogen mineralisation and in particular nitrification (White, 1991; Lodhi & Killingbeck, 1980; Baldwin *et al.*, 1983). In addition, Ellis and Pennington (1989) have suggested that 'non-labile, water-soluble substances' may inhibit nitrifiers in Tasmanian plant communities dominated by *Leptospermum* spp. Due to the difficulties in testing soils for allelopathic chemicals or testing the effect of chemicals on processes *in situ* the argument against allelopathy being an important influence on nitrogen transformations has developed more or less in parallel with that for allelopathy (Attiwill & Adams, 1993). Attiwill and Adams (1993) note that in a number of instances, attempts to test allelopathy have shown that (i) the concentrations of extractable tannins in the litter or soil are not correlated with rates of

nitrification (e.g. Thorne & Hamburg, 1985), (ii) extracts of leaves or of leaf litter have little or no effect on nitrification (e.g. Montes & Christensen, 1979) and (iii) the inhibitory action of leachates may be due to the addition of soluble carbon compounds to the soil (e.g. Robertson, 1982; Montagnini, *et al.*, 1989). Attiwill and Adams (1993) conclude that there are chemicals released from leaves and leaf litter which are capable of inhibiting the activity of microorganisms and there are variations in the rate of nitrification between forests of differing productivity, age and species composition which cannot be explained on the basis of C/N ratios or ammonium availability.

2.1.11. Conclusions

1. In discussing agroforestry as a land use system, a clear understanding of the theoretical objectives of such a system are required. In general, it can be described as a land use system that increases productivity and provides multiple products with the objective of conserving a resource base. Such a system reduces a producer's vulnerability to economic and environmental fluctuations and emphasises the sustainability and maintenance of a finite resource base.
2. The parent material from which soils are derived effectively sets the upper limit of nutrient supply by a soil. Contrasting this the vegetation component of the ecosystem acts as a means by which mineral nutrients are sequestered, and carbon and/or nitrogen is fixed, and subsequently added to the soil through litter fall and the decomposition of organic matter.
3. Soil organic matter is a fundamental component in the plant-soil nutrient cycle of ecosystems. The soil organic matter content reflects the balance between additions on the one hand and losses due to decomposition on the other. The decomposition process is catalysed by soil meso- and macro-fauna. The rate of decomposition of soil organic matter and the size of the soil biomass fluctuates in response to changes in the levels of substrate and environmental conditions.
4. Irrespective of a soils inherent organic matter content, the implementation of agricultural production systems results in a decline in organic matter due to (1) the inputs of plant carbon being generally low and (2) tillage and other agricultural practices increasing the rate of decomposition of soil organic matter by incorporation into the soil and thereby increasing the number and intensity of wetting and drying cycles.
5. The type and composition of organic matter applied, particularly the lignin / polyphenolic concentration influence the rate of formation of organic matter. Varying the amount and

diversity of the litter or crop residues retained will influence the rate of mineralisation and nutrient release.

6. Soil organic matter has the following major influences on soil chemical properties:

- (a) Acts as a source of nitrogen, phosphorus, sulphur and cations.
- (b) Has a direct influence in increasing the cation exchange capacity (CEC) of a soil, this being particularly important on sandy soils.
- (c) The complexing ability of components of soil organic matter results in the removal of potentially phytotoxic ionic species from soil solutions.
- (d) Incorporation of P in soil organic matter can reduce phosphorus fixation by soil minerals. Soil organic P can act as a slow release form of this element.

7. Roots can have a significant influence on nutrient acquisition through chemical changes in the rhizosphere (ie. pH), the production of specific rooting structures (ie. proteoid roots), the manipulation of microbial populations in close proximity to the root and the extraction of nutrients from depth within the profile.

8. Mycorrhizal associations significantly influence the acquisition and cycling of nutrients by enabling plants to gain access to organic nutrients by direct linkage to litter, by increasing phosphatase activity and by making the system less 'leaky'.

2.2. Nutrient cycling

2.2.1. Introduction

Considerable quantities of nutrients in organic form reach the soil through litter fall, below ground root turnover and, in agroforestry systems, as prunings (Szott *et al.*, 1991a). The relative quantities of nutrients in these materials vary greatly depending on tree species, spacing and management practices, soil characteristics and climate (Szott & Kass, 1993). Clearly however, nutrients in litterfall, root turnover and prunings (unless added from off-site) represent recycled and not additions to the system, whilst inorganic fertiliser and symbiotically fixed N and particulate inputs through rainfall are additions. The amount of nutrients in biomass are considerable, the most spectacular evidence comes from studies of plantation crop combinations in Central and South America. These consist of coffee or cacao grown in dense mixed combinations with shade trees, commonly species of *Erythrina*, *Inga* and *Cordia*, the first two nitrogen fixing. The nutrient content of the leaf litter, from the agricultural crop and the trees combined, is of the order of 150 to 300 kg nitrogen, 10 to 20 kg P, 75 to 150 kg K and 100 to 300 kg Ca ha⁻¹ yr⁻¹. Where these systems are fertilised, the nutrients recycled in litter can exceed the annual fertiliser input. However, frequent pruning which is commonly practised in alley cropping systems often reduces total biomass production, nitrogen fixation (Duguma *et al.*, 1988; Rogers & Rosecrance, 1992) and the production of Ca and Mg-rich woody tissue (Szott & Kass, 1993).

One of the objectives of agroforestry systems or for that matter the production of plantation timber should be to conserve and increase where possible the store of available nutrients in the soil. Young (1989) provides details of the major pathways of nutrient cycling which consists of storages and flows within the system, and gains and losses. The storage component is made up of roots, plant residues, organic matter and soil minerals. Flows within the system include the decomposition of plant residues and soil organic matter, and plant uptake. Gains to the system consist mainly of nitrogen fixation and fertiliser additions, rainfall and dry deposition and losses are attributed to leaching, erosion and product removal. During the early stages of tree growth most of the nutrients taken up are incorporated into new growth and structural biomass. This becomes significant for the nutrient balance in the system where there is removal of young plant material high in nutrients (as in the case of alley cropping and short rotation plantation forests). The more intensive the harvesting and the shorter the rotation the greater the demand imposed on nutrient storages on the site (Attiwill & Leeper, 1987).

2.2.2. Nitrogen cycling in alley cropping systems

Tree legumes appear to have considerable potential for improving the N status of soils and increasing the quality of fodder for animal consumption. The potential for N fixation in agroforestry systems is governed by several environmental constraints. In soils

with a high inherent N status legumes thrive without fixing N₂, fixation is suppressed and they derive all of their N requirement from the soil (Peoples *et al.*, 1995). However, in the majority of soils, levels of plant-available N are insufficient to satisfy plant requirements and therefore fixation of N₂ occurs through the legume component. Examples of the amounts of N fixed by various plant species are presented in Table 1. The total amount of N fixed is a function of the species, age of the plant and edaphic and environmental conditions.

Table 2. Examples of N₂-fixation by different tree species. Adapted from Peoples *et al.*, (1995).

Species	N yield (kg ha ⁻¹)	N ₂ fixation	
		^a P _{fix} (%)	Amount (kg N ha ⁻¹)
<i>Gliricidia</i> spp.			
OF1 12/86	165	52	86
OF1 14/84	483	64	309
<i>Cadariocalyx gyroides</i>	107	51	55
<i>Calliandra calothyrsus</i>	210	48	101
<i>Gliricidia sepium</i>	268	69	185
<i>Calliandra calothyrsus</i>	79	14	11
<i>Gliricidia sepium</i>	132	75	99

^a P_{fix} = percent plant N derived from symbiotic N₂ fixation.

2.2.3. Rates of mineralisation and recovery of N

There is scant information regarding the recovery of nutrients from organic and inorganic sources by trees in agroforestry systems (Szott & Kass, 1993). In alley cropping systems, usually less than 20% of the N in surface applied prunings ends up in the succeeding crop (Kang *et al.*, 1990; Mulongoy & Sanginga, 1990). Better utilisation of N has been observed when prunings are incorporated into the soil. However, this demands greater input of labour (Kang *et al.*, 1985). The remainder of the organic N is either not released (31%), is lost or taken up by the tree crop (39%), or incorporated into the soil organic matter (23%) (Mulongoy & Sanginga, 1990).

As well as the rate of N release from tree litters the recovery of this released N by the intercrop is of significance. Xu *et al.*, (1993) examined the rate of release of N from *Leuceaena leucocephala* leaves, stems and petioles and subsequent uptake of N by a maize (*Zea mays*) crop. Decomposition 20 days after addition to plots ranged from 50-58% with leaves, 25-67% with stems and 38-51% with petioles. More than 55% of the N was released

after 52 days. By 20 days after the addition of the residues containing labelled ^{15}N 3.3-9.4% of the added ^{15}N was found in the maize plants, 32.7-49.0% was in the leuceana residues, 36.0-48.0% in the soil and 0.3-21.9% lost. By 52 days 4.8% of the ^{15}N applied in the leuceana prunings was taken up by maize, 45.1% was detected in the residues, 24.9% in the soil and 25.2% lost. In contrast, when N fertiliser was applied, 50.2% of the fertiliser N was recovered by the maize crop, 35.5% was retained in the soil and 14.3% apparently lost. Most of the ^{15}N remaining in the soil profile, derived from the leuceana residues, was detected in the top 25 cm with less than 2% below this depth interval.

Compared to inorganic sources of fertilisers, many organic materials have greater residual effect on soil fertility due to their slow-release characteristics (Doran & Smith, 1987). Sisworo *et al.* (1990) observed that approximately 70 % of the N applied in legume residues was recovered within two years of application. In comparison, the recovery N from inorganic fertilisers by annual crops in the tropics is seldom in excess of 40%. These recovery efficiencies are likely to vary with climatic conditions, the timing and frequency of application, the type of nutrient applied and placement. Lowest recovery efficiencies are generally found under high rainfall conditions due to the greater potential for leaching and denitrification (Myers, 1988).

The wide variability in chemical composition of leaves and in release of N, Ca and Mg was shown in a study of eight agroforestry/fallow woody perennial species (*Acioa barteri*, *Alchornea cordifolia*, *Anthonata macrophylla*, *Dialium guineense*, *Pterocarpus santalinoides*, *Cassia siamea*, *Gliricidia sepium* and *Leucaena leucocephala*) and two cover crops species (*Mucuna pruriens* and *Centrosema pubescens*) in a 7 week incubation experiment (Tian, *et al.*, 1992). The most rapid N release was observed for *Gliricidia sepium*, *Leucaena leucocephala*, *Mucuna pruriens* and *Centrosema pubescens* whilst the slowest release was observed *Alchornea cordifolia*, *Macrolobium macrophylla*, *Cassia siamea* and *Pterocarpus santalinoides*. Nitrogen mineralisation rate (k) were calculated for each of the species and ranged from -0.0018 to 0.0064 kg N day⁻¹ for *Acioa barteri* and *Gliricidia sepium* respectively. Nitrogen release increased with increasing N content and decreased with increasing polyphenol and lignin. All of the species significantly increased the exchangeable Ca and Mg concentrations on the soil exchange complex, with Ca release being highly correlated with N release. The highest Ca and Mg release rates were shown by *Leucaena leucocephala*, *Gliricidia sepium*, *Centrosema pubescens* and *Mucuna pruriens*.

2.2.4. Mineralisation of basic cations and the role of fertilisers

Studies of mineralisation of nutrients from organic materials in agroforestry systems have placed more emphasis on N than on other nutrients. In the humid tropics, 50% or more of K is released from prunings in less than a month, whereas Ca release is slow with turnover times often longer than one year (Palm & Sanchez, 1990; Swift *et al.*, 1981). The release of P

from organic materials is difficult to model since there is strong interactions between the C, P and N cycles which determine patterns of immobilisation and mineralisation.

The timing and frequency with which nutrients are made available to plants influence nutrient recovery. In alley cropping systems, attempts have been made to synchronise organic and inorganic fertiliser applications with the nutrient demand of the crop (Szott & Kass, 1993). In the case of organic residues, nutrient release and availability for uptake are more complicated to predict for reasons outlined previously.

In shaded perennial crops and home gardens, the question of nutrient synchrony during a particular season may not be as important as in alley cropping systems since perennial-crop root systems are likely to be active for a greater part of the year (Szott & Kass, 1993). In perennial-cropping systems it may be more important to consider nutrient synchrony as related to a particular development stage of the plant or stand. The first year after planting is often the most critical time for several fruit and timber species, and nutrient deprivation at this time can often result in loss of productivity which is seldom recovered by later applications (Ballard, 1984; Herbert & Schöna, 1990). Nutrient deficiencies are often observed at canopy closure, when tree growth and nutrient demands are high, internal nutrient recycling is still low, and nutrient supply from the soil and external recycling mechanisms may be low (Miller, 1984). Even after this growth stage deficiencies may persist if nutrient removal in harvested products is high, particularly in the case of short rotation plantations.

For the long-term sustainability of agroforestry systems, supplemental additions of inorganic or organic fertilisers to maintain fertility levels must be considered. Combinations of these will influence the nutrient supply and availability to the crop or tree, this being dependent on the initial status of the soil and on biological processes that are present. Inorganic N or P when applied to the soil surface where residues are concentrated may be immobilised or in the case of urea N, volatilised (Szott & Kass, 1993). Similarly, additions of organic residues containing a high C status can result in the immobilisation of previously available N and P.

In contrast to organic materials, inorganic N or P fertilisers can result in greater immediate availability of nutrients. Increases in organic N and P forms then occur over time as plant residues are returned to the soil. Immobilisation of inorganic P or N in organic forms may reduce N leaching and buffer nutrient release (Doran & Smith, 1987; Stewart & Sharpley, 1987). On soils with a high P-fixing capacity the conversion of inorganic P to organic forms may sustain plant availability over a long period (Stewart & Sharpley, 1987; Haggard *et al.*, 1991).

2.2.4. Atmospheric inputs due to the presence of a canopy

Rain and particulate matter from the atmosphere are a source of soil nutrients. These inputs may be small compared to conventional agricultural inputs, this would depend on location, (i.e. in highly industrialised areas or in close proximity to industry, these inputs could be substantial). It is plausible to suppose that trees increase the deposition of dust. It is known that throughfall and stemflow can form a substantial source of soil nutrients, although to what extent this originates from rainfall as compared with leaf leachate is not known.

George (1979) estimated the nutrient contained in rainfall, stemflow and throughfall in a plantation of *Eucalyptus* hybrids at Dehra Dun, north India. The annual yield is presented in Table 2. It is of note that the elemental amounts in stemflow and to a lesser extent, in throughfall are greater than in the rainwater. It is however not clear whether these additions come from the leaching of the foliage or from the washing off of aerosols and dust from the leaves. Attiwill (1966) in a study of a mature stand of *Eucalyptus obliqua* concluded that the principal contribution was made by leaching nutrients from the leaves.

Table 3. Nutrient return through stemflow, throughfall and rainwater from a hybrid stand of *Eucalyptus*, in north India. From George (1979).

Source	Nutrient Concentration (kg ha ⁻¹ yr ⁻¹)				
	K	Ca	Mg	N	P
Stemflow	3.9	3.8	0.2	0.2	0.1
Throughfall	9.4	8.8	2.0	2.0	0.1
Total	13.3	12.6	2.2	2.2	0.2
Rainwater	5.2	5.9	2.5	1.7	0.2
Grand Total	18.5	18.5	4.7	3.9	0.4

Hingston (1977) gave estimates of elemental inputs in rainfall and that released through the weathering of granite (Table 3). These figures illustrate the orders of magnitude that can be expected from these two sources.

2.2.5. Nutrient cycling under plantation systems

In contrast to agroforestry systems where the crop can place a high demand on nutrient capital, short rotation plantation forestry may be more efficient in the utilisation of nutrient reserves. Wise and Pittman (1981) have studied the nutrient removal by short rotation eucalypt plantations and found that even the most productive short rotation stands removed small amounts of nutrients compared to cereal production. Over a ten year period,

based on one fallow year every fourth year, cereal crops could remove 2-4 times the nitrogen, 10-20 times the phosphorus and 2-5 times the potassium of a short rotation eucalypt plantation. However, the total amount of nutrients removed from site at harvest of the eucalypts can be significantly influenced by the harvesting method used. For example, losses of nutrients would be lower if logs were debarked on site.

Litterfall is a major pathway for nutrient return to the soil in forests and plantations. Litter fall ranges from 258 to 386 g m⁻² yr⁻¹ for pines and 388 to 686 g m⁻² yr⁻¹ for eucalypts growing in Gippsland Victoria (Baker, 1983). The nutrient content of litterfall in pines ranged from 1400 to 2400 mg N m⁻² yr⁻¹ and 97 to 230 mg P m⁻² yr⁻¹. In eucalypts the corresponding ranges were 2100 to 4600 mg N m⁻² yr⁻¹ and 94 to 200 mg P m⁻² yr⁻¹. In a 4.5 year old *Eucalyptus grandis* plantation in South Africa the average litter fall was 670 g m⁻² yr⁻¹ (Noble, 1992) which is similar to that of a 19 year old stand of *Eucalyptus regnans* (Baker, 1983).

Plantation forestry can utilise nutrients more efficiently than agriculture because of better nutrient cycling. Agricultural ecosystems are more open with inputs and outputs amounting to as much as 40% of internal cycling (Booth & Javanovic, 1991). In natural forests, on the other hand, inputs and outputs can be less than 10% of internal cycling.

Management of plantations can have a major impact on nutrient use efficiency. Raison and Crane (1981) compared plantations of *Eucalyptus delegatensis* and *Pinus radiata* and found a marked interaction between the tree species and the length of the rotation, with consequences for the rate of nutrient export and nutrient use efficiency. When the rotation length of *E. delegatensis* was reduced from 57 years to 18 years the removal of phosphorus per unit of wood harvested increased by 70%. Likewise removal of early thinnings resulted in a significant loss of nutrients from *P. radiata* forests. They conclude that rotations of about 7 years or less, as are commonly observed in eucalypt plantations in countries such as Brazil, may have nutrient removals comparable with over other species. Eucalypts exhibiting high growth rates (40-80m³ ha⁻¹ yr⁻¹) when managed on short rotations will place heavy demands on soil reserves for nutrients (e.g. 5 kg P ha⁻¹ yr⁻¹ stored in the wood) which are similar to those of annual agricultural crops (e.g. 7 kg P ha⁻¹ yr⁻¹ in maize). The harvesting of foliage in addition to wood will further increase the removal of nutrients and it is very likely that regular fertilisation (at rates similar to those used for agricultural crops) will be required if fertility of the soil and productivity of the forest are to be sustained. Raison and Crane (1981) concluded that the maintenance of organic matter is a critical factor on many Australian soils and that nutrient removals should not be compared with total reserves of nutrients in the soil as a basis for assessing the significance of harvesting. In general, inputs of nutrients should aim to maintain (or improve) the nutrient supplying capacity of the soil. They propose the following strategies in achieving this objective:

- a. Leaving nutrient-rich biomass on the site; not harvesting root systems on most sites; removal of bark from tree trunks and its retention on site.
- b. Use of conservative site preparation procedures which minimise disturbance and loss of nutrients from slash, litter layers and surface soil.
- c. Efficient use of fertilisers.
- d. The possible use of legumes (either inter-cropped or during a fallow period between rotations) to assist in the maintenance of soil organic matter and nitrogen economy.

Table 4. Inputs of nutrients into forest ecosystems through rainfall and weathering of granite. From Hingston (1977).

Element	Ranges of values reported for accession of elements in rainfall in Australia kg ha ⁻¹ yr ⁻¹	Estimated values released by weathering granite kg ha ⁻¹ yr ⁻¹
Na	2-111	9
K	0.3-14	9
Mg	0.3-15	2
Ca	0.8-35	6
Cl	2-180	0.06
NH ₄ -N	0.7-2	
NO ₃ -N	0.3-1	
P	0.1-0.3	0.07
Mn		0.11

2.2.6. Conclusions

1. Considerable quantities of nutrients in organic form reach the soil through litter fall, below ground root turnover and prunings. The relative quantities of nutrients in these materials vary greatly depending on tree species, spacing and management practices, climate, and soil characteristics.
2. Nutrients in litter fall, root turnover and prunings (unless added from off-site) represent predominantly recycled and not additions to the system. In contrast, nitrogen fixation, organic and inorganic fertilisers and inputs through rainfall and as particulate are true additions to the system.

3. Plant residue, particularly legume residue act as a source of nitrogen for subsequent crops. The contribution of nitrogen from this source is a function of the pattern and rate of mineralisation in relation to crop demand. Between 4 and 20 % of nitrogen applied to the soil surface as prunings is reported to be recovered in the immediate succeeding crop. Significantly higher recoveries have been observed where inorganic nitrogen is applied. However, compared to inorganic sources of fertiliser, organic materials have a greater residual effect on soil fertility due to their slow-release characteristics.
4. Many nitrogen-fixing trees grow rapidly on soils having a low inherent fertility. This in part is due to their ability to fix nitrogen and consequently have been used extensively in agroforestry to provide timber, firewood and forage.
5. In contrast to agroforestry systems where the cropping phase can have a high demand for nutrients, short rotation plantation forestry may be more efficient in the utilisation of nutrient reserves. However, the total amount of nutrients removed from site at harvest can be significantly influenced by the harvesting method.

3. Evidence of the Impact of Trees and Shrubs on Soil Chemical Properties.

3.1. Soil chemical effects

3.1.1. Alley cropping systems

Humid tropical forests are characterised by relatively high precipitation and temperatures with a small annual variation in photoperiod. Nutrient cycling in these forest ecosystems has resulted in marked accumulations of the nutrients in plant biomass and litter as opposed to the soil (Brinkmann, 1983). For this reason the vegetative biomass of these forests is critical in the maintenance of soil fertility. Replacing the natural forest by pastures and crops decreased organic matter, N, P, and K content of the soil (Table 4). In addition, the increase in exchangeable Al following clearing caused a decrease in the inherent fertility status of the soils. Under these circumstances productivity under pasture and crops could only be maintained by inputs of inorganic or organic fertilisers.

Table 5. Soil characteristics of the superficial soil horizon under different land uses. All soils were classified in the order Inceptisol. Adapted from Plamondon *et al.*, 1991.

Land Use	Slope	Texture ¹	O.M. (%)	N (%)	P (mg kg ⁻¹)	K ₂ O (kg ha ⁻¹)	Exch. Al (meq 100g ⁻¹)	Base Sat. (%)	pH	Al Sat. (%)
Forest	70-90	C3	10.2	0.459	16.4	994	0.64	29	4.0	4
	80	C3	11.6	0.522	50.8	844	1.36	22	3.3	11
Regeneration cleared	80	C1	11.6	0.522	11.3	678	8.73	41	3.2	58
1 year old	25	C2	11.9	0.535	5.3	526	10.22	33	3.2	70
cleared and burnt	70	C2	10.9	0.490	12.2	444	6.84	26	3.3	55
Pasture	40	C1	3.1	0.139	1.9	210	1.43	14	4.0	39
	30	C1	2.8	0.126	1.9	327	1.33	13	4.2	36
Crops	20	C2	1.9	0.085	4.4	198	0.47	28	4.6	8

¹ Texture classes with respect to surface and subsoil horizons: C1 = sandy loam over sandy clay/loam; C2 = loam over clay loam; C3 = loam over sandy loam.

A study of the effects of shifting and continuous cultivation of cassava (*Manihot esculenta*) intercropped with maize (*Zea mays*) on soil chemical properties of an alfisol in south-western Nigeria showed that soil organic matter, total N, exchangeable Ca, K, and Na, CEC and pH declined under cultivation compared with forest (Table 5). The soils were classified as ferruginous tropical soils and alfisols. Generally, the soils had coarse-textured surface layers with a clay-enriched subsoil. The effects of varying lithology and catena on

soil characteristics were minimized by sampling soil formed from granite-gneiss parent material and by locating all sample plots in the middle slope segment (the colluvial zone) of the catena.

Table 6. Properties of the 0-10cm layer of soil under forest and cassava intercropped with maize under shifting and continuous cultivation at three sites in Nigeria, 1990. Values are means $\pm$ SE. (From Aweto *et al.*, 1992).

	Rainforest	Cassava/maize shifting cultivation	Cassava/maize continuous cultivation
Organic matter (%)	4.94 $\pm$ 0.33	2.34 $\pm$ 0.17	1.47 $\pm$ 0.12
Total nitrogen (%)	0.28 $\pm$ 0.02	0.14 $\pm$ 0.01	0.08 $\pm$ 0.002
Exchangeable Ca (mmol kg ⁻¹)	44.75 $\pm$ 2.25	27.10 $\pm$ 1.90	24.65 $\pm$ 1.95
Exchangeable Mg (mmol kg ⁻¹)	12.15 $\pm$ 1.00	6.25 $\pm$ 0.30	12.15 $\pm$ 1.00
Exchangeable K (mmol kg ⁻¹)	4.80 $\pm$ 0.30	2.60 $\pm$ 0.20	2.10 $\pm$ 0.30
Exchangeable Na (mmol kg ⁻¹)	3.70 $\pm$ 0.10	3.40 $\pm$ 0.10	3.30 $\pm$ 0.10
Cation exchange capacity (mmol kg ⁻¹)	66.02 $\pm$ 2.74	40.10 $\pm$ 2.18	43.02 $\pm$ 2.98
Available P (mg kg ⁻¹)	3.80 $\pm$ 0.41	6.40 $\pm$ 0.51	3.20 $\pm$ 1.10
pH	6.9 $\pm$ 0.03	6.7 $\pm$ 0.04	6.5 $\pm$ 0.02

Continuous cultivation exerted a greater effect on soil organic matter, total N and available P status than did shifting cultivation. Aweto *et al.* (1992) suggested that inorganic and organic fertilisers and mulch should be applied to such cultivated soils to conserve their nutrient status. They suggest that following cropping for 1-3 years, fallows of 3-6 years are alone not capable of restoring fertility and that fertiliser should be applied. However, on tropical soils where there is a decline in the CEC due to soil organic matter decomposition during the cropping phase, the addition of inorganic fertilisers may be only partially effective due to susceptibility to leaching. Consequently, the conservation of soil organic carbon is a prerequisite for the maintenance of the soil nutrient status.

A comprehensive study of alley cropping on acidic soils high in exchangeable Al and low in fertility has been reported by Szott *et al.* (1991b). The quantities of nutrients supplied from the prunings of *Cassia reticulata*, *Gliricidia sepium*, *Erythrina* sp. and *Inga edulis* are presented in Table 6. This source could supply most of the macronutrients required by an average upland rice crop of 2t ha⁻¹ although P, K and N may be viewed as marginal. However, the nutrient recycling potential of these alley cropping systems was inadequate to support the higher nutrient demand of a crop such as maize. Supporting this is the

observations of Kang and Wilson (1987) who noted that the P content in *Leucaena leucocephala* prunings were inadequate for a single maize crop.

The efficient transfer of nutrients from prunings to the growing crop will in part depend on the synchronisation of nutrient mineralisation from the pruned material and nutrient demands by the crop, in relation to competition from microbes and tree roots for nutrients, and the rate of leaching. As stated previously the mineralisation rate of a particular nutrient is dependent on the quality of the prunings. In general, high quality is associated with a rapid decomposition rate and consequently nutrient release (Szott, *et al.*, 1991a). However, asynchrony of nutrient supply and demand in certain cropping systems may result in poor nutrient recovery from even high quality materials used as mulches.

Table 7. Average quantities of nutrients contained in the prunings of four leguminous tree species used in hedgerow intercropping systems. (From Szott *et al.*, 1991b)

Tree Species	Nutrient contents per pruning (kg ha ⁻¹)				
	N	P	K	Ca	Mg
<i>Cassia reticulata</i>	72	7	37	25	6
<i>Gliricidia sepium</i>	64	5	37	22	8
<i>Erythrina</i> sp.	67	6	36	16	7
<i>Inga edulis</i>	62	5	24	15	4
Mean	66	6	33	20	6

In the same study of Szott *et al.* (1991b) changes in soil chemical properties were monitored over 31 months. In both alley-cropped and sole-crop systems, neither of which received inorganic nutrient inputs, exchangeable nutrient cations declined to similar levels with time (Figure 1). Possible reasons for this were suggested as (1) the quantity of prunings, and therefore nutrients, applied to the alley cropped plots were too low to produce differences in soil nutrient levels; (2) the nutrients in the prunings were retained in organic or inorganic forms that was not detectable using routine analytical techniques; and (3) nutrients were removed in harvested crops or otherwise lost. In contrast, lime and fertiliser treatments did increase topsoil base status and available P which would have been expected since the amounts added were in excess of those likely to be removed by the crop. Soil acidity increased with time as evidenced by the decrease in soil pH and increase in exchangeable Al (Figure 1). Szott *et al.* (1991b) conclude that continuous alley cropping is unsustainable on acid, infertile soils without additions of fertiliser. This is largely due to the inherently low native fertility and insufficient nutrient cycling through prunings.

Long-term alterations in the chemical and nutritional properties of a relatively fertile tropical Alfisol used for row crops alone or in agroforestry systems have been reported by Lal (1989a,b,c,d,e). The study site was in a region where traditional farming systems use shifting cultivation and bush fallow rotations. The soil data (Lal, 1989d) indicated that intensive cultivation involving two sequential crops per year (maize and cowpea) for six years (i.e. 12

Figure 1. Changes in soil chemical properties (0-15 cm) in systems alley cropped with *Inga edulis*, *Cajanus cajan*, or cropped without trees. One of the treeless controls received lime and fertiliser, the other did not. (Source: Szott *et al.*, 1991).

consecutive crops) resulted in decreased soil organic matter, total N, pH and exchangeable bases in all systems. The plough-till treatment had the lowest organic carbon in the soil, probably due to rapid oxidation and accelerated soil erosion. Decreases in soil pH were accompanied by significant increases in total acidity. The cations on the exchange complex were depleted and replaced by Al^{3+} . Aluminium content of the 0-5 and 5-10 cm depths increased in all treatments. Differences in CEC among treatments were likely related to the

variations in soil organic matter content. Treatments with the least content of OC also had the lowest CEC and visa versa. The concentration of Ca^{2+} on the exchange complex in the 0-5 cm depth of the no-till treatment, slightly increased with increasing duration of cultivation. Similar increases were observed in the *Leuceana* and *Gliricidia*-based agroforestry systems. The initial increase in exchangeable Ca^{2+} during the 1 to 3 years of cultivation may be attributed to nutrient recycling from the subsoil. It is possible that the decline in exchangeable Ca^{2+} during the fourth year is due to depletion of Ca^{2+} in the root zone by crop removal under continuous cropping. There was a significant increase in exchangeable Mg^{2+} contents for the 0-5 cm depth in the no-till and all agroforestry treatments. There was a general trend for exchangeable K^+ to increase with cultivation duration. The exception, however, was the plough-till treatment. Decrease in exchangeable K^+ in the plough-till system was assumed to be due to depletion by crop removal and significant losses in runoff and soil erosion. An increase in soil contents of exchangeable K^+ in the 0-5 cm layer of the no-till treatment are probably due to the returning of crop residue to the soil surface.

Tilander (1993) reported the effects of mulching with *Azadirachta indica* and *Albizia lebbbeck* leaves on the yield of sorghum under semi-arid (mean annual rainfall 83 mm) conditions in Burkina Faso. Changes in soil nutrients, organic matter and pH were measured in the 0-30 cm depth interval. No clear effect of the mulch on soil properties could be documented. Even though contents of organic matter, total N and K as well as pH were higher in the leaf-treated plots than in the untreated ones after two growing seasons, there was relatively high variation between plots. The author concluded that the results reflect the general difficulty involved in detecting the effect of a mulch treatment on tropical soils in short term experiments. A probable reason for lack of significant differences between treatments may be related to the depth of soil sampling. It is suggested that in such studies smaller depth increments (5 cm) should be taken to detect changes which affect discrete parts of the soil profile.

Alley-cropping research continues today in many institutes in the tropics. The aforementioned results reflects some of the numerous observations made on the effects of alley-cropping on soil parameters. The positive results on crop yields as observed in the initial series of studies conducted by the International Institute for Tropical Agriculture (IITA) stimulated enthusiasm in this area of agroforestry which is still evident today. However, these initial results obtained in small research plots have been difficult, if not impossible, to reproduce under working farm management systems. One of the reasons for this is lack of proper controls in the small plot work because tree roots from neighbouring treatments could spread into control plots and depress yields. This raises the question whether alley cropping is "ecological pie in the sky?" (Ong, 1994). In an evaluation of results from alley-cropping studies undertaken by ICRAF Ong (1994) presented serious experimental and interpretational problems in much of the research. Furthermore, over half

the experiments showed alley-cropped maize yields were lower than the monoculture. In other cases increases in crop yields have been achieved through unrealistically high rates of mulch addition, about twice that which trees can produce. Based on ecological theory and limited data on tree-root profiles, there is growing agreement that competition between trees and crops is likely to outweigh the positive benefits of mulching the crop with tree prunings, especially on highly acidic and low-moisture soils (Ong, 1994). The strategy of using nitrogen fixing and fast growing trees to alley cropping systems may be counterproductive since their extensive root system may be too aggressively competitive with the crop. Ong (1994) suggests that it would be more worthwhile to use tree species with non-aggressive rooting habits selected from climax vegetation. In this respect tree species such as *Grevillea robusta* and *Markhamia lutea* show promise.

3.1.2. Silvopastural systems

In a silvopastural agroforestry system in a rubber estate in Kelantan, Malaysia, sheep grazing increased soil N, P, Ca and Mg levels and soil pH (Table 7). The grazed soil was significantly less acid than the non-grazed soil. The higher pH value of the grazed plot could be due to the large amount of ammonia produced from the hydrolysis of urea in sheep urine and cations being deposited from the sheep manure. Total N and available P were significantly higher in the grazed plot. The increased N was probably due to the increased input of organic matter from sheep manure. In the case of P, the increase could be attributed to the organic part of manure retarding P fixation by mechanically separating soluble P from the mineral part of the soil. The significantly high level of exchangeable cations (Ca, Mg and Na) under grazing compared to that in soil from the ungrazed plot was also due to the added manure and its subsequent decomposition.

Table 8. The effect of sheep grazing on the chemical properties of soil under rubber (From Jusoff, 1988).

Chemical Properties	Grazed	Ungrazed	t-value
Soil pH	4.3 ± 0.7	4.1 ± 0.4	**
N (%)	0.19 ± 0.01	0.14 ± 0.02	**
P (mg kg ⁻¹)	46.4 ± 1.2	15.0 ± 1.9	**
K (mg kg ⁻¹)	21.0 ± 0.1	28.7 ± 0.7	**
Ca (mg kg ⁻¹)	10.0 ± 0.4	6.9 ± 0.3	**
Mg (mg kg ⁻¹)	6.9 ± 2.1	4.3 ± 0.5	**
Na (mg kg ⁻¹)	37.6 ± 2.5	15.0 ± 3.5	**

Positive growth responses of the pasture species *Paspalum notatum* under the tree canopy of *Eucalyptus grandis* in Queensland has been linked in part to an effect of shade on the availability of soil nitrogen (Wilson *et al.*, 1990; Wild *et al.*, 1993). The grass under the trees had a greater proportion of green leaf, greater concentrations of nitrogen and potassium and greater moisture content than the grass in the full sun. Under a tree canopy there may be an additional benefit to soil nitrogen from accumulated leaf drop, which is likely to be more important under leguminous trees (Lowry *et al.*, 1988) than under eucalypts because of the low nitrogen content of their leaf litter (Wilson *et al.*, 1990).

Trees growing at low density in arid and semi-arid pastoral ecosystems have often been found to improve their understory environments. Compared to neighbouring grasslands, soils under tree crowns (canopies) have higher concentrations of organic matter, higher concentrations of available N and other nutrients, better physical structure and faster water infiltration rates (Belsky *et al.*, 1989, 1993; Kellman, 1979; Tiedemann & Klemmedson, 1973; Vetaas, 1992). In a study to determine the effects of trees on lightly, moderately, and heavy grazed savannahs in the presence of *Acacia tortilis* subsp. *spirocarpa* and *Adansonia digitata* (baobab), Belsky *et al.* (1993) observed significant differences in soil properties these are summarised in Table 8. Heavy grazing pressure and the denudation of sites appeared to be degrading the soils and largely obliterated the beneficial effects of trees on soil properties. The beneficial effects of trees on soil bulk density, water infiltration rate, soil organic -C and -N contents, and extractable nutrients were reduced or eliminated as grazing intensified. The lower bulk densities and higher infiltration rates in the crown zones of relatively undisturbed savannahs were most likely due to the higher soil organic matter contents resulting from tree litter and higher herbaceous productivity. As livestock numbers increased, soils were compacted by trampling and the aforementioned properties were lost. Increased N mineralisation rates of soil organic-N at the heavily grazed site compared to other sites were probably the result of loss of soil structure due to animal activity and / or to increased temperature and wetting/drying stress on bare soil. Higher microbial biomass levels at the heavily grazed site were consistent with enhanced N mineralisation. Trees improve site conditions in savannahs by adding organic matter and nutrients through leaf-fall, by reducing soil temperatures and water loss due to evapotranspiration and by attracting birds and large mammals whose droppings concentrate nutrients gathered over a wide area. These effects cannot easily be separated from each other. Where grazing intensity was low to moderate, the areas under tree crowns had a unique understorey flora and higher biomass, lower bulk densities, and higher levels of P, K, Ca, and mineralizable N than open grasslands.

In the moderately grazed site, soils associated with acacia trees had significantly more sand and less clay than soils associated with baobab. Soil bulk density was unaffected by the species of tree, however, the bulk densities of the surface (0-5 cm) soils were greater in the grassland than in the crown zones in the lightly and moderately grazed sites.

In southern Spain the term 'dehesa' is used for a land-use system in rural areas, mainly rangelands with scattered oak trees (*Quercus rotundifolia*, *Q. suber* and *Q. faginea*). The system has been known for many centuries for its multiple, mainly silvopastoral, use of renewable resources, and its strong linkages to recurrent cereal cropping in rangelands (Joffre *et al.*, 1988). In a study comparing soil chemical properties under the tree canopies and in the open, Joffre *et al.* (1988) found the following: (1) Under the trees, soil organic matter content, total exchange capacity, K, P, total N and C contents were twice those outside the tree canopy (Table 9); (2) Exchangeable Ca and Mg values were 1.5 times higher under than outside the canopy; (3) The same trends were observed both for the more biologically active surface horizon (0-5 cm), and for the second horizon (5-20 cm); and (4) differences were most marked on very poor soils. The increase in organic matter and nutrient levels in soils under tree canopies is due partly to leaf shedding and other litter fall but also to animal excretion since grazing animals are attracted to the scarce trees within these grasslands. Joffre *et al.* (1988) suggested that oak trees have the ability to extract nutrients from deep soil layers and concentrating them in the surface horizon, thereby making them available to herbaceous plants and consequently available to grazing animals.

Table 9. Summary of relative effects of native grazers and domestic livestock on vegetation and soils found below the tree crowns (Crown) and in open grasslands (Grassland) in three semi-arid (low-rainfall) sites in Tasvo National Park (West), Kenya. =, zones are similar; < and >, significantly lesser or greater levels in one zone than the other. Adapted from Belsky *et al.* (1993).

	Lightly grazed (native grazers)	Moderately grazed (native grazers + livestock)	Heavily grazed (livestock)
Soil temperature	Crown < Grassland	Crown < Grassland	Crown < Grassland
Soil particle size	Crown = Grassland	Crown = Grassland	Crown = Grassland
Soil bulk density	Crown < Grassland	Crown < Grassland	Crown = Grassland
Water infiltration rate	Crown > Grassland	Crown = Grassland	Crown = Grassland
Soil N, K	Crown > Grassland	Crown > Grassland	Crown > Grassland
Soil P, Ca	Crown > Grassland	Crown > Grassland	Crown = Grassland
Mineralizable soil N	Crown > Grassland	Crown > Grassland	Crown = Grassland
Microbial biomass C	Crown > Grassland	Crown = Grassland	Crown = Grassland

There are several reports of the influence of individual trees on microsite enrichment under trees and shrub canopies. In Miombo woodland in Zimbabwe changes in soil

properties were related to proximity to the tree trunk (Campbell *et al.*, 1988). In areas of open woodland, organic matter, extractable P and nitrate N were significantly higher in soils at the base of the tree trunk compared to several metres away.

In a study comparing changes in soil properties under a Neem (*Azadirachta indica*) fallow to that of abandoned farmland fallow, Radwanski (1969) observed increases in pH, organic carbon and total nitrogen under Neem but phosphorus was greater under the abandoned farmland fallow. Total cations, base saturation and cation exchange capacity were all higher under Neem. In a related species, white cedar (*Melia azedarach*) leaf litter was effective in significantly increasing soil pH exchangeable Ca and effective cation exchange capacity in a soil incubation study (Noble *et al.*, 1996).

Table 10. Main characteristics of soils collected beneath the oak tree canopy and in the adjacent grassland from a dehesa system in El Pedrosa, southern Spain. Adapted from Joffre *et al.* (1988).

	Oak canopy		Grassland	
	0-5 cm	5-20 cm	0-5 cm	5-20 cm
Organic matter (%)	7	5.2	4	3.2
CEC (cmol _c kg ⁻¹)	14	9	8	6.5
Exch. K (mg kg ⁻¹)	0.75	0.50	0.34	0.32
Exch. Ca (mg kg ⁻¹)	10	6	5.1	3.8
Exch. Mg (mg kg ⁻¹)	2	1.2	1.3	1.0
Organic C (%)	42	24	24	15
Total N (%)	3	1.65	1.8	1.1

The impact of trees on soil chemical properties is invariably positive as long as nutrient cycling is allowed to occur. This has been demonstrated in a study conducted in India evaluating the effects of *Populus deltoides* and *Eucalyptus hybrid* in combination with pastures of aromatic grasses (*Cymbopogon martinii* and *C. flexuosus*) on soil chemical composition after 60 months (Singh *et al.*, 1989). The litter of *P. deltoides* added annually 88.8 kg N, 43.6 kg P and 78 kg K per ha whilst the *E. hybrid* added 65.0 kg N, 23.8 kg P and 45.9 kg K per ha. These differences in nutrient deposition on the surface were reflected in changes in soil chemical properties in the 0-15 cm layer sampled. The increases over the grassland control from 33 to 83 % for organic carbon, 38 to 68% in available N, 3 to 32% in available P and 5 to 24% in available K. There was more fertility build up under a sole crop of *P. deltoides* followed by a sole crop of *E. hybrid* and aromatic grasses than when intercropped.

3.1.3. Plantation forestry

In contrast to agroforestry systems which have a cropping component, the influence of plantation forests on soil properties has been well researched and the results can be used to predict the long-term impact of high tree densities on soil properties. In Australia and New Zealand, several studies have been undertaken to evaluate the impact of these forests on soil properties. Concern has been expressed about the possible deleterious effects of pine plantings on soils, in particular *Pinus radiata* which has been suggested to be a strongly podsolising species (Hamilton, 1965; Khanna & Ulrich, 1984). Hamilton (1965) has shown that conversion of dry sclerophyll forest communities to pure stands of radiata pine can be accompanied by important changes in soil properties and although the A1 horizon proved to be most susceptible, alteration also extended into the deeper horizons of the solum. These effects included increases in colour value, bulk density, pH and C/N ratio, and decreases in loss-on-ignition organic carbon, total N, P, exchangeable cations, cation exchange capacity and soluble salts. Such trends suggest declining fertility for plant growth. Soils that developed beneath wet sclerophyll forest were texturally and morphologically much better soils than the dry sclerophyll soils, and had suffered substantially less or no reduction in fertility after conversion to radiata pine.

Studies of the influence of forests species on soil properties are difficult to interpret because it is difficult to separate the effects of species from those due to management e.g. harvesting (Turner & Lambert, 1988). Commonly, soils beneath exotic plantations may be compared to those on adjacent sites under vegetation similar to that existing prior to the establishment of the plantation (Turner & Kelly, 1985; McIntosh, 1980; Turner & Lambert, 1988; Musto, 1991). In such a study covering both low-fertility and relatively fertile sites, Turner & Lambert (1988) compared soil properties under *Pinus radiata* and native eucalypt forest. At the low-fertility site *Pinus radiata* decreased the soil pH, total N and exchangeable Mg but increased organic matter and exchangeable Al concentrations compared to the adjacent native forest. The *P. radiata* site also had lower soil water contents. They suggested that part of the difference in soil N content could be accounted for by greater accumulation of N in the biomass of the more productive *P. radiata*. At a relatively fertile site, concentrations of soil N and organic matter were lower under pine than under native forest but other properties were not significantly different. These workers suggest that soils at the lower end of the fertility range may be subject to accelerated nutrient depletion under pine, although in practice these are the soils most likely to be fertilised. The application of phosphatic fertilisers to nutrient-poor sites commonly leads to increased productivity with an accelerated increase in nitrogen accretion. On duplex soils nutrient depletion in the surface horizons may be more severe than on uniform or gradational soils. This results from the more intense exploitation of the surface soil by tree roots owing to physical impediments to root proliferation at depth. No evidence of accelerated podsolization was observed under the

pinus. In a similar study comparing plantations of *P. radiata* and *Eucalyptus regnans*, mineral soils under *P. radiata* contained less total nitrogen and exchangeable Ca but more Mg while the forest floor litter under pine contained more N, P, and K and lower Ca (Jurgensen *et al.*, 1986). Differences in mineral soil nutrient status had developed by 4 years after planting with more total N and exchangeable Ca but less exchangeable Mg in the top 40 cm of the soil under *E. regnans* than under *P. radiata*.

Feller (1983) has made similar observations on a 37 year old *P. radiata* plantation and a nearby *Eucalyptus obliqua* - *Eucalyptus dives* forest of the same age. Annual soil nutrient balance indicated more favourable balance of each nutrient (N, P, K, Na, Mg and Ca) in the soil beneath the eucalypts than in soil beneath the pines.

Will and Ballard (1976) have reviewed the effect of *P. radiata* on soil. They conclude "that there is no evidence to support the popular misconception that pure coniferous forests cause serious and irreversible soil deterioration". They add that where deterioration has occurred it has been the result of human mismanagement in allowing such practices as litter removal to occur, and failure to apply fertiliser to infertile soils. Similar conclusions were drawn by Carey *et al.* (1982) from studies in New Zealand investigating factors influencing organic matter and nutrient dynamics in forest floors of *P. radiata*. The forest floors of 41 first rotation and 7 second rotation stands of *P. radiata* contained on average 20.7 tonnes of organic matter per ha and 258 kg ha⁻¹ N, 18 kg ha⁻¹ P, 32 kg ha⁻¹ K and 33 kg ha⁻¹ Mg although there was considerable variation between forests. The forest floors in the second rotation contained on average twice as much organic matter and nutrients as in the first rotation. This was attributed to the fact that there was no burning of slash.

Comparing the impact of plantations of three timber genera (*Eucalyptus sp.*, *Acacia mearnsii* and *Pinus patula*) with grassland on chemical properties of soils, Musto (1991) observed significant soil acidification under the trees. Acidification appeared to be more severe under the eucalypts and acacia than under pine. On average, exchangeable Ca²⁺ levels of topsoils under eucalypt were only 57% of that of corresponding grassland soils suggesting that this tree species has a high demand for Ca. The depletion of Ca from the exchange complex resulted in an increase in exchangeable acidity. Declines in soil pH observed in *A. mearnsii* were suggested to be due to nitrate leaching after clear felling. Similarly Madeira (1989) observed substantial declines in exchangeable Ca²⁺ under *E. globulus* plantations in Portugal and ascribed this to the higher mineralisation rate of organic matter with increased disturbance of the soil, since the mineralisation of carbon and nitrogen are considered to be essential prerequisite to the leaching of bases.

Turner and Lambert (1983) noted that the Ca concentration in *E. grandis* was 3.5 times higher than that in *E. obliqua* mainly as a result of the higher Ca concentration in the bark, a feature common to all smoothed-barked *Eucalyptus* spp. Further, the decorticating habit of bark in *E. grandis* leads to an additional significant nutrient transfer within the

nutrient cycling system of these stands. Consequently, concerns may arise from the continual logging of these smoothed bark species which could critically affect the calcium status of the site. However, in-field debarking would overcome this problem to a large extent.

Eucalyptus grandis (flooded gum) has been utilised in plantation programs in Australia, southern Africa, Brazil, India and the USA. It is valued for its rapid growth rate and biomass accumulation with mean annual increments ranging from 35 m³ ha⁻¹ yr⁻¹ from stands in Brazil to 47 m³ ha⁻¹ yr⁻¹ on selected sites on the Zululand coastal plain in South Africa (Evans, 1984; Jacobs *et al.*, 1989). Intensive silvicultural practices benefited the growth of *E. grandis* with biomass accumulation in the treatment with fertiliser, herbicide and insecticide more than double the untreated control at 9.25 years (273.9 kg ha⁻¹ compared to 123.2 kg ha⁻¹) (Birk & Turner, 1991). The amounts of nutrient removed from the soil were substantial, exceeding removals by most other eucalypts of equivalent biomass. Fertilisers can replace nutrients removed through harvesting but the effects of high rates of uptake by plantations on site buffering capacities have yet to be determined (Herbert & Schönau, 1990). Competition between an understory of *Acacias* and *E. grandis* resulted in growth suppression, which is in contrast to studies showing that eucalypt biomass production in some plantations is enhanced by mixed plantings of N₂-fixing species such as *Acacia* and *Albizia* (DeBell *et al.*, 1985, 1988).

Eucalyptus camuldulensis plantations have been used to reclaim tin-mine spoils on the Jos Plateau of Nigeria. The hope was that the eucalypts would speed up the process of amelioration so that agriculture could be established on these sites within 20-30 years. By 1983, 15-20 years since their establishment, the plantation had had little impact on the morphology of the soils. Despite litter accumulation, large areas of the ground surface beneath the eucalypts remained completely bare and ground vegetation was very limited in extent, tending to be concentrated in wetter hollows. This was thought to be due to a combination of surface compaction caused during reclamation and the allelopathic properties of the eucalypt leaves. The eucalypts significantly increased the amount of organic carbon and total nitrogen in the soils. This was accompanied by an associated increase in CEC and a significant fall in both pH and base saturation. This decrease in base saturation and pH indicates that, under current management practices, the long-term effect of eucalypts is one of progressive degradation of already infertile sites. It was concluded that a change in management practices to allow the slash produced during coppicing of the plantations to be left to decompose in situ, may help to reduce the long term deterioration of the soil (Alexander, 1989).

In summary, tree plantations have a variety of desirable and undesirable effects on soils. Successive rotations of a single tree species may differentially deplete certain nutrients, resulting in diminished growth rates particular on soils with an inherently low fertility status. Complete tree harvesting may impoverish the site through the export of nutrients in the

harvested product. In addition, mechanical site preparation and harvesting may greatly increase erosion and lead to deterioration of soil physical parameters. These factors should all be considered when evaluating the impact of plantation forests on site quality.

3.1.4. Soil acidification amelioration by trees

Soil acidification in its broadest sense can be considered as the summation of natural and anthropogenic processes that lower soil pH (Krug & Frink, 1983). In forest ecosystems, natural acidifying processes include base cation uptake (by plants and microbes); natural leaching by carbonic, organic or nitric acid; and humus formation (Ulrich, 1980). Anthropogenic acidifying processes include biomass harvesting (Binkley *et al.*, 1989), land use conversion (Johnson *et al.*, 1988), fertilisation (van Breeman *et al.*, 1982), as well as atmospheric inputs of acidifying compounds (Reuss & Johnson, 1985). Barring the inputs of lime forest ecosystems developed on noncalcareous parent materials in humid environments will have or will develop acid soils.

Strongly acid soils, (those with a $\text{pH}_{\text{water}} < 5.0$), are commonly found throughout the humid tropics, subhumid tropics and temperate regions of the world. In Australia, soil acidification under pasture and ley farming systems is estimated to affect 17 million hectares. This acidity is largely due to the introduction of pasture and grain legumes which have played an important role in increasing productivity. The dominant processes contributing to the acidification of these soils is nitrate leaching and product removal (Helyar & Porter, 1989). In the case of nitrate leaching a corresponding counter ion (usually calcium and magnesium) must accompany the nitrate ion resulting in a depletion of exchangeable bases on the exchange complex. The same process occurs with excessive applications of nitrogenous fertilisers. This can result in several nutritional problems arising, such as, P deficiency, Mo deficiency and Al and Mn phytotoxicity.

Trees may play a role in reversing these effects through the development of deep root systems that are capable of taking up bases such as calcium and magnesium from deep in the profile and returning them to the soil surface as leaf litter containing organic anions. This would have a similar effect to liming on the surface. However, it should be noted that increases in pH on the surface would be at the expense of acidification elsewhere in the soil profile and that this potential biological pumping mechanism may be greater with tree species having litter with a high ash alkalinity and non acidic water-soluble organic extracts.

Some trees have shown potential for selectively accumulating certain nutrients. Sanchez *et al.* (1985) report that litter and detritus from *Gmelina arborea* contained twice as much Ca as that of virgin forest or mature pine plantation while the Mg content of litter was three times as much as in *Pinus* litter. Chijoke (1980) reports 117 and 161 kg Ca ha⁻¹ yr⁻¹ were returned in *G. arborea* litter for two plantations sites in Brazil. Trees that produce base rich litter may have the potential for ameliorating soil acidification on the soil surface.

The application of organic matter to aluminium toxic soils has increased crop yields by decreasing the activity of toxic Al species in the soil solution (Ahmad & Tan, 1986; Hargrove & Thomas, 1981; Bessho & Bell, 1992; Hue & Amien, 1989). With the addition of organic matter to soils there is an increase in soil pH and ionic strength of the soil solution which results in increases in CEC due to the generation of charge on the variable charge colloids. This results in an increased ability of the soil to retain nutrients.

Direct evidence of the influence of trees on increasing soil pH is scant. Dann (1992) mentioned that Tagasate (*Chamaecytissus palmensis*) growing on acid soil raised the pH beneath the shrubs.

Traditional agroforestry systems have utilised the concept of liming in order to improve crop productivity through the burning of plant material. The *chitemene* shifting cultivation system practiced in Zambia and parts of Malawi is an example. In this system, savanna trees cut from about 1 ha are piled up onto a smaller area and burnt, leaving a nutrient rich and alkaline ash. This has been shown to raise pH by up to 2.0 units. However, the nutrients have been accumulated, not only from the larger area of land, but over many years of growth.

3.1.5. Trees in Semi-arid regions

Rooting depths of 5-50m have been reported for desert, grassland, savanna and Mediterranean shrubland systems (Chaney, 1981; Kummerow, 1981). Many plants with a taproot capable of accessing water deep in the soil profile also have a lateral root system to utilise surface moisture and nutrient resources. The contribution of roots deep in the soil to the nutrient economy of a plant is poorly understood (Virginia *et al.*, 1986). In a large number of soils, plant nutrient availability typically decreases with increasing depth (Russell, 1973).

Woody legumes are often found in arid and semiarid environments, and having evolved under these specific ecosystems have developed physiological adaptations to water and salinity stress. They have the ability to symbiotically fix atmospheric N₂ and, in addition, several species have a well developed deep root system (Phillips, 1963; Allen & Allen, 1981; Felker *et al.*, 1981). The productivity of these woody legumes is determined by the availability of water and the ability of the soil to meet plant nutrient requirements other than N (Virginia, 1986).

Woody legumes such as mesquite (*Prosopis glandulosa*) produce two distinctive lateral root systems, as an adaptation to dry climates; one near the surface which is supported by precipitation, and another located at depth in the phreatic zone above the watertable (Virginia, 1986). Over 90% of the water used by the tree is derived from a permanent water table at 5 m depth. While prolonged periods of low water content in the surface soil limit the activity of surface roots during much of the growing season these roots may be important for

the uptake of nutrients released from decomposition of surface litter during brief periods following infrequent rainfall (Virginia *et al.*, 1986).

The alteration of soil properties by *Prosopis* can be related to the pattern of root distribution, litter decomposition and the water regime of the system. Both NO₃-N and PO₄-P accumulate in the surface and to a lesser degree, to depth in soils beneath *Prosopis* (Virginia, 1986). Values in excess of 900 mg kg⁻¹ NO₃-N have been observed to accumulate under mesquite canopies (Virginia & Jarrell, 1983). The concentration of NO₃-N decreases rapidly below the absorbing surface root system (0-60cm) which delineates the depth of infiltration and only reaches concentrations of 10% of that of the surface soil in the subsaturated zone (3.5-5.5m).

The increase in N beneath mesquite canopies is largely an accumulation of symbiotically fixed N. Root nodules have not been found in the surface root systems of mature trees (Virginia & Jarrell, 1983). From estimates of mesquite nodulating rhizobia it has been suggested that fixation occurs at depth and from measurements of naturally abundant ¹⁵N the stand derives 60% of its N from N₂ fixation.

The decomposition of litter that accumulates beneath *Prosopis* plants results in a marked increase in soil N. In contrast, very little N accumulates at depth near the watertable since this zone is continually moist and any N which is released from root and nodule turnover is taken up by roots. Consequently, a mechanism is in place to keep soil N from accumulating at depth in concentrations that would inhibit N₂-fixation (Virginia, 1986). In contrast, low water availability near the soil surface limits root activity to short periods and prevents complete uptake of mineralised and nitrified N.

It is suggested that in Africa there is a large reservoir of nitrate nitrogen at depth in soil profiles and that trees can tap into this source and pump it up for use by the crop. It is also claimed that if this nitrate was not pumped up it would pollute the ground water. The implications of such a mechanism are important from an agroforestry perspective. These woody legumes might act as N pumps by fixing N₂ at depth and depositing a portion of this fixed N on the soil surface as litter or through the turnover of surface roots (Virginia, 1986). This N may become available to less deeply rooted grasses or crop plants growing in association with the woody legume (Rachie, 1983).

3.1.6. Conclusions

1. The replacement of forest ecosystems by pasture and crops in shifting agricultural systems have invariably resulted in a decreased soil organic matter, N, P and the K content of soils. Agricultural productivity can only be maintained through the inputs of inorganic and organic fertilisers. However, on soils which are dependent on soil organic matter for their cation exchange capacity inorganic fertilisers may be inefficiently used due to susceptibility to leaching.
2. The efficiency of transfer of release of nutrients from prunings to the crops growing in alley-cropping systems will in part be determined by the synchronisation of nutrient mineralisation from the pruned material and nutrient demands by the growing crop, competing soil microbes and roots of the tree component, and the rate of leaching. The nutrient content of several species of trees used in alley-cropping systems have been shown to be inadequate to support the high nutrient demand of a crop of maize. In particular, phosphorus concentrations were extremely low and ineffective in supplying crop demands.
3. It is generally agreed that continuous cropping in the presence of an alley crop is unsustainable on acid, infertile soils without the addition of fertilisers, in particular phosphorus. This is largely due to the inherently low fertility and insufficient nutrient cycling through prunings. On all but the most fertile soils, productivity decreases with the intensity of soil use unless nutrients are imported to replace those that are leached or removed through product removal.
4. Based on ecological theory and limited data on tree-root profiles there is growing agreement that competition between trees and crops is likely to outweigh the positive benefits of mulching especially on highly acidic and low-moisture soils. The current strategy of introducing nitrogen fixing and fast growing trees to alley-cropping systems may be counterproductive since their extensive root system may be too aggressively competitive with the alley crop. It has been suggested that it would be more worthwhile to select trees with non-aggressive rooting habits from climax vegetation. In this respect species such as *Grevillea robusta* and *Markhamia lutea* may be of use.
5. In silvopastoral agroforestry systems, positive growth responses of pasture species under the tree canopy of *Eucalyptus grandis* in Queensland and has been linked in part to an effect of shade on the availability of soil nitrogen.

6. Trees growing at low densities in arid and semi-arid pastoral ecosystems (ie. the savannahs of Africa, Australia and the 'dehesa' system in Spain) have often been found to improve their understory environment. Trees improve site conditions in these savanna ecosystems by adding organic matter and nutrients through leaf-fall, by reducing soil temperatures and water loss due to evapotranspiration and by attracting birds and large mammals that add nutrients to the soil in their droppings.

7. In contrast to agroforestry systems which have a cropping component, the influence of man-made forests on soil properties has been well researched and the results can be used to predict the long-term impact of trees on soils. Despite several potential site improvements associated with trees, some site degradation may occur. Successive rotations of a single tree species may differentially deplete certain nutrients, resulting in diminished growth rates particular on soils with an inherently low fertility status. Harvesting and removal of complete trees may impoverish the site through the export of nutrients in the harvested product. In addition, mechanical site preparation and harvesting may greatly increase erosion and lead to deterioration of soil physical parameters. These factors should all be considered when evaluating the impact of plantation forests on site quality.

8. Selected tree species have shown potential for selectively accumulating certain nutrients. The litter and detritus from *Gmelina arborea* has been shown to contain twice as much Ca as that of virgin forest or mature pine plantation while the Mg content of litter was three times as much as in *Pinus* litter. The role of trees that produce base rich litter in managing acid soils needs further study.

3.2. Effects of trees on soil physical properties

3.2.1. Introduction

The physical properties of soils depends on the degree of aggregation between peds and the volume and size distribution of pores which determine available water holding capacity. Although these parameters are influenced primarily by texture and clay type, soil organic matter and fungal mycelia can bind soil particles into aggregates resulting in structural stability and desirable pore size distribution which in turn provides adequate water holding capacity, favourable permeability and aeration and resistance to surface erosion. The value of soil organic matter in this role is evident when its loss brings about surface crusting, compaction, and pan formations. Favourable physical properties are clearly essential for the efficient utilisation of nutrients by roots.

3.2.2. Water erosion

The loss of soil through water erosion has both a direct and an indirect impact on the environment. Productivity of the site decreases through the loss of nutrients contained in the topsoil while indirectly regional or catchment effects are manifested in high sediment loads being deposited in dams and storages structures. This ultimately reduces the long-term operating life of these structures. Several reviews and articles have been written with particular reference to the impact of forestry operations on soil, sediment and nutrient losses from point to catchment scale (Hopmans *et al.*, 1987; Grayson *et al.*, 1993; Norris, 1993). In this respect harvesting and extraction operations can have a significant influence on the amount of sediment and therefore nutrient loss from a catchment.

Young *et al.* (1989) suggested that there is a direct role and a supplementary role for the tree component in an agroforestry system in controlling soil erosion. In the direct role, trees act as barriers or soil cover. The barrier effect is through reduced runoff water velocity, thereby checking suspended sediment. Tree cover reduces the kinetic energy from raindrop impact that dislodges soil aggregates and, more importantly, increasing plant cover reduces runoff. However, there is evidence to suggest that tree cover may concentrate raindrops thereby producing larger drops which have the potential to generate greater kinetic energy. Trees serve their supplementary role through stabilising erosion control structures such as contour banks and making productive utilisation of land. Tree species with moderate to slow litter decay are to be preferred for erosion control (Young *et al.*, 1987). It is generally agreed that tree canopies in communities of bush fallows with varied strata are more effective than monoculture plantation crops, although runoff and erosion measured under plantation crops can be comparable to that under natural forest (Sanchez *et al.*, 1985).

In studies in an *Acacia auriculiformis* plantation in Java the removal of the tree canopy, undergrowth and litter on soil loss were compared. The canopy itself had little effect on soil loss whilst surface litter reduced soil loss by 95% compared to a bare fallow (Wiersum, 1985).

Trees often take 12-24 months to attain canopy closure in the humid to subhumid tropics during which time the soil surface is exposed to erosional forces since litter loads are insufficient to effectively protect the surface. The intercropping of cowpeas (*Vigna unguiculata*) between *Eucalyptus grandis* saplings on highly erodible coastal sands resulted in a dense protective soil cover being attained within 35 days thereby offering protection until canopy closure at 12 months (Noble *et al.*, 1991).

In studies undertaken in the a catchment in southeastern Australia, Grayson *et al.*, (1993) showed that harvesting and regeneration operations of an old-growth mountain ash (*Eucalyptus regnans*) forest did not have a major impact on the stream physical or chemical water quality. Increases were detected in turbidity, iron and suspended solids at baseflows, but these were small in absolute terms and of a similar magnitude to the measurement of

error. The suspension of logging during wet weather, the protection of the runoff producing areas with buffer strips and the management of runoff from roads, snig tracks and log landing areas eliminated intrusion of contaminated runoff into streams, thereby avoiding the adverse effects of logging. Annual sediment production from forest roads ranged from 50 to 90 t ha⁻¹ of road surface per year, with approximately two-thirds being suspended sediment and one-third coarse material. The use of gravel reduced sediment production, provided sufficient depth of material was used.. Grayson *et al.* (1993) concludes that by identifying areas that produce runoff it is possible to prevent contaminated runoff reaching the streams. Roads, on the other hand, produce large quantities of sediment, even when well maintained, so careful consideration of their placement and management is paramount.

A comprehensive review on the application and effectiveness of vegetated buffer zones maintaining water quality control has been undertaken by Norris (1993). Buffer zones were shown to work well on a small scale but were less successful on a broad catchment basis. It was important that runoff should enter a buffer zone as shallow, overland flow in order to be slowed or delayed. Excessive channel runoff would pass through a buffer zone unhindered. Therefore buffer zones close to sources of surface water were more successful in controlling water quality. The successful use of buffer zones for water quality control would require that they be comprehensively arranged along streams and around pollution sources in a catchment and therefore that a large proportion of a catchments area be set aside for this purpose. Considerable success in the establishment of buffer zones to reduce sediment losses from roads/firebreaks in plantations has been achieved through the establishment of Vetiver (*Vetiveria zizaniodes*) grass hedges (Nicholson, 1991).

Studies on sediment production from plantations of *Eucalyptus globulus* in India have shown that there is no net soil loss due to the presence of trees as long as the litter collection from beneath the trees is restricted (Samraj *et al.*, 1983; Venkataraman, 1983). It should be noted that the planting of eucalypts at high densities can suppress the growth and development of an understorey that acts as a ground cover; and if the litter layer is also removed this could result in severe surface erosion (Charles-Edwards, 1990).

Under plantation conditions the retention of slash after clear-felling can act as a natural mulch positively influencing soil temperature, soil moisture and physical properties such as infiltration rate, soil aeration and structural stability (Stigter, 1988). Soil microbial activities and the occurrence of microfauna will be influenced by the aforementioned factors as well as protecting the mineral soil from mechanical impact of rain, wind and heavy machinery.

In an alley-cropping study Lal (1989c) reported that runoff, erosion and nutrient losses were generally greater from maize grown in the first season than from cowpea grown in the second. Mean seasonal erosion from maize and runoff in the first season from a series of different management systems are presented in Table 11. The greatest amount of soil loss

and percent runoff was observed in the conventional tillage system, whilst no-till and the establishment of hedges of *Leucaena* or *Gliricidia* at different row spacings had a significant effect in reducing these losses. There were high losses of Ca and K in water runoff from the plough-till treatment. In contrast to runoff and erosion, losses of bases in water runoff from agroforestry treatments were relatively high; the high concentration of bases in runoff was probably due to nutrient cycling from depth by the deep-rooted perennials (Lal, 1989c).

Table 11. Mean seasonal erosion and percent runoff from maize grown under different management systems.

Management system	Seasonal erosion (t ha ⁻¹)	Mean runoff as percent of first season (%)
Plough-till	4.30	17.0
no-till	0.10	1.3
<i>Leucaena</i> - 4m spacing	0.57	4.9
<i>Leucaena</i> - 2m spacing	0.10	3.3
<i>Gliricidia</i> - 4m spacing	0.64	4.3
<i>Gliricidia</i> - 2m spacing	0.60	2.4

3.2.3. Wind erosion

In Australia the combined effects of drought, overgrazing and cropping, together with high winds, have resulted in significant wind erosion on soils considered to be erosion free in their undisturbed state. The establishment of windbreaks, shelterbelts and retention of natural stands of trees, along with sound grazing management practices can have a positive role in protecting soils from wind erosion (Booth & Jovanovic, 1991).

The planting of trees and shrubs is instrumental in protecting the soil from wind erosion through retarding the movement of soil particles. On the coastal sandplain of the southern Cape, South Africa, the introduction of strip-cropping systems was adopted in response to wind erosion (Lefroy, 1994). Initially, strips of natural grassland were left uncleared as protection from prevailing winds and crops grown between them. However, these strips were subject to overgrazing and degraded through sand drifts. The establishment of the fodder shrub *Atriplex nummularia* (old-man saltbush) on these strips have virtually eliminated wind erosion. Similarly, the establishment of *Chamdecytisus palmensis* (tagasaste) and *Acacia saligna* on sandy soils of Western Australia have resulted in protection of soil from wind erosion (Lefroy, 1994). The higher clay percentages found under *Acacia albida* and *Prosopis cineraria* may in part be explained by the trapping of particles during dust storms (Mann & Saxena, 1980).

The most promising spatially zoned system for soil conservation is hedgerow intercropping. Hedges are established on the contour and provide a semi-permeable barrier to wind while their prunings augment soil cover particularly when ground cover is sparse during the early part of the growing season of the crop. Under plantation conditions, trash left after clear felling is often burnt in order to reduce fuel loads and assist in land preparation for subsequent tree crops. Depending on the intensity of the burn, the soil surface is exposed to erosion forces. In studies conducted on coastal sands in South Africa the maintenance of a ground cover in the form of branches and leaf litter after clear-felling of pure stands of *Eucalyptus grandis* significantly reduced the amount of sand blasting of young seedlings and soil loss from the compartment (Schumann, 1993).

Leguminous trees can alter the physical properties of the soil beneath the canopy. Wind-blown soil particles and litter can be trapped by the surface root and stem system of the plant resulting in an accumulation of sand near the base of the plant. The sand content of the surface 30 cm of soil beneath mesquite trees was 43.4%, compared to 30.3% for the soil between plants (Virginia & Jarrell, 1983). The higher sand content along with an increase in soil organic matter beneath the tree canopy would result in increased infiltration beneath the tree thereby reducing surface flow during infrequent but intense precipitation events. Tree legumes have been used to stabilise soil and provide wind breaks for the establishment of other plants (Zollner, 1986).

3.2.4. Water repellency

Soils are normally completely wettable because of the strong attraction between soil particles and water molecules. It is not uncommon however to find soils showing resistance to wetting, i.e. they are water repellent, hydrophobic or hard-to-wet. Water repellency is of interest since it affects (i) the hydraulic properties of soils, and therefore the distribution and availability of water to plant roots, and (ii) the catchment behaviour (Scott, 1991). In most cases water repellency in soils can be attributed to coatings on the soil particles of hydrophobic substances of organic origin. In a eucalypt forest in Australia, water repellent soil caused greater run off from eucalypt forest relative to grassland (Burch *et al.*, 1989). Water repellent soils cause impeded infiltration and percolation, resulting in water moving along preferred paths through and over soil (Van Dam *et al.*, 1990). Preferred paths may be wettable zones or macro-pores in the soil profile, or they may be channels or rills on the surface. Gullyng, resulting from increased overland flow, may be associated with vegetation types causing water repellent soil (McGhie, 1981).

In a study of water repellency under plantations in South Africa, Scott (1991) found that soils under eucalypts have greater repellency than soils under other plantation tree species or native vegetation. In addition, wildfire through a plantation caused water repellency to be burnt off the surface soil but intensified it in the lower soil layers. Scott

(1991) suggests that forest managers should be aware of the tendency of eucalypt plantation soils to become water repellent and take heed of the resultant implications with respect to soil erosion and reduced water holding capacity.

Microphytic crusts may also significantly influence the infiltration of water into a soil profile. On the coastal sands of Zululand, South Africa, the development of microphytic crusts under young stands of Eucalyptus have been noted on several occasions. This can have a significant influence of water erosion during intense rainfall events.

3.2.5. Compaction

Compaction involves the rearrangement and movement of solid particles closer together. Fine grains are forced into the voids between coarse grains thus increasing bulk density. Compaction therefore modifies pore volume and pore structure which are reflected on a larger scale by changes in the packing state. It is important to note that compaction should not be confused with hardsetting referred to in some circles as natural compaction. While the effects of both processes on soil properties are similar eg. increase in shear strength, compaction is related to the application of an external whereas hardsetting refers to soils that set to a hard structureless mass during drying and wetting (Gupta and Allmaras, 1987). Although this condition can be exacerbated by cultivation it is essentially a naturally occurring phenomenon.

A major impediment to intensive land utilisation on upland soils in tropical environments is the rapid deterioration of soil physical properties (Lal, 1989c). Soil physical constraints can severely limit crop production and may take the form of compaction, high bulk density and penetration resistance, infiltration and water transmission properties, and soil moisture retention characteristics and depth of root penetration. Soil surface management systems that maintain these index properties at a level for optimum crop production are desirable for the long-term sustainability of a production system. Lal (1989c) reported significant changes in soil physical parameters over time in a tree based agroforestry system. In comparison with the pre-clearing control, soil physical properties deteriorated with continuous cultivation. The introduction of mechanised farm operations and the resultant soil compaction was an important factor responsible for soil degradation (Lal, 1985). A maize-cowpea rotation involving two crops per year brought about significant increases in bulk density and penetrometer resistance and a decrease in moisture retention at low suction. The relative decrease was, however, less in agroforestry compared with non-agroforestry systems. Over the 6-year period there were no significant differences in relative contents of sand, silt and clay for the 0-5 and 5-10 cm layers. The gravel concentration of the surface 0-5 cm and 5-10 cm layers increased significantly due to ploughing and mixing of the surface and subsoil layers. Soil bulk density of the 0-5 and 5-10 cm layers, respectively, increased in all treatments from initial values of 1.02 and 1.16 g cm⁻³ in 1982 to 1.43 and 1.65 g cm⁻³ at the

end of the cropping cycle in 1986. The maximum increase in soil bulk density was observed for the no-till treatment. Accordingly there was an increase in penetrometer resistance of the surface 0-5 cm layer from an average value of 25.3 kPa in 1982 to 210.7 kPa in 1986. The highest penetrometer resistance (353 kPa) of the 5-10 cm layer was recorded for the no-till treatment.

Within an established forest, macropores dominate the pore space and facilitate a rapid movement of water through the soil profile (Humbel, 1975). Afforestation of degraded soils is likely to improve soil physical properties and increase infiltration rate (Patnaik, 1978). Improvements in soil physical properties in tree-based systems are attributed to (i) elimination of surface soil disturbance (ii) presence of leaf litter that encourages activity of soil fauna, and (iii) ameliorative effects of root channels on total and macroporosity.

Soil compaction reduces porosity, especially macroporosity. On compacted forest soil in southern Australia, Sands *et al.* (1979) observed that the penetration of radiata pine (*Pinus radiata* D. Don) roots was severely restricted above a critical penetration resistance of about 3 MPa. In general, where roots are unable to use soil structural features to bypass the bulk soil, soil penetration resistance of between 3 and 6 MPa is found to terminate root growth and a penetration resistance of 1 MPa is likely to significantly reduce root growth rate (Bengough & Mullins, 1990).

There is a considerable body of literature devoted to the impact of forestry logging operations on the extent of profile disturbance and compaction (Greacen & Sands, 1980; Howard *et al.*, 1981; Butt & Rollerson, 1988; Wronski *et al.*, 1989; Soane, 1990; Rab, 1992, 1994; Ghuman & Lal, 1992; Lacey, 1993). The level and extent of profile disturbance and compaction vary with soil moisture content at the time of operations, inherent soil physical properties, slope of the site, the number of times a vehicle passes over the site and machine weight. Rab (1994) reported that logging significantly increased the bulk density and decreased organic carbon, organic matter, total porosity and macroporosity on over 72 % of the coupe area in a study conducted in southeastern Australia after harvesting of *Eucalyptus regnans*. On 35% of the coupe area, the snig tracks, log landings and subsoil disturbed areas of the general logging area, bulk densities and macroporosities reached critical levels where tree growth could be affected.

In a study of a silvopastoral agroforestry system with sycamore (*Acer pseudoplatanus* L.) and sheep in the UK, sheep were observed to shelter beside trees in preference to open pasture possibly resulting in damage to tree roots by treading and restricted root growth due to compaction (Wairiu *et al.*, 1993). Although matric water potential under the trees was generally greater than in the grassed rows between trees, mean penetration resistance in the 37 to 107 mm depth interval was significantly greater under the trees (Wairiu *et al.*, 1993). Even when the soil was close to field capacity, less than 10 % of penetrometer readings were

< 1 MPa under the trees, in comparison to 44 % in grassed areas between the trees. This demonstrates that significant surface compaction due to treading by the sheep had occurred.

3.2.6. Infiltrability

The infiltrability of undisturbed soils supporting tropical rainforests is generally high for both horizontal and vertical components of water flow (Lal, 1975; Wolf & Drosdoff, 1976). With cultivation, however, the infiltration rate of most upland soil declines because of the rapid deterioration in soil structure and susceptibility of these soils to the formation of surface crusts and sealing (Lal, 1986). Fallowing with various legume and grass cover crops is known to improve soil infiltrability (Pereira *et al.*, 1958; Lal *et al.*, 1978; 1979). The benefits accrued during the fallowing are, however, easily lost by cultivation (Lal, 1985; Wilkinson, 1975).

Soil infiltrability was evaluated once a year for five consecutive years in a long-term agroforestry experiment established on an Alfisol in western Nigeria. Continuous cultivation based on 2 crops per year caused drastic reductions in infiltrability in all treatments. The rate of decline was however, the most severe in no-till treatment. Following five years of continuous cultivation, the equilibrium infiltration rate was 8, 19, 21 and 24 cm h⁻¹ for no-till, *Gliricidia*-based, plough-till, and *Leuceana*-based treatments respectively. The decline in equilibrium infiltration rate was due to structural degradation, decrease in soil organic matter content and reduction in activity of earthworms and other soil fauna (Lal, 1989c).

A decline in infiltration rate with continuous cultivation with motorised farm operations on these soils has been observed (Lal, 1985). For sandy soils, soil compaction in no-till treatments can drastically decrease soil infiltrability. A major difference between this and the previous study lies in the fact that the rate of decline in infiltration rate is less with agro-forestry than food-crop systems. Tree based systems maintain favourable infiltration rates due to root channels and better soil structure than in food-crop systems.

Declining infiltration rates and saturated hydraulic conductivities are commonly observed after forestry operations. Rab (1994) reported significant decreases in saturated hydraulic conductivities after harvesting of a *Eucalyptus regnans* stand. The reduction in saturated hydraulic conductivity varied between 60 and 90 % for the disturbed areas. Rab (1994) concludes that the reduction in saturated hydraulic conductivity was likely to generate significant runoff, the frequency and magnitude of which would depend on the level of soil profile disturbance, soil compaction and rainfall duration and intensity. The majority of the runoff would be generated from snig tracks, log landings and subsoil disturbed areas of the general logging area.

3.2.7. Water holding capacity and extraction

A study conducted on an Alfisol in Nigeria using *Leuceana* and *Gliricidia* indicated that in the dry season hedgerows acted as windbreaks and reduced the desiccation effects of 'harmattan' winds. Soil moisture content at 0-5 cm depth was generally higher in the vicinity of hedgerows than in non-agroforestry systems. High soil moisture content was likely due to the reduced evaporation of soil-moisture and the effect of shade (Lal, 1989b).

In a study investigating the influence of boundary trees (*Acacia nilotica*) on the growth and yield of associated wheat crops under irrigated conditions in Punjab, Pakistan, the detrimental effects of the tree on yield did not extend beyond 8.5m from the base of the tree (Khan & Ehrenreich, 1994). The size of tree had less impact on wheat yields than distance from trees. It was assumed that the reason for reduced yields may be competition between tree roots and wheat for moisture, nutrients and space.

On conifer plantations in southwest Oregon, competitive understory vegetation often retards the growth and establishment of tree seedlings. In overcoming this problem livestock have been used to control understory vegetation and increase the availability of site resources to tree seedlings. Karl and Doescher (1993), concluded that repeated grazing of orchardgrass (*Dactylis glomerata* L.) reduced the transpirational surface area and root growth sufficiently to increase soil water availability to seedlings. They conclude by suggesting that prescribed cattle grazing on conifer plantations can enhance seedling physiological status by acting as a regulator of above- and below ground competition.

In most rangeland ecosystems of the Mediterranean basin, tree cover has been drastically reduced by human activity (Joffre & Rambal, 1993). However, there is a notable exception: the 'dehesas', which occupy almost 55 000 km² of southern and southwestern Spain and southern Portugal. Dehesas are characterised by the presence of a savanna-like open tree stratum dominated by three oaks, *Quercus ilex*, *Q. suber* and to a lesser extent *Q. pyrenaica*. These oak species have a density of 40 - 50 trees/ha and have been selected to produce sweet acorns for human and animal consumption (Joffre & Rambal, 1993).

The relative low tree density gives rise to two ecologically distinct components in the dehesa ecosystem: an open herbaceous layer dominated by annual species, and an area affected by tree canopy which includes an herbaceous stratum (Gonzalez Bernaldez *et al.*, 1969). Eagleson and Segarra (1985) have emphasised that, where a marked seasonality in water availability occurs, a mixed formation of grasses and woody plants is the only stable equilibrium state. Joffre and Rambal (1993) reported a water balance of the two ecological components of the dehesas namely; the tree-grass component and the open areas between the tree canopies with unshaded grass vegetation. The mean annual evapotranspiration was 400 mm outside the tree canopy and 590 mm under the tree cover in a region where the annual rainfall ranges from 600 to 800 mm. Of significance is that in the open areas (outside the tree canopy) the water yield defined as the sum of deep drainage and surface runoff, ranged from

65 to 100 % of the total evapotranspiration, whereas under the tree canopy water yield was only 20 to 40 % of the evapotranspiration. Under the tree canopy, when annual precipitation was < 570mm, water yield was negligible and all precipitation was lost as transpiration or evaporation by interception. Outside the tree canopy, water yield occurred as soon as annual precipitation exceeded 250 mm. These results show that both water storage and evapotranspiration are greater for the grass-tree component than for the grass alone. Koechlin *et al.* (1986) also described an improvement of soil water conditions under tree crowns. The environmental modifications caused by tree cover in the dehesas have shown that soils developing under the tree canopy are richer in nutrients and organic matter and have a greater water-holding capacity and a macroporosity favourable to infiltration and redistribution of soil water (Joffre & Rambal, 1988; Escudero, 1985).

Modelling of the transpiration from forest plantations is of importance in evaluating the impact of trees on soil water and water yield from catchments. In South Africa transpiration from forestry plantations accounts for a large proportion of the total rainfall in some catchments. Species such as *Eucalyptus grandis* are frequently planted on marginal forestry sites where trees experience periodic water deficits. Dye (1996) investigated soil water abstraction in 3 and 9 year old age classes of *E. grandis* under artificial drought conditions. He observed that there was considerable resistance to drought in these two age classes which could be explained by the depth of water abstraction. In the 3 year old stand water abstraction from the 1 and 8 m depth interval was estimated to account only 13.8 % of the sap flow, pointing to a heavy reliance on deeper soil water reserves. Deep drilling at this particular site revealed a permeable, stone-free and uniform profile extending down to 38 m. In the 9 year old stand abstraction of water between 1 and 8 m was estimated to account for 1.6 % of the sap flow and the trees survived almost entirely on soil water reserves below 8 m. Deep drilling at this site revealed live roots at 28 m below the surface. This is clear evidence of the ability of trees to exploit soil profiles to depth as long as there are no physical or chemical impediments to root proliferation. It is also clear that exploitation of historic water by young trees would have important implications for the long term sustainability of such plantings. In addition, Dye (1996) points out that modelling the water balance of such deep rooting zones is impractical for the purpose of simulating non-potential transpiration rates.

In a study undertaken to evaluate the effectiveness of two tree species (*Eucalyptus camuldulensis* and *Chamaecytisus proliferous*) and a pasture in their ability to reduce rising saline water tables, Eastham *et al.*, (1993) reported higher evapotranspiration and water depletion under the tree species when compared to the grass pasture. This was due to greater extraction to depth under the tree species. In addition, upward movement of water from the unsaturated zone was also greater beneath the deeper rooted perennials than under the pastures.

3.2.8. Conclusions

1. The major adverse effects of erosion are loss of soluble nutrients and organic matter as soil is washed or blown from site. This results in a decline in soil physical properties. Trees effectively slow down the rate of soil loss because they provide soil cover by the tree canopy and litter. The addition of organic matter increase the nutrient status of the soil, and subsequently improve structural stability and aggregation of soil particles and stimulate biological activity. The accumulation of organic matter can increase the water retention capacity of a soil and influence the soil fauna population, in particular, earthworms. Tree roots can also directly promote water infiltration and help to bind soil.
2. Under plantation conditions the retention of slash after clear-felling can act as a natural mulch positively influencing soil temperature, soil moisture and physical properties such as infiltration rate, soil aeration and structural stability. Such a mulch will also promote soil microfaunal and microbial activities as well as protecting the mineral soil from mechanical impact of rain, wind and heavy machinery.
3. Leguminous trees growing in arid environments can alter the physical properties of the soil beneath the canopy. Wind-blown soil particles and litter can be trapped by the surface root and stem system of the plant resulting in an accumulation of sand near the base of the plant. The higher sand content combined with an increase in organic matter beneath the tree canopy would result in increased infiltration beneath the tree thereby reducing surface flow during infrequent but intense rain.
4. Water repellency affects (i) the hydraulic properties of soils, and therefore the distribution and availability of water to plant roots, and (ii) the catchment behaviour. In most cases water repellency in soils can be attributed to coatings on the soil particles of hydrophobic substances of organic origin. Water repellent soils cause impeded infiltration and percolation, resulting in water moving along preferred paths through and over soil. Gullyng, resulting from increased overland flow, may be associated with vegetation types causing water repellent soil.
5. Compaction, high bulk density and resistance to penetration can severely limit crop production. These factors will influence soil moisture retention characteristics and depths to which roots can grow. Soil surface management to maintain these index properties at levels for optimum crop production are desirable for the long-term sustainability.

6. The environmental modifications caused by tree cover in the dehesas have shown that soils developing under the tree canopy are richer in nutrients and organic matter and have a greater water-holding capacity and a macroporosity favourable to infiltration and redistribution of soil water.

7. Modelling of the transpiration from plantation forests is of importance in evaluating the impact of trees on soil water and catchment yields. A study investigating soil water abstraction in two age classes of *E. grandis* (namely 3 and 9 years old) under artificial drought conditions, showed that there was considerable drought resistance which can be explained by the depth of water abstraction. In the three year old stand water abstraction from the 1 and 8 m depth interval was estimated to account only 13.8 % of the sap flow, pointing to a heavy reliance on deeper soil water reserves. In the 9 year old stand abstraction of water between 1 and 8 m was estimated to account for only 1.6 % of the sap flow and that the tree survived almost entirely on water reserves below 8 m. This is clear evidence of the ability of trees to exploit soil profiles to depth as long as there are no physical or chemical impediments to root proliferation. In addition, modelling the water balance of such deep rooting zones is thought to be impractical for the purpose of simulating non-potential transpiration rates.

3.3. Rehabilitation of saline/alkaline soils

3.3.1. Introduction

Large areas of land have become salinised in several parts of the world, but particularly in the semi-arid climates associated with irrigation schemes (Marcar *et al.*, 1993). For example in India and Pakistan 13 million ha have been estimated to have been affected by salinity and waterlogging. Dryland salinity is a major environmental concern in most states of Australia and is estimated to affect 776 000 ha (Schofield, 1991). The dominant cause of dryland salinity in agricultural areas has been the clearing of native vegetation and its replacement with annual agricultural species (Schofield *et al.*, 1989). This has resulted in a reduction in the quantity of water transpired by vegetation and has led to groundwater rising. The planting of trees has been shown to increase annual rainfall interception and transpiration, thus reversing the effects of clearing the original vegetation (Greenwood, 1986).

The scope for various reforestation strategies to reduce stream salinity have been discussed by a number of authors (Schofield *et al.*, 1989; Squires, 1995; Khoo, 1994; Farrington & Salama, 1996; Walsh *et al.*, 1995). Agroforestry trials using mainly eucalypts planted in recharge areas resulted in reduction of the saline watertable. Results of investigations in Western Australia on the groundwater response to intensive plantations

show substantial lowering of the watertable level beneath the plantations (Schofield *et al.*, 1989).

Bell *et al.* (1987) have reported on streamflow data after reafforestation of a Western Australia catchment to a level of 81% forest cover. Results show a dramatic reduction in streamflow and salt discharge in the first 9 years following treatment. It also resulted in increased stream salinities in rainfall years below 800 mm yr⁻¹ and decreased stream salinities in rainfall years above 800 mm yr⁻¹.

3.3.2. Species tolerance to saline/sodic soils

Many tree species may be unaffected by relatively low soil salt concentrations (EC up to 5 dS cm⁻¹), however, their survival, growth and water usage will inevitably be affected at higher salt concentrations. In this respect saline drainage water which can often have salt concentrations of 10 dS cm⁻¹ or higher would significantly reduce growth and water usage of pulpwood species such as *E. grandis*, *E. globulus* and *E. camaldulensis* (Stewart, 1988). More salt tolerant but less productive species, such as *E. occidentalis*, *E. microtheca* and *Cassurina glauca* could be used. However, where the EC of the groundwater exceeds 15 dS cm⁻¹ the long-term productivity of even salt tolerant species is questionable (Morris & Thomson, 1983). Studies from India and Pakistan have identified *Prosopis juliflora*, *P. chilensis*, *P. alba* and *Tamarix aphylla* as highly tolerant to salt and *Acacia tortilis*, *E. camaldulensis*, *Casuarina equisetifolia*, *Azadirachta indica*, *E. tereticornis*, *E. microtheca*, *Acacia auriculiformis* and *A. nilotica* are all moderately salt-tolerant (Jain *et al.*, 1985; Sheihk, 1987; Singh 1989; Yadav, 1989). Several salt tolerant native Australian tree species have been identified for both temperate and subtropical zones. For details of species the reader is referred to Macar *et al.* (1993).

The major constraints to plant growth on sodic soils are: (i) poor physical conditions and correspondingly poor aeration when wet; (ii) nutritional imbalances including deficiencies of calcium and magnesium (due to high pH); and (iii) phytotoxicity of selected ionic species, e.g. sodium and boron. Tree species that have a proven record for high sodicity (pH>8.5) tolerance include *E. tereticornis*, *E. camaldulensis*, *Prosopis juliflora*, *Acacia nilotica*, *A. auriculiformis* and *Zizyphus spp.* (Khanduja, 1987). Recent studies in Pakistan have also shown that *A. modesta*, *A. stenophylla*, *A. ampliceps*, *P. chilensis*, *P. siliquastrum*, *P. alba* and *Casuarina obesa* are all high tolerant of sodic soils.

Shrub species such as *Suaeda fruticosa*, *Kochia indica* and *Atriplex amnicola* show a 50 % reduction in growth relative to controls at salt concentrations ranging from 33 to 48 dS m⁻¹. This compares favourably with tree legumes such as *Prosopis juliflorus* and *Acacia cambagei* which showed a 50 % reduction in growth at about 27 dS m⁻¹, and wheat with a 50% reduction at 15 dS m⁻¹ (Aslam *et al.*, 1993).

3.3.3. Impact plants on soil properties

Information on the direct impact of trees on the soil properties of saline/sodic soils is largely confined to that of sodic soils. From a soils perspective, significant accumulations of organic C, N, Ca, P and K have been measured in the surface horizons beneath *Prosopis* canopies (Barth & Klemmedson, 1978; Virginia & Jarrell, 1983). In addition to increasing the concentration of nutrients in the beneath-canopy soil, the relative abundance of some nutrients may be altered compared to the surrounding soil. Many woody legumes are salt tolerant and some species can tolerate salinities equal to that of seawater (Felker *et al.*, 1981). One of the mechanisms imparting salt tolerance to these tree legumes is sodium exclusion by roots (Eshel & Waisel, 1965). Since other cations such as Ca and Mg are not excluded by the plant, leaves will have a different relative abundance of cations than the soil on which they are growing. Over time the decomposition of the leaves beneath the plant canopy will alter the cation balance of the surface soil. Virginia & Jarrell (1983) found that the sodium absorption ratio of the surface 30cm beneath *Prosopis glandulosa* canopies was 7.9 compared to 17.3 for soil from between canopies.

A long-term field study was initiated in 1984 on an alkaline soil abandoned for agriculture (pH 10.4 and exchangeable Na 90%) in the Karnal District of India (Singh *et al.*, 1989). Results indicate that abandoned alkali lands can be improved by growing *Prosopis juliflora* trees in association with *Leptochloa fusca* (Karnal grass) in a unified agroforestry system. *Leptochloa* growing in association with *prosopis* produced 46.5 t of green fodder per ha over a 50-month period in the absence of any fertiliser or soil amendment. The two species improved the soil to such an extent that it was possible to plough under the *Leptochloa* after four years and grow less tolerant species such as *Trifolium resupinatum*, *T. alexandrinum* and *Medicago* spp., under the *prosopis* trees.

After 52 months under *prosopis* and *Leptochloa*, soil pH decreased from 10.3 to 9.4 and electrical conductivity decreased from 2.20 to 0.42 dS m⁻¹ (Table 10). Organic carbon in the topsoil increased from 0.18 to 0.43 % and available nitrogen increased from 79 to 139 kg ha⁻¹. The phosphorus and potassium status of the soil decreased slightly, but water infiltration rate improved.

These results suggest that *prosopis* and *Leptochloa* are highly tolerant to alkali conditions. When planted together for fuelwood and forage production they appear to be useful species for exploiting abandoned alkali lands not economically reclaimable by conventional means. Where soil amendments are either scarce or too costly, this biological approach may be the only viable means of improving and managing salt affected lands.

Similar results have been observed have been observed under *Prosopis cineraria* when planted on alkaline soils. Soil pH was observed to decline from 8.2 in the open to 8.0 whilst the electrical conductivity under the tree was 0.01 mS cm⁻¹ compared to 0.22 mS cm⁻¹ under *P. juliflora* and 0.20 mS cm in the open (Shankarnarayan *et al.*, 1987). The reduced pH

beneath *P. cineraria* was attributed to higher organic matter contents and soluble Ca. In addition there was enhanced soil N-content due to higher leaf litter accumulation.

Table 12. Effects of prosopis-Leptochloa agroforestry system on an abandoned alkali soil 52 months after planting, measured at two soil depths.

Soil Property	Original Soil	Prosopis Only	Prosopis + Leptochloa
pH			
Soil depth: 0-15 cm	10.3	9.7	9.4
Soil depth 15-30 cm:	10.3	9.9	9.8
Electrical Conductivity (dS m⁻¹)			
Soil depth: 0-15 cm	2.20	0.66	0.42
Soil depth 15-30 cm:	1.50	0.78	0.63
Organic Carbon (%)			
Soil depth: 0-15 cm	0.18	0.30	0.43
Soil depth 15-30 cm:	0.13	0.19	0.21
Available Nitrogen (kg ha⁻¹)			
Soil depth: 0-15 cm	79.0	100.0	139.0
Soil depth 15-30 cm:	73.0	84.0	104.0
Available Phosphorus (kg ha⁻¹)			
Soil depth: 0-15 cm	35.0	30.0	22.0
Soil depth 15-30 cm:	31.0	32.0	19.0
Available Potassium (kg ha⁻¹)			
Soil depth: 0-15 cm	543.0	528.0	402.0
Soil depth 15-30 cm:	490	478.0	412.0
Water Intake Rate (cm / 48 h)	2.4	4.2	5.4

The establishment of *Eucalyptus tereticornis* and *Acacia nilotica* plantations in India have had a positive effect in reclaiming soils that were mildly saline (EC of surface soils 4.24 dS m⁻¹) and highly sodic (ESP of 97) (Gill & Abrol, 1993). There was a marked reduction in EC (from 4.8 to 1.8 dS m⁻¹), pH (from 10.6 to 9.5) and increase in soil organic carbon (from 0.3 to 0.9%) to surface soils which was associated with the presence of litter. Improved water storage allowed prolific growth of Kanak grass (*Leptochloa fusca*) between the rows of trees and the growth of this species further ameliorated soil conditions.

3.3.4. Conclusions

1. Dryland salinity is a major concern in most states of Australia and is estimated to affect 776 000 ha. The dominant cause of dryland salinity in agricultural areas has been the clearing of native vegetation and its replacement with annual agricultural species. This has resulted in a reduction in the quantity of water transpired by vegetation and has led to groundwater rising. Salinity *per se* is not a local scale problem but one that is linked to an entire catchment, consequently, planning either preventative or rehabilitation must be undertaken with off-site impacts in mind. The planting of trees has been shown to increase annual rainfall interception and transpiration, thus reversing the effects of clearing the original vegetation.
2. Agroforestry trials using mainly eucalypts planted in recharge areas resulted in reduction of the saline watertable. Results of investigations in Western Australia on the groundwater response to intensive plantations show substantial lowering of the watertable level beneath the plantations. However, interactions with geological structures and groundwater can have a profound effect on the efficacy of trees to achieve this.
3. Research results indicate that abandoned alkali lands can be improved by growing *Prosopis juliflora* trees in association with *Leptochloa fusca* (Karnal grass) in a unified agroforestry system. The two species improved the soil to such an extent that it was possible to plough under the *Leptochloa* after four years and grow less tolerant species such as *Trifolium resupinatum*, *T. alexandrinum* and *Medicago* spp., under the *prosopis* trees.
4. Significant accumulations of organic C, N, Ca, P and K have been measured in the surface horizons beneath *Prosopis* canopies. In addition, the establishment of plantations of specific eucalypts and acacia have resulted in significant declines in soil pH, EC and increase in soil organic carbon on soils affected by high levels of sodicity.

4. Agroforestry and Plantations on Farms in Australia

The clearing of trees in the coastal and subcoastal woodlands of Australia is a well established management practice to promote greater growth of native grasslands for livestock production (Wilson *et al.*, 1990) or to establish improved pastures or crops. Recognition of problems which follow excessive tree clearing has resulted in attention to the benefits of retaining trees in the landscape and to an interest in agroforestry as a means of minimising soil erosion and land degradation due to salt ingress.

The growing of trees in rural areas of Australia has changed significantly over the past decade. Primary producers have become aware of the value of trees in maintaining the general well being of their land, for income diversification, for increasing agricultural production and the development of sustainable farming systems (King, 1994). The perceived benefits of establishing trees on farms are as follows:

1. Trees provide a habitat for indigenous wildlife which act as predators of insects commonly associated with agricultural enterprises.
2. Prevention of saline discharge.
3. Reduction in soil erosion by wind and water.
4. Increased agricultural production. Crops grown near shelterbelts (windbreaks) can out yield crops grown in exposed paddocks.
5. Trees provide protection to livestock. Higher lamb survival rates, greater off-shears survival rates, increased milk production, better weight gain by meat-producing animals and greater wool production have all been reported as benefits
6. Trees can provide marketable products such as seed, essential oils, flowers and branchlets for floral arrangements.
7. The production of commercial timber species in plantation systems.

Although all of these factors may have a net benefit there is a reluctance by many producers to integrate agroforestry into their production systems. Although it is beyond the scope of this review to discuss reasons for the poor adoption of agroforestry systems some of the pertinent constraints are the high costs involved in tree-establishment, the inherent risks and lack of markets for agroforestry products. Price (pers. communication) summarised the three issues preventing the adoption of agroforestry in Australia under three headings:-

1. Technical failure.
2. Market failure.
3. Government failure in its ability to guarantee resource security and policies inhibiting agroforestry.

One of the most commonly anticipated uses of tree biomass produced from on farm woodlots or other agroforestry systems in Australia is for firewood from stemwood (Allender, 1987). In addition, other products such as pulp chips (from stemwood), wood fuel chips

(from braches and foliage) and cellulose feedstock for industrial purposes like manufacturing plastics, chemical and liquid fuels, are possible (Whitehead *et al.*, 1988). When viewing current tree planting programs to reclaim salt affected lands, many salt-tolerant species would produce firewood of adequate quality, however, very few species (e.g. *E. camaldulensis*) have proven good-quality pulping characteristics.

For more information on agroforestry systems for the higher rainfall regions of Australia the reader is referred to Race (1994). He discusses various agroforestry systems and their management that have been implemented in Victoria, the results of which would be applicable to the higher rainfall regions of the continent. In contrast to the higher rainfall regions which comprise a relatively small part of the land mass, the drier and semi-arid zones make up a major portion of the continent. In developing agroforestry strategies for these regions examples from Western Australia have been drawn upon.

Agricultural development in Western Australia has involved extensive clearing of natural vegetation and consequently considerable land degradation has resulted due to wind erosion and salinisation. An interest has developed in trees to reduce land degradation and improve productivity. The climate of this region is Mediterranean with winter dominant rainfall ranging from 300 to 1200 mm, depending on latitude and distance from the coast. Farming systems are dominated by extensive sheep and cattle grazing and dryland winter cropping with the major crops being wheat and lupins.

One agroforestry strategy currently being tested is livestock grazing between widely spaced tree species such as *Pinus radiata*, *P. pinaster*, *Eucalyptus globulus*, *E. maculata* and *E. saligna*. The trees are grown for high-quality sawlogs or pulp wood and pasture productivity is maintained by wide spacing and high pruning of the trees. Economic analyses showed that mixed trees and grazed pasture can be substantially more profitable than grazing alone (Malajczuk *et al.*, 1984). In addition, there is clear evidence to suggest that widely spaced stands of trees can lower watertable levels thereby reducing the risk of salinisation (Schofield *et al.*, 1989). However, the long-term viability of vegetation-based strategies alone for the reclamation of salt affected soils, reuse of saline drainage water and/or industrial and domestic effluent disposal is questionable. Without adequate leaching fractions to reduce the salt concentration within the root zone, even the most tolerant of plant species will eventually succumb.

In the low rainfall zones of Australia trees and shrubs represent a major source of animal fodder in commercially viable agroforestry systems (Lefroy & Oldham, 1992). The three main species used in southern Australia are tagasaste (*Chamaecytisus palmensis*), salt bush (*Atriplex spp.*) and acacias (mainly *Acacia saligna*) and the area planted to these species amounts to 30 000 to 40 000 ha (Lefroy & Oldham, 1992). Tagasate has been successfully established on deep infertile sandplain soils in the 400 - 500 mm rainfall zone of Western Australia. These hedges are spaced approximately 5 m apart and at a density of

approximately 1 000 stems ha⁻¹. The productivity from these hedges is estimated to be around 3 000 kg ha⁻¹ yr⁻¹ of dry matter which is considerably higher than from annual species. Approximately 10 000 ha of saltbush has been established on saline soils in Western Australia (Lefroy & Oldham, 1992). Constraints to further use are poor establishment from seed and low nutritive value of *Atriplex spp* due to high concentrations of sodium. A diet of around one-third saltbush and two-thirds grass may be more appropriate and have significant implications for reducing the cost of establishment and increasing the productivity of revegetated saline land (Lefroy & Oldham, 1992). In addition, low productivity of *Atriplex amnicola* has been observed on salt-affected duplex soils at Tammin, Western Australia (Davidson *et al.*, 1993). The main contributing factors were the shallowness of the sandy soils, the density and impenetrability of the clay subsoils to plant roots, the extreme heterogeneity in salinity and waterlogging (Davidson *et al.*, 1993).

The objective today is to establish salt tolerant grasses in broad inter-rows between widely spaced rows of saltbush rather than pure stands of either. Approximately 5 000 ha of *Acacia saligna* has been established in southern Australia despite the fact that *Acacia* species generally have a low feeding value due to the high levels of indigestible lignin and the presence of tannins which inhibit intake and limit the availability of protein to sheep (Lefroy & Oldham, 1992). It may be possible to introduce exotic rumen-microflora that are more adapted to breaking down these tannin-protein complexes and thereby increase the effective digestibility and nutritive value of these materials (Miller, 1991).

Lefroy and Oldham (1992) discuss 'alley-farming' as means of introducing fodder shrubs into commercial crop and pasture production systems. Alley-farming here is defined as growing these shrubs in hedgerows 30 - 50 m apart with crops or pasture between them. The success of such a system depends on demonstrating that the benefits of shelter on crops and animals and the provision of fodder outweigh the costs of establishment and loss of area devoted to the shrubs. This is of importance since as previously alluded to, the adoption of agroforestry in Australia will be largely driven by economics. The contribution of fodder trees and shrubs in such a system to livestock production still needs to be quantified.

In contrast to agroforestry systems for livestock production currently being adopted and investigated in parts of Australia, it may be more appropriate to investigate production systems that revolve around natural ecosystems and endemic animals. Such production systems are commonplace in several parts of Africa. For example, 'game' ranching in southern Africa has been shown to be financially lucrative as well as ecologically sustainable (Lefroy & Oldham, 1992). These systems utilise natural vegetation grazed by endemic animal species which are then hunted for their meat and other products.

While not a viable proposition in much of the semi-arid regions of Australia, the establishment of compartments of pure stands of commercially important tree species offers an alternative land use in the higher rainfall regions. Such systems are an integral component

of farming operations around the world. In North America (CRP, Conservation Reserve Program of the United States Federal Government), Brazil and South Africa farmers have adopted trees as a component in their farming enterprises. These may also include a livestock (cattle) and crop component (ie. sugarcane, maize, soybean etc.). Recently the New South Wales Government has established a tree planting program on privately owned land and anticipate establishing approximately 10 000 ha per year (Lambert pers. communication). A diversified farming system offers some buffer against price fluctuations and may result in more stable and sustainable land utilisation. As has been discussed previously the establishment of pure stands can have a major impact on the site both from a nutritional and water perspective.

There is a general perception tree plantations can be relegated to sites unsuited to agricultural production. Although this may be the case in certain instances (ie. waterlogged soils), in reality plantation productivity is a function of site quality. Consequently, there is the potential for direct competition between agricultural and timber enterprises. However, if timber production is viewed as an integral component of a farming enterprise it is doubtful whether this will be a major obstacle in adoption.

It seems clear from work undertaken in tropical environments, where soils are often acid and poorly buffered, with sloping lands and little opportunity for much fertiliser or other amendments, that organic matter build up may not be sufficient through green manuring, use of prunings or any other cultural practice to support high crop productivity. In these cases the establishment of alley-cropping or vegetation-contouring systems may have their greatest benefit in reducing soil erosion thereby allowing continued settlement to take place. In the Australian context it is neither good practice nor good economics to attempt to introduce agroforestry systems without adequate supplemental nutrition and soil amendments.

Of concern in the implementation programs to establish trees on farms, and in particular the establishment of pure stands, is the lack of information on the best species and provenances for specific sites, market prospects for products, risk analyses and long-term effects of trees on soil and catchments. This results in a lack of confidence by primary producers in the prospects for growing trees on farms. Key areas of concern regarding the current status and perceived gaps in our knowledge on the growing of trees on farms are identified in the Summary of Workshop Proceedings and are discussed later. However, it is the opinions of the authors that our understanding of site / species / provenance interactions with respect to Eucalypts is severely lacking and the basic infrastructure for the implementation of an ambitious planting program is lacking. In addition, it is doubtful whether seed stocks of desirable provenances (if defined) are available for projected planting programs and therefore the establishment of clonal nurseries would be required to provide desirable planting material. This in itself is a major undertaking judging by the problems experienced in Brazil and South Africa. It is suggested that comprehensive studies be

undertaken of the forestry industries in the aforementioned countries in order to avoid the pitfalls that are associated with plantation forestry.

5. Workshop on Effects of Trees on Soil Fertility

Summary of Workshop

The purpose of the three day workshop was to assist the Rural Industries Research and Development Corporation, the Land and Water Research and Development Corporation and the Forestry and Wood Products Research and Development Corporation in identifying research and development priorities in the field of agroforestry research in Australia. Several papers based on current or proposed work were presented by those invited to the workshop some of which are included in Appendix 1. Comprehensive discussions on research priorities were undertaken in interdisciplinary groups and the outcomes from these discussions were used in prioritising research and identifying areas where current knowledge is inadequate.

The first day of the workshop was devoted to the presentation of invited papers and the second and third days to the presentation of research proposals and prioritising research areas.

First Round of Group Discussions

Four groups were set up to discuss and establish perceived areas of research and potential constraints that may hinder achieving these goals. In the initial phase of setting research priorities the four groups suggested the following research issues that needed addressing:

Group 1.

Chairperson Dr Graham Sparling

1. Catchment scale hydrology

Water retention and infiltration rates of soils and their influence on the catchment as a whole.
Quantification of runoff, erosion and its control from catchments.
Wettability of soils and factors influencing this parameter.

2. Impact of grazing animals in agroforestry

Determination of carrying capacity of these systems.
Impact of management regimes on animal performance and site.
Nutrient transfers and cycling from the animal component.

3. Patterns of nutrient uptake under agroforestry systems and the biomass accumulation.

Patterns of nutrient uptake from the soil profile. Particular attention to root architecture and spatial influence of the tree component.

Influence of species composition of nutrient uptake.

4. Organic matter accumulation and turnover under agroforestry systems.

The decomposition and mineralisation of litter material from different species.

Influence of soil micro -flora and -fauna populations on nutrient turnover. In addition, the interaction and diversity of these populations on nutrient turnover.

Spatial influence of these populations on nutrient cycling.

Group 2.

Chairperson: Dr Snow Barlow

1. Site classification.

Site classification for the suitability of introducing trees into a landscape to be undertaken at both the catchment and farm scale. Specific emphasis on climatic and soil properties influencing site selection.

2. Long term effects of trees on soil.

Influence of trees on chemical and physical properties of soils with particular reference to soil pH and sodium. Both positive and negative effects should be quantified.

3. Tree effects on the soil micro environment.

The influence of trees on soil temperature and water need to be quantified.

4. Species and species by climate interactions under agroforestry systems.

Detailed studies on rooting patterns of different species.

Temporal and spatial influences of species on soil water and nutrients.

Group 3.

Chairperson Phil Scott.

1. Effects of trees on soil biology and nitrogen mineralisation.

Quantify effects of trees on the aforementioned parameters with special reference being made to the top 5 cm depth interval of the solum.

The use of indicator species in assessing the aforementioned parameters.

2. Ability of trees to intercept and use nutrients and water from depth with in a profile.

Quantification of rooting patterns and architecture of species.

3. Effects of trees on soil physical properties and soil loss.

Quantify the positive and negative effects of trees on soil physical properties.

Evaluate the influence of these physical properties on soil erosion.

4. Uptake and redistribution of salts by trees.

Quantify the effects of tree species on the uptake and redistribution of salts (ie. sodium) with in soil profiles.

Group 4.

Chairperson: Dr Peter Randall

1. Root growth and morphology.

Determine species difference in root morphology and architecture.

Evaluate the interaction of species with respect to nutrient uptake redistribution from profiles.

Interaction of tree species with respect to problem soils (ie. acid and saline soils).

2. Litter quality.

Determine quality parameters for litter material for different uses (ie. nutrient supply, soil organic matter, soil protection).

Identify indicators to predict litter quality.

3. Predicting rates of litter breakdown and mineralisation, temporal patterns and nutrient availability.

Quantify for both above and below ground components of an agroforestry system.

Quantify the influence of litters on soil characteristics such as pH, microbial biomass activity and soil temperature.

Evaluate sustainability of these systems in the context of nutrient additions and removals.
Development of predictive models.

4. Effects of particular species on nutrient availability to that species and to other species in the system.

Evaluate the selective nutrient requirements of particular species (ie. phosphorus and micronutrients).

Second round of Group Discussions

In a second round group meetings were asked to identify (1) the issues most constraining to agroforestry and (2) those participants issues which would provide technical information that will boost the uptake of agroforestry by primary producers. These are summarised below.

It was generally agreed that there is a lack of knowledge of the ecology of woody species used in agroforestry. This makes it difficult to recommend species combinations for soils with specific fertility problems such as saline and acidic soils, soils with physical constraints and unfavourable water relations. In addition, there is a need to investigate the potential to use species requiring low maintenance agroforestry these would include species for many purposes (ie. saleable product, fodder and for conservation purposes). It was suggested that a rigorously selected data base needs to be developed to enable advisers to provide site specific species recommendations for particular agro-ecological regions.

Selecting the appropriate species for particular sites was perceived to be a constraint to the adoption of agroforestry. The current knowledge base was moderate and both attractiveness and feasibility of this work were rated as high. Linkages between interested groups eg. Landcare, State research and extension agencies, other researchers and Greening Australia were considered important. It was suggested that a standard protocol for species x site trials should be developed in order to make better use of resources. In addition, existing tree databases such as GREX and TREEDAT should be assessed for incorporation into an overall species x site computer data base.

The long term biological, physical and chemical effects of trees on soils was considered to be an important area of research because they would determine resource sustainability. The existing knowledge base is poor and the attractiveness of this research was viewed as being high since the effects of agroforestry, be them positive or negative, need to be quantified. Linkages were identified with other projects ie CSIRO, Universities, State Government agencies, NGO, ACIAR, and industry. The outcomes from this research would yield

information on indicators of changes in site quality and methodologies for measuring and quantifying changes that have occurred. It would provide management options for primary producers.

The effects of trees on soil physical properties and soil loss (erosion) was viewed an area of research where information was needed. While the research was short term it would have long term implications. The use of existing models and their modification was viewed as a means of achieving these goals. This research would complement existing studies such as the National Windbreak Program which could serve as potential trial sites. Outcomes from this research would indicate quantification of the influence of tree canopies in reducing the erosivity of rainfall and the identification of erodible soils and determinates of the long term implications of agroforestry on soil physical properties and soil loss.

The sequestering and use by trees of excess nutrients in the ecosystem was viewed as an important area of research. This could have short term implications in that the 'leakiness' of a system with respect to nutrients would be identified. This research would link into work on catchment hydrology and nutrient movement. Existing knowledge in this area is low and the degree of difficulty in achieving desired outcomes was viewed as high. There is a perception that agroforestry systems are more efficient and less prone to 'leakiness', but very little evidence to support or discredit this hypothesis.

A final research area identified is the effect of trees on soil biology and nitrogen mineralisation with particular reference to the top 5 cm of soils. The research would provide short term indicators that could be used to predict long term trends. Outcomes would be response curves of biological activity (linked to soil organic carbon), the development and validation of predictive models, quantification of spatial variation and nutrient production. Studies could be made of existing sites under different climatic conditions in order to take advantage of existing resources and infrastructures. The existing knowledge base was moderate to high and difficulty perceived to be low.

Final Round of Discussion

From the research and development priorities identified earlier, the workshop was asked to develop three priority areas which covered the issues and constraints identified. These were as follows:

- 1. Use of (excess) nutrients and water by agroforestry systems taking into consideration root architecture.**
- 2. Influence of agroforestry systems on soil physical, chemical and biological properties.**

3. Information on the best species combinations for different climatic zones, water availability and different soils - sodic soils, acidic soils, soils with structural and physical problems. The information would be made available in a tree database.

The workshop discussed the establishment of a number of key sites representing different agroforestry systems in different regions of Australia. The following matrix was drawn up with 6 combinations.

Agroforestry system	Location	
	Summer rainfall regime	Winter rainfall regime
Tree/pasture	Northern Queensland Profitability/conservation	WA Productivity/conservation
Tree/pasture/crop	Southern Australia Windbreaks/watertable	Southern Australia Windbreaks/watertable
Shrubs/tree/pasture/crop	Rockhampton leucaena Productive/conservation	WA Productivity/conservation/water

It was considered that such a concept was useful for planning purposes. Established sites representing at least some of these combinations may already exist. Some effort should be put into identifying and evaluating such sites as they may provide a valuable resource for a variety of research and extension projects and a focus for collaborative work.

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Appendix 1

Forest into pasture and pasture into forest: Impacts on soil organic matter and nutrient contents

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Summary: Forestry operations can have both a negative and positive effect on soil nutrient status and organic matter content. Clearance of native forest for agriculture usually results in the loss of nutrients in tree biomass, though there may be short-term nutrient releases after clearing operations and burning. Conversion to an agricultural output is much more exploitive of soil nutrients than longer-term use for forestry. Agroforestry combines aspects of both conventional forestry and agriculture and has the benefits and problems from both components. Some examples of changes in soil organic matter and nutrient status under native forests, agroforestry, plantation forest and agricultural use are given. Longer-term sustainable land use depends greatly on management, inputs, and patterns of use. There is a vast array of different agroforestry combinations which need to be carefully selected and managed to derive maximum benefit, in both economic, social, conservation and environmental aspects. There are advantages in using established methodologies in monitoring programs.

Forest into pasture

Mature forest ecosystems generally accumulate plant debris as forest floor material, which is then decomposed to humus and soil organic matter. Typically, levels of soil organic matter under native forests are greater than under agricultural use. However, greater organic matter does not automatically mean greater fertility and the amounts of 'plant available' nutrients in the mineral soil under native forests are usually very low. Most of the nutrients in forest ecosystems are concentrated in the living components, that is the living tree biomass plus the microbial biomass in the decomposing litter (Jordan, 1985). The litter and forest-floor material comprises additional nutrient reserves, but also originates from the living biomass.

Clearance of native forests for agriculture usually involves removing any saleable timber, and felling and burning of unwanted slash and understorey. A large proportion of the nutrient stock is exported from the site at this stage because the timber is removed. Modest amounts of nutrients are released into mobile plant available forms by the burning of trash (Miller *et al.*, 1955; Jordan, 1985) but when used for agriculture this resource can be depleted after only 1-2 years, because the annual offtakes from agriculture are very much higher than for a forest system. For example Boremann and Gordon (1989) show that temperate zone hardwood and coniferous forests are almost self sufficient in nitrogen over a 30-38 year cycle, but that a wheat or maize crop has an annual demand of 79 and 168 kg N ha⁻¹ respectively (Table 1). Nutrient deficiencies in cleared lands quickly become apparent, in contrast, organic matter takes many years to stabilise at a new, usually lower, level.

Nutrient and organic matter depletion are not inevitable, however, and with adequate inputs, soil organic matter contents and nutrient status of forest soils after conversion to agricultural use can be greater than under the original forest cover. There have been surprisingly few comparisons between soils after changing from native forest to agricultural use where factors such as soil type, climate and topography have all been comparable. Sparling *et al.* (1994) compared native forest with radiata pine plantation forest, and fertilised and non-fertilised grass pastures in New Zealand. They reported that, 120 years after the initial clearance, and 30 years after establishment of the current land use, organic C contents were only slightly lower in cleared land (Table 2). Grass pastures are known to benefit the accumulation of organic matter in soils (Grace *et al.*, 1994), and this change had apparently compensated for any earlier soil organic matter losses.

Table 1. Nitrogen self-sufficiency level (kg N ha⁻¹) for silvicultural and agricultural systems in the temperate zone (After Boreman and Gordon, 1989).

	Age (yr)	Harvest losses		Nitrogen sufficiency	
		Stems only	Whole tree	Stems only	Whole tree
Hardwood	30	136	266	+1.7	-8.6
Conifer	38	101	280	+3.1	-2.4
Wheat	1				-79
Potatoes	1				-84
Maize	1				-168

The soil nitrogen status was greater in the soils under pasture and also under radiata pine, compared to the native forest, this was interpreted as reflecting the benefits of legumes in the pastures, and the presence of lupin and gorse as nursery plants during the establishment of the pine (Table 2). As may be anticipated, P status was greatest on the fertilised pasture soil as a result of super-phosphate applications.

In contrast to the New Zealand pattern of land use, in the Highlands of Papua New Guinea the soils receive very little external input following traditional methods of forest management. Clearance is followed by “agroforestry” of “gardens” planted beneath mature shade trees retained from the original forest with addition of wood ash from trash and understorey. Sweet potato is the usual crop in the first year, followed by casava and bananas for 2-3 years, after which cropping declines with eventual reversion to forest and a fallow period of 10-15 years. However, because of increased population pressures and demand for

Table 2. Total C, N and P (kg ha⁻¹) in soil organic (litter plus FH) and mineral horizons (0-20 cm) in native forest (*Nothofagus*), after the establishment of pine (*Pinus radiata*), or fertilised ryegrass-clover pasture on a Dystrochrept in New Zealand.

Land use	Horizon	Organic carbon	Nitrogen	Phosphorus
Native forest	Litter/FH	28 909	613	64
	Mineral soil	81 900	2 583	756
	Total	110 809	3 196	820
Radiata plantation	Litter/FH	11 981	344	30
	Mineral soil	98 000	4 361	527
	Total	109 981	4 705	557
Ryegrass pasture	Litter/FH	nil	nil	nil
	Mineral soil	84 846	6 589	1239
	Total	84 846	6 589	1239

land, the current practice is to completely clear the land and sell the timber, the fallow period is shortened or completely absent, and cleared areas end up as a fire-climax ecosystem of canegrass characteristic of nutrient poor soil, with a large net loss of organic C (Sparling, 1991). Microbial C, a more labile fraction of soil organic matter, shows even greater change (Table 3).

Table 3. Changes in soil organic C and soil microbial C contents in topsoil after forest clearance in Papua New Guinea and New Zealand.

Ecosystem	Organic C (%)	Microbial C ($\mu\text{g g}^{-1}$)
Papua New Guinea		
Indigenous forest	13.80	990
Fire climax grasses	11.45	657
	-17%	-34%
New Zealand		
Indigenous forest	3.90	470
Fertilised pasture	2.58	550
	-8%	+17%

Pasture into forest

After European settlement in Australasia expended so much effort in converting forest into pasture or clearances for other land use, forestry and agroforestry options are now being reconsidered for this land. There are several factors driving the trend; (i) low prices for pastoral products have prompted a search for more economic land use; (ii) land degradation by erosion has required a program of soil stabilisation; (iii) trees have been planted as a catchment plan to ameliorate rising water tables, recharge areas and salinity problems, (iv) the value of shelter belts and windbreaks is now recognised; (v) motives for flora and fauna conservation such as habitat creation and forest corridors.

The organic matter and nutritional status of the agricultural land returned to forestry or agroforestry undergoes a series of changes (Noble and Randall, 1995). The nutrient status of former agricultural soils may well be better than the original cleared forest, reflecting the previous inputs of fertiliser. In contrast to agricultural use, under agroforestry and forestry use, there is frequently a reduction in fertiliser inputs, and consequently nutrient supply becomes much more dependent on cycling through organic matter.

At Tikitere, in North Island, New Zealand, an area previously under long-term (80 year) fertilised permanent pasture was used for an agroforestry trial. The existing ryegrass and white-clover pasture was planted with radiata pine at a culling ratio of 5:1. The trees were thinned and pruned after 3 and 9 years to achieve a final density of 50, 100, 200, and 400 saw-log quality stems per ha. The pasture was rotationally grazed by sheep. The establishment of radiata pine had a marked effect on pasture production, stock carrying capacity, soil nutrient status and distribution of organic matter. On the plots with 400 and 200 stems ha^{-1} , canopy closure was complete after 15 years and pasture production was negligible after this time (<2% of the initial amount), organic matter had declined by up to 20% in the top 7.5 cm and 17% in the 7.5-20 cm depth of soil, and the nitrogen status had declined by 43% and 15%, respectively (Table 4). The decline soil organic matter can be attributed to the shading out of pasture grasses, while the much lower N status reflects the loss of the legume component (Sparling, *et al.*, 1989).

Such a decline in soil N status is not desirable where good quality stock feed is required. However, such changes are beneficial in reducing the mineralisation of organic N and the leaching of nitrate into streamwaters (Dyck *et al.* 1985). Inhibition of the microbial nitrification process by compounds derived from trees may also be a contributing mechanism (Heng and Goh 1984; Dyck *et al.* 1985).

The pattern of tree planting can greatly influence the ability of the pasture component to survive in the presence of trees. At the Tikitere agroforestry project Radiata was planted in both a double row system at 100 stems/ha at 28 x 5 m spacing and at regular spacing of 10 x 10 m. In the double row system, pasture survived well in the inter-rows and soil N status remained similar to that of pasture with no trees. (Table 5).

Table 4. Total soil N (%) and mineralisable N ($\mu\text{g g}^{-1}$) under various planting densities of *Pinus radiata* into ryegrass-white clover pasture.

Final density	Total N	Mineralisable N
	Soil depth	Soil depth

(stems/ha)	0-7.5 cm	7.5-20 cm	0-7.5 cm	7.5-20 cm
Pasture	0.39a	0.17a	111a	27a
50	0.40a	0.16a	95b	18a
100	0.21b	0.08b	81c	21a
200	0.26b	0.15b	62d	22a
400	0.26b	0.13b	63d	23a
LSD (0.05)	0.71		13	

Within columns, figures followed by the same letter do not differ significantly.

Table 5. Influence of density and pattern of *Pinus radiata* plantings into pasture on mineralisable N ($\mu\text{g g}^{-1}$) contents in the topsoil.

Planting density and pattern	Soil depth	
	0-7.5 cm	7.5-20 cm
Pasture	142a	45.1a
100 stems at 10 x 10 m	(81)*	(21)*
100 stems at 3 x 28 m	124-128ab	30.4-45.0ab
400 stems at 5 x 5 m	77.5c	24.3b
LSD	15.1	

Within columns, figures followed by the same letter do not differ significantly.

*Data from previous season included for comparative purposes only.

Trees into degraded soils

At Tammin, Western Australia, *Eucalyptus spp* have been planted into degraded pastures as part of a catchment plan to alleviate rising water tables and salinity. Eucalypts, mainly *E. camaldulensis*, *E. occidentalis*, *E. platypus*, and *E. torquata* have been established on the yellow sandplain soil at the rate of about 625 trees ha^{-1} (ca. 4 m apart). The pasture species were mainly annual exotic grass weeds such as *Hordeum* and *Bromus*, with *Arctotheca*, *Trifolium*, *Lupinus* and *Avena* also present. The sites were examined 10 years after planting of the Eucalypts and compared with remnant native woodland dominated by *Banksia prionotes* and *Xylomelum angustifolium*.

The main effect of reforestation on organic C at these sites after 10 years was to accumulate C in the litter and FH horizons relative to a nearby pasture site. The native forest had the greatest overall C status and the pasture the least. However, there was a great deal of difference in the quality and type of organic material with the C:N ratio of the organic matter in both forested sites was very much higher than in the pasture site. Despite having the lowest overall C content, the rate of decomposition of the pasture organic matter (assessed by CO_2 respiration) was greater on the pasture ($0.96 \text{ kg ha}^{-1} \text{ h}^{-1}$) compared to the reforested area ($0.44 \text{ kg ha}^{-1} \text{ h}^{-1}$) and the native *Banksia* woodland ($0.37 \text{ kg ha}^{-1} \text{ h}^{-1}$).

Monitoring of soil parameters

There are many agroforestry systems all of which will have unique impacts on organic matter and soil nutrient levels (see review by Noble and Randall, Proceedings of this Workshop). To determine the impact of trees and agroforestry on soils, certain minimum data sets (MDS) need to be collected. The type and extent of data collection will depend on the intended end use and various schemes and MDS for chemical, physical and biological characteristics have been proposed (Doran *et al.* 1994). From the MDS it may be possible to derive additional information. For example, an estimate of soil bulk density can be obtained provided the MDS includes the sand, silt and clay fraction and total C content (Larson and Pierce 1994). Preferred methodologies have also been published by several organisations such as ISBF (Anderson and Ingram 1989), ASSS (Doran *et al.* 1994), and IBSRAM.

Standardised methodologies have advantages when comparing different ecosystems and for agrotechnology transfer.

Acknowledgment: This paper was prepared while I was the Senior Wheatgrower Fellow at the Department of Soil Science and Plant Nutrition, the University of Western Australia, with funding provided by the Grains Research and Development Corporation.

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Ecological interactions and nutrient relations tree-crop production systems

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The aim of this review is to identify the principal (and researchable) limitations to improvement of the productive potential and sustainability of land use systems at the 'forest-agriculture interface'. Interfaces are defined as those areas where different production systems merge to create regions in which the influences of each can be identified (ODA, 1994), i.e. the amalgamation, in space or time, of forestry and agriculture into agroforestry. More specifically, the review focus is on research which increases our understanding of the accumulation, utilisation and recycling of nutrients within tree-crop based production systems, leading to improved strategies for agroforestry production.

Agroforestry embraces a set of land use practices which are described as having the 'potential to increase productivity and provide multiple products while conserving resources' (Corlett *et al.*, 1992). Such a description is similar to that of sustainable agriculture, a practice that 'involves the successful management of resources for agriculture to satisfy humane needs, while maintaining or enhancing the quality of the environment and conserving natural resources' (FAO, 1989). Agroforestry is more formally defined as 'a collective name for land-use systems in which woody perennials are grown in association with herbaceous plants and/or livestock in a spatial arrangement, a rotation, or both, and in which there are both ecological and economic interactions between the tree and non-tree components of the system' (Young, 1989). Considerable effort has been applied to classifying agroforestry systems in (descriptive) terms of the various spatial and temporal arrangements of the components (e.g. Nair, 1991), but it would appear that farmers tend to incorporate trees within land use systems in a remarkably flexible way (Swift, pers.comm.).

The 'forest-agriculture interface', similarly, should not be perceived of as a rigid spatial or temporal delineation but, rather, the incorporation of existing forest 'into land use systems which benefit local people and fundamentally underpins them' (Shepherd, pers.comm.). Forest-agriculture interfaces often occur in remote locations, and the protection of such pockets of forest resources is not usefully served by intensifying the marketability of other farm produce; this simply results in transport problems for the local people, and risks flooding local markets and depressing prices.

Noting these caveats, the three key objectives of agroforestry given above (increased total yield, multiple products, and resource conservation) can be restated in socioeconomic terms as productivity, reduced vulnerability through diversification, and sustainability (after Conway, 1987); concepts which have analogous ecological hypotheses concerning overyielding, reduced yield variance and maintenance of resources (Anderson and Sinclair, 1993). It is difficult to know whether these are the actual or researcher-perceived objectives of farmers who adopt agroforestry; it may simply be that farmers leave useful trees in the landscape when clearing bush for crop cultivation in order to provide income at a later date, and then replant on the farm boundaries for purposes of demarcation and shelter (Shepherd, pers.comm.). It may also be that diversity of farm produce is the major concern of farmers because it reduces the extent to which the farmer is vulnerable to economic or environmental fluctuations (the 'sensitivity' or 'stability' of the land use system) and increases the ability to recover from such disturbing forces (the 'resilience').

Whatever, in order to meet rising demands for food production, agriculture in developing countries is expanding into lands that are marginal and relatively nutrient poor. Whilst soils in these areas can be enriched by fertiliser application, and thus support crop varieties that have been selected to accumulate large amounts of nutrients and utilise them by conversion into biomass production on highly enriched soils, such a possibility is limited by the cost and availability of fertilisers (Chapin, 1987). If a significant contribution to food production has to come from crops grown in relatively nutrient-poor soils, the emphasis must be on efficiency as measured by production from limited nutrient inputs (Clarkson and

Hanson, 1980); identifying these traits of plant species that successfully occupy infertile soils and selecting for these traits in breeding programmes.

Plants from nutrient-poor soils, however, are characterised by their small size, their tendency to have small, leathery, long-lived leaves, and their high root:shoot ratios (Chapin, 1980; Vitousek, 1982). The physiological adaptations of such plants include (i) adjustment of growth rate to make it compatible with nutrient supply, (ii) efficient acquisition of nutrients, and (iii) efficient mechanisms of internal nutrient recycling to ensure minimal losses through leaf fall, exudation or leaking (Clarkson and Hanson, 1980; Crawley, 1986). Chapin (1987) notes that 'to a large degree these traits are associated with a syndrome of slow growth and conservative use of resources that may be incompatible with the agricultural goal of maximising yield'. The development of agriculture in such areas thus may require a combination of soil improvement to meet the demands of crop plants, acceptance of a lower yield than would be possible on more fertile soils, and the breeding of crops for high efficiency in the acquisition and utilisation of nutrients so that they can more effectively exploit infertile soils (e.g. a large fibrous root system).

As a framework for reviewing nutrient relations in tree-crop systems it would, therefore, be feasible to take the key objectives of agroforestry and relate increased productivity to nutrient acquisition and utilisation, diversity of products to species differences in nutrient efficiency, and resource conservation to the recycling of nutrients. Such an (essentially agricultural) approach would, however, tend to overlook the main property of agroforestry systems, namely the existence of interactions between tree and crop components. By considering negative and positive tree-crop interactions a simpler theoretical framework can be formulated which associates nutrient relations directly with productivity.

The acquisition and use of nutrients by crops represents a double transformation problem (Vandermeer, 1989), in which the plant and the environment affect, or modify one another; the environment causes a response in plant function and growth, and the plant then has an effect upon the environment by changing one or more of its factors (Clements, 1928). Interactions between individual plants or populations of plants are thus mediated by the environment through this 'response and effect' principle (Goldberg and Werner, 1983), so that a plant influences its neighbours by changing their environment either directly or indirectly (Harper, 1977).

The plant may affect the environment in a negative way with respect to other plants (e.g. it may take up potassium and thus partially deplete the environment of potassium) or in a positive way (e.g. by increasing cation exchange capacity of the soil through input and subsequent accumulation of organic matter). An interaction between two individual plants or two populations of plants which results in at least one exerting a negative effect on the other can be defined as competition (Williamson, 1972; Schoener, 1988), whereas an interaction between two individual plants or two populations of plants which results in at least one exerting a positive effect on the other can be defined as facilitation (Vandermeer, 1989).

Thus in a tree-crop system, when one species, say, the tree, has an effect on the environment which causes a negative response in the crop, yet both can more efficiently utilise necessary resources when in combination than when in monoculture, the 'competitive production principle' applies (Vandermeer, 1981). When the environment of the crop is modified in a positive way by the tree such that the crop is facilitated by the tree, the 'facilitative production principle' applies (Vandermeer, 1984). These two concepts form a dichotomous theoretical framework concerning the productivity of polycrop systems, based on (i) reduced competition and (ii) facilitation (Vandermeer, 1989).

Such a framework is valuable in considering nutrient relations in tree-crop agroecosystems, where crop productivity can be optimised by reducing below ground competition for nutrients between the tree and crop (e.g. through niche diversification in a spatially heterogeneous environment), and/or by augmenting facilitative mechanisms (e.g. through the tree absorbing quantities of nutrients that would otherwise leach out of the system, and later making some of that absorbed nutrient available to the crop). Care must be taken, though, to differentiate between mechanisms that reduce competition (e.g. a nitrogen fixing legume may have a reduced demand for nitrogen from the soil because an alternative

source is available, leaving a greater amount of soil nitrogen for neighbouring plants) and enable facilitation (e.g. the nitrogen fixed by the legume is transferred to neighbouring plants in some way).

To determine whether there is a yield advantage ('overyielding') in growing, say, *Grevillia* and maize together, the land equivalent ratio (LER) can be calculated. This is defined as the amount of land needed to produce as much under monoculture as can be produced on one hectare of polyculture (Mead and Willey, 1980). The LER is thus simply the sum of the relative yields (the yield per ha. in polyculture divided by the yield per ha. in monoculture), and identical to the relative yield total (Vandermeer, 1989). If the value is greater than 1.0, the polyculture is more productive, and if less than 1.0, the monoculture is more productive. A yield advantage ($LER > 1.0$) can therefore be obtained through a reduction in competition (competitive production principle), facilitation (facilitative production principle), or both.

Snaydon and Harris (1979) have listed possible mechanisms for reduced below-ground competition. Weak competitive interactions can occur because the tree and crop are using the same limiting nutrient but from different sources (partially different soil zones or times of use) or different limiting nutrients (either different requirements or the same requirement met by a different ion). Strong competition may also lead to a yield advantage if it is localised because the environment is spatially or temporally heterogeneous for a given non-mobile nutrient (i.e. the environment is patchy). Weak competition thus concerns niche diversification (Colwell and Fuentes, 1975; Harper, 1977) whilst strong competition concerns the concept of coarse-grained environments (MacArthur and Levins, 1967).

Returning to the 'response and effect' principle of Goldberg and Werner (1983), if, say, the tree has a positive effect on the environment, i.e. to the benefit of the crop, then facilitation occurs. This could happen because the tree is mining a source of nutrients not available to the crop and then making it available, e.g. through litterfall or root turnover and subsequent release of nutrients into the upper soil layers. It could also result from 'luxury consumption', where plants store nutrients whenever supply exceeds immediate demand (Chapin, 1987). Luxury consumption acts to reduce the rate of nutrient flow out of the system with the indirect consequence that other plant species may benefit from the later release of the trapped nutrients (Vandermeer, 1989). The most frequently cited way in which the tree can ameliorate the environment to the benefit of the crop is, however through the release of nitrogen from the leaf or root litter of a nitrogen-fixing tree (e.g. Gillier and Wilson, 1991).

This review, to which the above is introduced, was produced as part of a consultancy commissioned by the Overseas Development Administration's Renewable Natural Resources Strategy Programme in Plant Sciences.

The site-species cocktail for eucalypts in agroforestry: does success depend on an understanding of one part nutrients plus one part water, mixed with a dash of salt and some basic ecology?

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Introduction

The planting of eucalypts in agricultural settings almost always means that the selected species are planted 'offsite' - in soils and under climatic conditions different to those in their native habitat. Nevertheless the evidence that eucalypts grow successfully in plantations and in agroforestry both in Australia and throughout the world - and in tropical regions may grow at rates at least equal to those of the most productive tropical forests (see numerous reports in Schonau, 1991) - is sufficiently strong that we need not consider serious suggestions or indeed romantic notions that 'exotics' are somehow doomed to failure. The strength of evidence is illustrated by the fact that in a specific area such as nutrition, we have compiled a computerised data base of more than 1400 references (which will be drawn upon by a number of chapters in the forthcoming book 'Nutrition of the Eucalypts') and from which a synthesis by Judd *et al*, (1995) concluded that nutritionally, 'eucalypts are the same abroad as at home'. A similar conclusion can be reached in relation to the effects of water availability on metabolism and growth - the effects on plant processes remain the same irrespective of where the trees are growing.

We have noted previously that there is no evidence that eucalypts (or other 'exotics') - 'poison' the soil (Attiwill and Adams, 1993) or that they deplete the soil of nutrients. What is clear from the literature is that eucalypts maintain good growth on soils on which the growth of other species would be seriously constrained. There has been a considerable research emphasis on soil processes like mineralisation which are part of the nutrient cycle and responsible for the supply of major nutrients like nitrogen and phosphorus to the plant - while these studies are important, recent research showing plant control over nitrogen uptake (for example, see below) emphasises that measuring rates of supply or indices of supply is not the sole answer to predicting rates of growth or the maintenance of growth since species will differ markedly in nutrient demand and in their control over nutrient uptake.

From observations throughout the world, it is clear that a combination of eucalypt species is required if land managers wish to maximise growth across landforms or soil types or climatic zones etc. The recent spectacular failures amongst the bluegum plantations established on inappropriate soils/landforms in SW Western Australia are a salient reminder of this obvious and critical point.

At the fundamental level, answering questions about the 'sustainability' of agroforestry (e.g. can we maintain or improve growth and soil and water quality) requires the same types of fundamental research as answering the same questions for plantations. In other words, there is no evidence that agroforestry presents 'unique' problems for discipline-based research which aims to identify and characterise the processes which either determine growth (eg nutrient and water availability) or assist the plant in coping with 'stress'. On the other hand, agroforestry can imply that trees will be growing under conditions which are at the extremes of the range.

I argue that there are a number of gaps in our fundamental knowledge of the effects of differing availability of water and nutrients (particularly at the extremes of the range) on eucalypt growth and survival which can be addressed in the short to medium term and which will improve our matching of species to site and our ability to manage agroforests and plantations.

Proposals for fundamental research

1. Biochemical or metabolic markers of water and salinity stress in eucalypts.

Currently, a large proportion (sometimes > 50%) of the trees planted in agricultural landscapes die due to drought and salinity - this trend is worst where trees are planted for purposes other than for wood production (eg shelter belts, conservation reserves, water management, soil conservation) and is a huge waste of physical and financial resources. Without exception, studies of eucalypt response to water deficits show that osmotic regulation is a primary means by which eucalypts survive drought (or 'physiological drought' produced by salinity). The mechanisms and solutes responsible for osmotic adjustment in eucalypts have not been identified and their characterisation and that of the processes responsible for their accumulation are essential if we wish to improve selection of trees for breeding programmes. By way of comparison, there has been abundant, and well-funded (for the types of reasons advanced here) research on a variety of agricultural species which has shown that a limited range of nitrogenous and organic solutes play the major roles in osmotic regulation in those species and this information is a cornerstone of research into developing drought resistant cultivars.

2. Nitrogen nutrition of eucalypts

Apart from some aspects of the gross uptake and cycling of nutrients (eg uptake by roots especially mycorrhizal roots, distribution and redistribution of nutrients) the nutritional physiology of all eucalypt species is poorly described. Most of our knowledge is empirical and goes little further than measurements of the concentration of total nitrogen in different tissues (Kreideman and Cromer, 1995). That is, the pathways of nitrogen metabolism are largely undescribed, the response of major intracellular pools (cytoplasm, vacuole, chloroplast) to changes in the rate of supply of N are known for only a few species, the major sites and forms of nitrogen storage are unknown and we can only guess at the effects of changing environmental conditions on all of the above. In short, for an Australian icon and for a species which is becoming central to improving land management around Australia, we know little.

An important and topical question is at what rate can different species of eucalypt take up and assimilate nitrate? Increasingly, eucalypts are being planted on ex-agricultural soils which are strongly nitrifying. This situation is exacerbated when eucalypt plantations are used for effluent disposal (and hence subject to often heavy rates of applications of nitrogen).

Recent research in other plant species has shown that nitrate uptake is under active control by the plant (Imande and Touraine, 1994) rather than being a passive process determined by water flow and ion exchange. Furthermore, results from effluent application trials suggest that there are substantial differences among eucalypts in their capacity to take up nitrate. An improved fundamental understanding (at the biochemical level) of nitrogen storage, transport and redistribution during senescence and the variation between species is essential if we are to improve species and site matching. Identification of those species which have the capacity to (i) take up nitrate and (ii) store nitrogen excess to current requirements for growth, will greatly assist selection of species for high-nitrogen sites or where effluent disposal is required.

3. Water x Nitrogen interactions and insect herbivory

The availability of plant nitrogen (ie. form and digestibility of nitrogenous compounds in the presence of 'plant defences' such as phenolics, waxes, tough leaves, thick cuticles, other anti-nutritional factors) is crucial to the feeding activity, longevity and fecundity of phytophagous herbivores. White (1984) and Cockfield (1988) have hypothesized that many of the observations of insect outbreaks, especially those on plants under some form of stress (eg drought, salinity), are explained by the increase in foliar and sap concentrations of simple nitrogenous solutes, especially amino acids. Furthermore both authors suggest further that the

known patterns of nitrogen translocation during fruiting and leaf development are consistent with observations of insect activity.

Irrespective of these claims, it must be said that the role of N-solutes in herbivory remains contentious. Bright *et al.* (1982) suggested that proline accumulation did not increase herbivory in barley but other authors (Raven, 1983; Brodbeck *et al.*, 1990; Prestige and McNeill, 1981) provide specific evidence that the activity of both sapfeeding and leaf chewing insects in northern hemisphere ecosystems is increased by high concentrations of soluble - N in plant tissues. In Australia, the most exhaustive studies of insect/eucalypt associations have probably been those of Clark and Dallwitz (1974) who noted in a long-term study that psyllid numbers and feeding activity on *Eucalyptus blakelyi* were markedly affected by climate, by flowering and fruiting, by the mineralization of N in the soil and by interactions with other factors (fires, other herbivores etc). In all cases, those factors which increased the transport of N to leaves, increased insect activity and those which reduced the transport to leaves reduced insect activity.

Clearly, the interaction of nitrogen nutrition and water/salinity stress may play major roles in determining insect herbivory in agroforestry and in plantations. This is an area of research in which we have made some recent advances (Adams *et al.*, 1994; Marsh and Adams, 1995; Adams and Atkinson, 1991) and that we can capitalise on in order to develop predictive capabilities for insect outbreaks and for developing protocols which may assist in controlling such outbreaks.

4. Plasticity (in response to water and nutrient) of root growth of eucalypts

Rates, patterns and, most importantly, the plasticity of root growth are poorly described for all but a handful of eucalypt species. Again, studies of eucalypts lag well behind those of other plants from which we know that such attributes are critical determinants of the ability of the plant to penetrate hard pans in the soil, to tap water or nutrient reserves deep in the soil profile and to adapt to differing soil types (Fitter, 1994). 'Root research' has always been neglected not because of technical problems but on the basis that it is too time consuming and labour intensive. There is a clear need to develop methods for relating patterns of root growth in the field to that which can be induced under controlled conditions and hence develop faster methods of screening species/clones/ecotypes etc for desirable attributes for difficult soils.

Summary

We need to begin this fundamental research if we are to move away from the 'trial and error' approach to agroforestry which is practiced today and to avoid the mistakes which have been made so far. Ploughing dollars into the 'applied' end of the research spectrum at the expense of supporting fundamental research makes no sense, worse, such a trend will ultimately prove to be poor economics.

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Effect of mono versus mixed species tree plantings on nutrient cycling in soils

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Introduction

Agroforestry systems are always mixed species systems and these have been reviewed by Nair (1989, 1993). A number of positive interactions among processes associated with soil, plant and environment have been suggested which affect growth of plants when grown in mixtures compared to monocultures. Of special significance are the enhanced nutrient cycles. An increase in N cycling is achieved by including N-fixing plants as a component of the mixture (Dommergues, 1987). A number of soil processes are postulated to increase P cycling under mixtures, eg. mycorrhizal facilitation of uptake, organic acid production by roots, mineralization of organic P (Binkley *et al.*, 1992; Young, 1989). Not much work has been done on changes to the cycling of K, but a better utilisation of the throughfall flux under multistorey systems is a possibility (Khanna and Nair, 1980).

Emphasis on the enhancement of nutrient cycling processes under mixture has been directed towards the effects of aboveground biomass (prunings) and litterfall, although it has been recognised that root turnover may be contributing towards the cycling processes in a significant way. For example, Sanginga *et al.* (1986) estimated that the N contribution from *Leucaena leucocephala* roots, nodules and litter mineralization to maize grain yield was equivalent to an average of 36 kg urea N ha⁻¹. Dommergues (1987) concluded that N transfer studies are urgently needed to improve management strategies. Such information is important because changes in the nutrition of the tree or crop plants due to mixed plantings may occur before the aboveground nutrient cycle becomes established. This raises the questions: What methods can be used to detect these changes? What critical soil or plant parameters should be used? What elements are involved in the belowground interactions? This paper addresses some of these questions.

Growth and nutrition of a monoculture eucalypt plantation growing on a highly N and P deficient soil will be compared with mixed stands of eucalypt and acacia growing in different proportions. The aims of the study were to determine: 1. If the productivity of eucalypts would be affected by including acacia as a mixture, 2. how the cycling of N and P would be affected, and 3. the best soil and plant parameters to assess changes in N and P cycles.

Experimental site and methods

An experimental plantation of *Eucalyptus globulus* (E) and *Acacia mearnsii* (A) was established at Cann River (Victoria) in 1992. The two species were planted in five different mixtures: 100% E, 75% E + 25% A, 50% E + 50% A, 25% E + 75% A and 100% A and at two plant densities, 3.3 m (between rows) x 3 m (within rows) and 3.3 m x 2 m. The soil at the site is a yellow podzolic with very low available P (undetectable using Bray 1 extraction) and very low mineralisable N. Phosphorus (25 kg P ha⁻¹) as superphosphate was spot applied (20 cm from the tree) four months after planting, but no N was applied.

Tree heights were measured periodically and dbhob after 2 years. One year and two years after planting, mature leaves, senescent leaves and fine roots (<0.5 cm in diameter) were collected for N and P analysis. Soil samples were collected for mineralization rates under laboratory conditions. Details on indices and methods are given by Khanna (1994).

Results and Discussion

1. Tree growth

The growth rates at this site are very good. A positive effect of acacia on the eucalypt heights (increments between 18 and 24 months) was evident (Fig. 1), with a 50:50 mixture the best. At higher proportions of acacia the eucalypt height decreased indicating that the competition for other soil resources (probably soil water) was outweighing the positive effects of additional N made available by the acacia. The diameter of eucalypts showed a similar trend to that for height but differences were not statistically significant (data not presented). Fully expanded leaves of eucalypts from mixtures had larger and had higher specific leaf area (were thinner) than those from monocultures.

2. N dynamics

Two years after planting, the concentration of N in the fully expanded eucalypt leaves, senesced leaves and fine roots was higher for trees growing in mixtures (Fig. 2). The differences were only significant for the senesced leaves and fine roots. Aboveground litterfall was not significant at this time and the differences observed in N concentrations could only be assigned to belowground transfer of N. Root development at the site was rapid and within 6 months of planting roots of acacia and eucalypt were found to be interacting even for trees growing 3 m apart. In mixed stands, most fine roots in the surface (0-20 cm) soil depth belonged to acacia, whereas below 20 cm eucalypt roots dominated. The climatic fluctuations at Cann River would lead to wetting and drying of surface soil many times over a year, with likely turnover of acacia fine roots and nodules that have high N concentrations.

Mineral-N content and the potentially mineralizable N fraction of soils taken from mixed stands were higher than in those from eucalypt stands, further suggesting that the belowground N transfer was taking place. Quantification of this transfer will only be possible after biomass data become available. It may be possible to make better estimates of transfer by using N¹⁵ enrichment techniques.

Very low concentrations of N in senesced leaves indicates strong N retranslocation. The retranslocation was about 65 % or more for N in eucalypts, but less than 50% for acacia.

N concentration differences in leaf litterfall and fine roots, and potentially mineralizable N in soils were useful indicators of the differences in the N cycling and status of mixed stands.

3. P content in foliage and fine roots

The P concentration in all components of eucalypt foliage (young, fully expanded and senesced leaves, twigs) and fine roots decreased with increasing proportion of acacia in the stand, although only differences in fully expanded leaves and fine roots were statistically significant. A very significant withdrawal of P during leaf senescence occurred (to values <200 mg P g⁻¹) indicating the strong deficiency of P on the site and that the litter produced would probably be of low quality and decomposability. Availability of P due to presence of acacia has so far been reduced and cycling via aboveground litter is not yet important. The effects of acacia on longer-term P availability to eucalypts is being assessed.

Conclusions

Initial data suggest that turnover of root components in mixed stands may play an important role in the transfer of N from acacia to eucalypts in the early phases of tree growth, whereas for P cycling turnover of aboveground biomass may be essential.

Acknowledgment

Financial support by ACIAR and technical support by Mr S.J. Smith and Mr K. Jacobsen of CSIRO are highly appreciated.

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Fig 1. 6-monthly increments of eucalypts growing alone or in varying combinations with acacia at two plant densities.

Fig 2. N-concentration (mg g^{-1}) in fully expanded (mature) and senescent leaves of eucalypts (E) growing in varying proportions with acacia (A); 1 = 100% E, 2 = 75% E + 25% A, 3 = 50% E + 50% A, 4 = 25% E + 75% A.

Ash alkalinity of the leaf litter of tree species and effects on pH and phytotoxic aluminium in an acid soil

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Abstract

Soil acidification is a major limiting factor in the sustainability of agricultural production systems throughout the world. Liming may not be economically possible and therefore alternative or complementary methods of amelioration are required. The effects of different leaf litter materials collected from several tree species are currently being examined for their ash alkalinities, Al complexing ability and abilities to ameliorate an acid soil. Ash alkalinity values obtained by titration of the ash and by calculation as the difference between cation and anion content were highly correlated. Values obtained by the latter method ranged from 247 cmol₊ kg⁻¹ for *Melia azedarach* (white cedar) to 36 cmol₊ kg⁻¹ for *Eucalyptus globoidea* (white stringybark). A highly significant linear correlation between ash alkalinity and the Ca concentration in the litter was observed. When incubated with soil, leaf litter raised the pH above the initial soil pH of 3.95 with white cedar having the greatest effect on soil pH. Aluminium levels on the exchange complex were significantly reduced by leaf litter through direct precipitation of a solid phase and again white cedar litter was most effective. Indirect evidence of formation of Al-organo complexes controlling the level of monomeric Al in *Liquidambar styraciflua* (liquid amber), *Quercus robur* (English oak) and *Pinus radiata* (radiata pine) were evident.

Introduction

Aluminium phytotoxicity is a major factor limiting productivity on acid soils around the world. Conventionally acid neutralising amendments such as lime and dolomitic lime have been used to rectify this problem. However, in many developing and developed countries the cost of applying lime are high and returns are low given prevailing commodity price structures. Under these conditions alternative means of rectifying the problem need to be developed using resources that are inexpensive or locally available.

In general the ashes of plants are alkaline due to the excess of cations over inorganic anions. This means that plants may have the ability to take up bases from the soil in the whole of the root zone and deposit them in litter on the surface from where further decomposition the bases are concentrated in the surface horizons of the soil. During the decomposition process of litter, acidic products are produced. Whether or not the plants will increase or decrease the acid/base ratio in the soil will, therefore, depend on the seasonal growth cycle, the nature and intensity of decomposition and the soil horizon. The acid-base balance in an ecosystem becomes a balance between the production of organic acids and the leaching of bases on the one side and the destruction of the organic acids and the rate at which plants recover leached bases and recycle them to the surface - the "biological pump" - in their litter on the other.

Some tree species have the potential for selectively accumulating certain nutrients. Sanchez *et al.* (1985) reported that litter from *Gmelina arborea* contained twice as much calcium as that of virgin forest or mature pine plantations while the magnesium content of the litter was three times as much as in the *Pinus* litter. Additionally, Chijoke (1980) reported that in two plantations of *G. arborea* litter returned 117 and 161 kg Ca ha⁻¹ yr⁻¹ to the soil surface. The potential therefore exists for trees that produce base rich litter to check or reverse soil acidification. However, the improvement of the topsoil fertility through the addition of nutrients via litter from trees *in situ* is effectively only a reflection of the inherent nutrient status of the whole soil profile.

In large areas of southern Australia where subsurface acidification has developed on duplex soils the potential exists for plant species with a deep rooting profile to sequester bases that have accumulated in the B horizon and return them to the surface through

litterfall. Studies evaluating the ash alkalinities of freshly fallen leaf litter collected from several tree species was undertaken. In addition, the acid neutralisation capacities of selected litters was evaluated in a soil incubation study.

Results and Discussion

Litter composition

Forty nine leaf litter samples have been collected over the past 12 months from both indigenous and exotic species. Their nutrient composition and ash alkalinities were determined using XRF spectroscopy and by titration respectively (Norrish and Hutton, 1977; Jarvis and Robson, 1983). Of the cations determined calcium (Ca) concentrations ranged from 5.0 to 41 mg g⁻¹. Magnesium (Mg) and potassium (K) concentrations ranged from 0.5 to 5.2 and 2.2 to 19.8 mg g⁻¹ respectively. Calcium is immobile in the phloem in contrast to Mg and K (Mengel and Kirkby, 1978). Consequently less Ca is likely to be withdrawn from leaves during senescence which could account for it being the dominant cation found in these litter samples. The highest concentration of Ca was observed in *Melia azedarach* (white cedar) whilst *Eucalyptus nitens* had the lowest. Of the anions, phosphorus (P) concentrations ranged from 0.17 to 2.5 mg g⁻¹, with the highest concentration being observed in *Eucalyptus elata* collected from Flushing Meadows, Wagga Wagga. Total nitrogen (N) in the leaf litter ranged from a 21.0 mg g⁻¹ in *Acacia mearnsii* (black wattle) to 4.1 mg g⁻¹ in *Liquidambar styraciflua* (liquid amber). *Acacia terminalis* (sunshine wattle) and *Brachychiton populneum* (kurrajong) had the second highest N level. In general, the nutrient concentration in the indigenous Eucalypts and Acacia were lower than the deciduous temperate species reflecting either differences in uptake or the efficiency with which these groups of species withdraw nutrients from senescing leaf tissue prior to abscission. For comparison with the titrametric method, ash alkalinity was estimated by calculation of the excess base, the difference between total cations and total anions viz. $\Sigma(\text{Ca}^{2+} + \text{Mg}^{2+} + \text{K}^{+} + \text{Na}^{+}) - \Sigma(\text{SO}_4^{2-} + \text{H}_2\text{PO}_4^{-} + \text{Cl}^{-})$. These two estimates were highly correlated ($y = 1.072 (\pm 0.022) x$; $r = 0.983$; $n=16$) where the origin is forced through zero. However, in a sub-sample of species, those collected from Flushing Meadows a wide divergence in values was observed and no significant linear relationship was observed. This has being ascribed to the loss of Cl and/or SO₄ on ignition since these samples were high in these two anions. Although the titrametric method is simple and relatively quick, it should be noted that an over estimations of ash alkalinity will occur in samples having high levels of Cl and SO₄ and therefore the method by difference is preferred. Several collections of *Melia azedarach* have been made from different locations and in each case the ash alkalinity of the material has been significantly higher than all other species.

Of all the cations influencing the ash alkalinity of individual species, a highly significant linear relationship was observed between $\Sigma\text{Ca} + \text{Mg}$ concentration in the litter and ash alkalinity (Figure 1). Therefore the ash alkalinity in the suite of species examined was significantly influenced by the concentrations of Ca and Mg and thus could be used as a simple method of assessing the ash alkalinity of a species.

Soil incubation studies

Leaf litter material of each of the species collected has been included in a soil incubation study to ascertain their acid neutralising abilities. Ground leaf litter was mixed into 350 g air dry soil at rates equivalent to 5, 10, 20 and 40 t ha⁻¹ and a series lime treatments (0, 0.5, 1.0, 2.0 and 4.0 t ha⁻¹) were included as controls. For brevity the results of selected species are presented outlining the extremes observed.

In order to evaluate the liming potential of each of the leaf litter materials rates of application were converted to kg CaCO₃ assuming that 1 kmol H⁺ requires 25 kg CaCO₃ to be neutralised. A highly significant linear relationship between pH and equivalent CaCO₃ rate was obtained for the species presented in Figure 2. The most effective litter source being *Melia azedarach* and the least effective *Liquidambar styraciflua*. The fact that the

leaf litters behave in a similar fashion to lime suggests that the acid neutralisation mechanisms are similar.

With the increase in soil pH there was a concomitant decrease in exchangeable Al. Since the Al concentration in the soil solution increases with decreasing pH, the Al complexing abilities of these leaf litter materials was assessed by plotting the monomeric Al concentration measured in 0.01 M CaCl₂ extracts against pH (Figure 3). The pH/monomeric Al relationship for *Melia azedarach*, *Betula alba*, *Brachychiton populneum* were very similar to those of lime while that for *Liquidambar styraciflua*, *Quercus robur* and *Pinus radiata* were markedly different. This would suggest that organic complexes with Al play a greater part in controlling the level of monomeric Al in solution in the case of the latter group of species. In studies evaluating the Al complexing ability of water soluble fractions extracted from leaf litter, *Quercus robur* and *Pinus radiata* complexed significantly larger amounts of Al than species such as *Melia azedarach*.

In the leaf litter treatments exchangeable Ca and Mg increased at the expense of Al such that at a rate of 40 t ha⁻¹ in the case of *Melia azedarach* the saturation percentage of Ca + Mg and Al were 88 and 0 % respectively after incubation. In contrast, the addition of an equivalent amount of leaf litter from *Pinus radiata* resulted in a Ca + Mg and Al saturation of 68 and 15 % respectively. A highly significant linear regression ($y = 1.45 (\pm 0.05) + 0.76 (\pm 0.02) x$; $r = 0.978$) was observed between the amount of Ca applied in the leaf litter treatments and exchangeable Ca, however the slope of the line was significantly less than 1 suggesting incomplete decomposition of applied materials during the 8 week incubation. In general, the increase in Ca and Mg on the exchange complex reflected the elemental content of the materials applied.

Conclusions

The results from the study have demonstrated the range of ash alkalinities of leaf litter material of several tree species and their potential role as soil liming materials. Soil incubation experiments indicated that the addition of leaf litter material increased soil pH and reduced phytotoxic Al. There were substantial differences between species - *Melia azedarach* being far more effective than, for example, *Pinus radiata* at any given rate. These differences appear to be related to the composition of basic cations in the plant materials, with *Melia azedarach* having higher concentrations of Ca and Mg than the other species. Calcium and Mg, which have stronger affinities for exchange sites, will increase the base saturation of the soil more effectively than K and Na. The levels of these divalent cations may be important indicators of the "liming" quality of leaf litters.

Differences between species in the ash alkalinity of senescent leaf material could be due to (a) differences in the proportion of cations and anions taken up and / or (b) differences in the proportion of nutrients withdrawn from the leaves during senescence prior to abscission. Assuming uptake differences are significant we would expect that the more alkaline the litter the more acid the soil around the roots. The cycling of nutrients through the soil / tree system and the redistribution of alkalinity in the soil profile will have important consequences for soil acidification (Helyar and Porter, 1989). On poorly buffered soils amelioration of acidity in the surface by leaf litter may be at the expense of undesirable acidification of the subsurface soil. In duplex soils with acid surface horizons and an accumulation of bases at depth the deposition of alkaline litter in the surface would be entirely beneficial.

Acknowledgments

The work was supported by a Vincent Fairfax Family Foundation fellowship to A D Noble and a grant from Rural Industries Research and Development Corporation. Mr T J James provided technical support in the analysis of soil samples and Ms R A. Wallace the XRF analysis.

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Figure 1. Relationship between as alkalinity and $\sum \text{Ca} + \text{Mg}$ concentrations in the leaf litter of tree species.

Figure 2. Relationship between soil pH and CaCO_3 equivalents of leaf litter added to soils after 8 weeks incubation.

Figure 3. Relationship between monomeric aluminium as measured in a 0.01 M CaCl_2 extract and pH after 8 weeks incubation with leaf litter.

Increased Soil Nitrogen Availability under Tree Canopies

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Introduction

Young (1989) discussing the contribution of agroforestry systems to sustainable land use put forward ten hypotheses for soil agroforestry research. These ten hypotheses covered areas in which he considered the tree component improved soil fertility, viz; erosion control, maintenance of organic matter, improving soil physical properties, N fixation by leguminous trees, redistribution of nutrients from deep soil layers, reducing leaching and keeping nutrients in the soil system, amelioration of acidity, conserving moisture, reclamation of saline soil and tree root/mycorrhizal contributions to nutrient distribution. Some of these hypotheses, in his opinion, remain to be proven.

My own research, lead to the proposal of an 11th hypothesis (Wilson 1990), viz: that the shade influence of a tree canopy improves the rate of mineralization of soil N. This paper discusses research that supports this hypothesis.

Positive influence of shade on grass growth

Wong and Wilson (1980) and Eriksen and Whitney (1981) reported 40% greater yields of tropical grass under artificial shade than in full sun under low soil N conditions. Not only was yield increased under shade, but plant N% was higher giving rise to the conclusion that soil N availability had been increased (Wong and Wilson, 1980). This shade effect was confirmed by artificially shading old, sown pastures deficient in N in both a coastal (bahia grass, Samford) and subcoastal (green panic, Narayen) environment (Table 1).

These increases in grass growth under shade are also evident with pastures under tree canopies. Table 1 lists a few examples, viz; guinea grass under albizia (Lowry *et al.* 1988), bahia grass under eucalypt, temperate pasture grasses under acacia (Ovalle and Avendano, 1987), and tropical grasses under acacia and baobab (Belsky *et al.*, 1993). The physiological rationale for achieving more growth of grass even at 50 % light is explained by comparing photosynthetic light response curves at different levels of N supply. With N deficiency the gain in photosynthesis by moving to a higher plane of N nutrition is greater than the decrease in photosynthesis by moving from 100 to 50 % light (Wilson and Wild, 1991). If tree density is too great and/or light reduced to <30-40% (Robinson 1991; Cameron *et al.*, 1991), then extra N resulting from shade effects cannot compensate for low light.

Increase in herbage nitrogen yield under shade

Wong and Wilson (1980) postulated that shading of pasture increased the availability of soil N. In all of the experiments shown in Table 1, N yield was increased to an equal or greater extent than dry matter yield. Data of Cruz *et al.* (1993) for *Dichanthium* under *Gliricidia* trees (Table 1) indicate no effect of tree canopies on dry matter yield but a 113% increase in N yield. Wilson *et al.* (1986) calculated that the gain in N in pasture tops of green panic under shade was equivalent to an extra 26 kg N ha⁻¹ over the basal mineralization rate of 23 kg N ha⁻¹ yr⁻¹ in full sun conditions. The increased recovery of soil N in plant tops appears consistent in all the artificial or tree shade conditions. It does not appear to arise from retranslocation of N from diminished root systems (Wilson *et al.*, 1986; Belsky *et al.*, 1993; Wild D M W (unpublished data)).

The concentrations of other major nutrients in the herbage, such as phosphorus and potassium, are either unaffected or increased where shade effects of trees on growth have been positive (Wilson *et al.*, 1990), or increased substantially where pasture yields under trees and in the open were the same (Cruz *et al.*, 1993). This is perhaps to be expected if nutrient cycling due to the shade environment is stimulated (Wild *et al.*, 1993) or

concentrations of soil nutrients are higher under tree canopies than in the open (Belsky *et al.*, 1993).

Table 1: Relative effect of shade compared to full sun on dry matter (DM), nitrogen (N) and phosphorus (P) yield of pasture herbage.

Conditions	Shade Effect on Yield			Reference/
Grass/shade	DM	N	P	Site
Green panic under artif. shade 50%	+70%	+116%		Wilson et al. 1986 Narayan, SE Qld.
Trop. grass under Albizia: Grazed : Ungrazed	+82% +127%			Lowry et al. 1988 Townsville, Qld.
Bahia grass under Eucalypts	+35%	+67%		Wilson et al. 1990 Samford, SE Qld.
Bahia grass under Eucalypts 50% shade	+37% +135%	+50% +143%	+19% +170%	DM Wild (unpub.data) Samford, SE Qld.
Temperate grass under Acacia	+19-38%	+15-42%		Ovalle & Avendano 1987 Chile
Dichanthium under Gliricidia	+0%	+113%	+28%	Cruz et al. 1993 Guadalope
Trop. grass under Trees ¹ : dry site : mesid site A B	+95% +52% +18%	+102% +53% +6%		Belsky et al. 1993 Kenya

¹ A = acacia, B = boabab

Shade benefits related to litter/organic matter breakdown

Evidence strongly suggests that higher soil N availability and hence growth of grass under shade in N-limited environments is due to faster organic matter turnover and N mineralization. Firstly, with a responsive grass like green panic grown under shade in solution culture, there is no shade response. A 50 % reduction in light gave c. 56 % reduction in shoot yield (Wild *et al.*, 1993), indicating the need for a soil/organic matter presence. Secondly, N¹⁵ studies indicate greater N recovery from soil surface layers under shade than in the open (D M W Wild, unpublished data). Thirdly, litter yields under tree or artificial shade are lower than in full sun (despite greater pasture growth) and rate of litter breakdown is higher under shade (Wilson and Wild 1995).

Wilson and Wild (1995) assess reasons for faster litter breakdown and N cycling in their tree canopy and artificial shade treatments. They believe a crucial factor is shade creating a more favourable soil surface/litter environment for biological activity and organic matter breakdown. Daily maximum temperatures at the soil surface may exceed 50°C in the open but rarely exceed 35°C under shade. In temperate situations, mineralization rates reach an optimum at about 35°C (*loc cit*), so these extreme temperatures in open pasture could severely restrict microbial activity. However, for tropical soils there is evidence that mineralization rate increases up to temperatures as high as 50°C. This response curve requires verification, but, if general, then reduced surface temperatures *per se* cannot explain the shade benefits for tropical pastures. However, high surface temperatures are accompanied by lower soil surface moisture, and almost certainly lower litter moisture (which has not been measured). Microbial activity is consistently decreased by low moisture, so the benefits of shade could often result from better soil surface moisture relationships; either from slower soil drying after a rainfall event or perhaps slower drying of morning dew from litter on a daily basis. However, this explanation is not complete because in an experiment at Samford, the soil under Eucalypt trees in a low rainfall year was

equally as dry as under open pasture, yet a strong shade effect on pasture dry matter and N yield was observed (*loc cit*).

Higher earthworm populations under trees or artificial shade have been measured at several experimental sites (Wild *et al.*, 1993), presumably due to amelioration of the surface soil temperature and moisture environment. This effect on earthworms, plus probable increases in other macrofauna, should increase rate of organic matter turnover.

Another possible contribution to increased soil N availability is through reduced root excretions of carbon compounds (B A Keating, personal communication). Shading typically re-partitions more C from roots to tops. In N deficient soil situations, often due to low quality, high C:N litter input, C excretions would exacerbate N immobilisation by soil microfauna. In shade environments, C excretion from roots should be much lower than in full sun, thereby lessening immobilisation potential and increasing soil N availability. Bushby *et al.* (1992) found that C excretions to soil from shaded green panic was only one-third of that in full light.

Clearing trees for extra grass growth

Tree clearing is a common practice to increase grass growth which seems in conflict with the benefits of trees for soil physical and chemical fertility in the 10 hypotheses enunciated above, and with the above views on shade of tree canopies stimulating N mineralization and grass growth (in N deficient situations!). Several explanations spring to mind. Most experimental demonstrations of positive influences of trees on grass growth have been in savanna woodlands or spaced plantations of low tree density. Most clearing within Australia is of coastal hinterland forests where tree density is much higher, hence shading perhaps too dense and competition for water and nutrients too high for satisfactory understory growth. In many cases, phosphorus is a primary growth limitation, whereas in most of our experimental sites this was not so. Because of limited understory cover in dry sclerophyll forests, there is little herbaceous litter input for nutrient re-cycling, and in Eucalypt forests, the tree litter may be of extremely poor quality and very slow to breakdown. Also, the soil surface is exposed, compacted, and water infiltration perhaps low, thereby exacerbating surface dryness and slow organic matter decay. The process of clearing itself may increase nutrient availability in the short term through soil disturbance and burning, and better soil moisture. Especially so, if pastures are sown on the cleared land, but productivity of these grass pastures (e.g. in cleared Brigalow lands) clearly declines rapidly over 5 years (Myers and Robbins, 1991). Even if pastures are not sown, there is some evidence that initial stimulus to grass growth after clearing or killing trees is discounted greatly with time (Harrington and Johns, 1990). The latter authors list removal of competition for soil water by trees as the prime factor resulting in better herbaceous growth after clearing. This factor is probably equally important in the shade responses described above and in achieving a productive association between trees and pastures.

Figure 1 illustrates differences in soil water status between tree species at common density, with soils under leucaena and acacia being wetter than for open pasture, and those under eucalypt and albizia being drier. Albizia had a minimal canopy compared to the other species.

Conclusions

Soil fertility can be higher under trees than in open pasture for a variety of reasons. This paper highlights one important benefit for N cycling associated with the shade of tree canopies. The causes of this benefit need to be proven but appear due to faster litter decay, probably because of an amelioration by shade of the surface soil/litter environment allowing more micro- or macro-fauna activity, and faster N mineralization. Understanding water use patterns of different tree species, and their extent of competition with the understory for A horizon water, will be important where selective clearing is possible or where replanting into existing pasture is being considered. Finally, there is reason to expect that the potential for better N cycling under tree canopies will be widespread in the subhumid and semiarid

subtopics and tropics because of amelioration of soil surface environment. This may not be so in the wet tropics where conditions for N mineralization are mostly near optimal in soil temperature and moisture. Better grass growth than in open pasture will only be seen where soils are N deficient and the associated pasture species have a degree of shade tolerance.

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Figure 1. Variation in soil water potential between four tree species planted into an old green panic pasture as mini-plantations of 25 trees at spacing of 5 m, compared to open pasture (Narayan, SE Qld). Trees planted January, 1989. [J R Wilson, unpublished data].

Nitrogen cycling in a *Leucaena* agroforestry ecosystem

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Field experiments were conducted on an Alfisol in the semi-arid tropics of northern Australia to investigate nitrogen (N) cycling in the leucaena (*Leucaena leucocephala*) alley cropping system. This is a farming system in which maize (*Zea mays* L.) is grown in alleys formed by leucaena hedgerows spaced 4.5 m apart. Mineralisation of N from leucaena (prunings) and maize residues was studied under field conditions. Response of maize growth to residues was evaluated both in field plot and microplot experiments. The fate of N was examined over four consecutive seasons.

The decomposition (loss of mass) of dry, cut ¹⁵N-labelled leucaena residues differed from that of intact fresh leucaena prunings in the first cropping season although no difference was detected after one year. The extent of decomposition of fresh leucaena prunings (28-37%) was similar at two loading rates (2.4 and 4.7 t DM ha⁻¹) by 3 months after addition. About 72% of young ¹⁵N-labelled maize residues was decomposed by 3 months after addition in the presence of fresh leucaena prunings. Decomposition of ¹⁵N-labelled leucaena residues and unlabelled fresh prunings was 91% and 88% respectively 14 months after addition. After 2 years the corresponding values were 96% and 94%. When N content of the recovered residues was taken into account, the values were 95% and 94% after 14 months, and the same (97%) after 2 years.

Maize yield and N uptake were significantly increased following addition of either unlabelled fresh leucaena residues or ¹⁵N-labelled dry leucaena residues. Application of N-fertiliser produced a further increase in the presence of the residues. The maize yield and N uptake with the ¹⁵N-labelled leucaena were not different from those with the unlabelled residues. There was a significant positive interaction between N fertiliser and leucaena prunings which increased maize production. Addition of maize residues decreased the yield and N uptake of maize compared with that obtained in the presence of N fertiliser at 40 kg N ha⁻¹ and leucaena residues (2.4 t DM ha⁻¹). There was a marked residual benefit of N fertiliser applied in the first season at 36 kg N ha⁻¹ in the presence of leucaena prunings on the second maize crop yield and N uptake, but not on the third crop. However, a significant residual benefit of leucaena prunings added in the first season was found in DM yield and N uptake of the second and third maize crop.

The short-term fate of ¹⁵N applied in plant residues was examined during two separate cropping seasons. By 20 days after application of separate ¹⁵N-labelled leucaena leaves, stems and petioles, 3-9% of the added ¹⁵N could be found in maize plants, 33-49% was in the surface residues, 36-48% in the 2 m soil profile and 0.3-22% unaccounted for. In a separate experiment when leucaena components were not separated, 5% of ¹⁵N applied in leucaena residues was taken up by maize 52 days after addition, 45% was in residues, 25% was in soil and 25% was unaccounted for. In another experiment, maize recovered 6% of the added leucaena ¹⁵N after 2 months, 39% remained in residues, 28% was in soil and 27% was not recovered. Incorporation of ¹⁵N-labelled leucaena residues in the soil did not increase recovery of leucaena ¹⁵N by maize compared to placement of the residues on the soil surface. By the end of one cropping season (3 months after application) 9% of added ¹⁵N was recovered by maize from ¹⁵N-labelled leucaena. There was a similar ¹⁵N recovery from ¹⁵N-labelled maize residues applied as mulch at 1.7 t DM ha⁻¹ together with unlabelled leucaena prunings at 2.4 t DM ha⁻¹. In both cases, 30-32% of added ¹⁵N was detected in soil, 28% in residues, and 31-34% apparently lost.

The long-term fate of fertiliser ¹⁵N was compared with that of leucaena ¹⁵N in an experiment over four cropping seasons. In the first season, maize tops recovered 50% of the

fertiliser ^{15}N but only 4% of the leucaena ^{15}N . In the second, third and fourth seasons, maize (tops + roots) recovered 0.7%, 0.4% and 0.3% of the initial fertiliser ^{15}N compared with 2.6%, 1.8% and 1.4% of the initial leucaena ^{15}N . In the second, third and fourth seasons, recovery of the initial fertiliser ^{15}N (12-14%) in soil was much lower than that of the initial leucaena ^{15}N (38-40%). There was no further loss of the fertiliser ^{15}N after the first season. However, the cumulative ^{15}N deficit for the leucaena ^{15}N in the first two seasons was 50% - this suggested an additional loss of 25% since the end of the first season. There was no further loss of ^{15}N from either residual ^{15}N or residual ^{15}N in the third and fourth seasons.

In conclusion, application of leucaena prunings could substantially increase maize yield and N uptake although some supplementary N fertiliser may be required to achieve maximum crop yield. Maize recovered only a small amount of added leucaena N in the first year. Most of the leucaena residue N was present in the soil and remaining residues after one season. This residue N would be gradually available for plant uptake and subsequent crops. Of course, annual additions of leucaena prunings would appreciably increase the pool of available N over time. Thus application of leucaena prunings could substantially improve soil fertility in the long term.

Relevant Publications

- Xu, Z.H., Saffina, P.G., Myers, R.J.K. and Chapman, A.L. 1993. Nitrogen cycling in Leucaena (*Leucaena lucocephala*) alley cropping in semi-arid tropics 1. Mineralisation of nitrogen from leucaena residues. *Plant and Soil* **148**: 63-72
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