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Soil Organic Matter Management for Sustainable Agriculture

A workshop held in Ubon, Thailand, 24–26 August 1994

Editors: R.D.B. Lefroy, G.J. Blair and E.T. Craswell

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Foreword

ORGANIC matter plays a multitude of roles in soil, but most importantly it is the source of nutrients and energy to the soil biota, the activities of which create the distinction between an agglomeration of lifeless minerals and a soil. In agricultural soils, physical and chemical properties are also strongly influenced by the nature and amount of organic matter in the soil. In essence the maintenance of soil fertility — i.e. the suitability of a soil as a medium for crop growth — can be equated with the conservation of soil organic matter. This is especially true of rainfed farming systems in which the risk of drought constrains the use of purchased inputs. Many of the rural poor in the Asian region live in these rainfed areas and exploit their resource base to the point where serious soil degradation is occurring. The challenge facing agronomists and soil scientists has been to devise management systems that optimise the level of organic matter in a soil in relation to the environment, resource endowment of the farmer and the economics of farm production.

The importance of soil organic matter management has prompted a number of national and international agencies to develop research programs aimed at improving the sustainability and productivity of Asian cropping systems. In 1992, ACIAR commissioned the University of New England to undertake a research project on this problem in collaboration with the Visayas State College of Agriculture in the Philippines and the Rice Research Institute of the Department of Agriculture in Thailand. Since this project was scheduled for external review in 1994, a workshop on the subject was organised to provide a forum to examine ongoing research within the region while at the same time disseminating the results of the project. The Ubon Rice Research Centre agreed to host the Workshop and we are especially grateful to Dr Supavat Tippayarak and the staff of the Ubon Centre for their hospitality and hard work catering for the influx of 55 participants. Scientists came from 12 Asia – Pacific countries to present papers at the workshop. We were pleased that, in addition to scientists from national programs in ACIAR's partner countries, staff from several international agricultural research centres in the region were able to attend the workshop. We thank the national and international agencies that supported the attendance of their staff, especially the International Rice Research Institute which sponsored eight staff from headquarters and the region to attend.

The workshop was designed to review current research and identify future research opportunities, in organic matter dynamics and nutrient cycling in tropical and temperate agro-ecosystems, in the context of recent developments in technology. It is up to the readers of the papers and the summary of the discussions in this volume to judge how well the workshop achieved its objectives. We hope that the Proceedings will be especially useful to scientists in ACIAR's partner countries.

Finally, I would like to record ACIAR's appreciation to Mr Peter Lynch for the key role that he has played in editing and producing these Proceedings.

G.H.L. Rothschild
Director
ACIAR

Role of Soil Organic Matter in Sustainable Agricultural Systems

J.K. Syers* and E.T. Craswell†

Abstract

The maintenance of soil organic matter benefits the sustainability of agricultural systems by improving soil physical properties and protecting the soil surface from erosion, providing a reserve of plant nutrients, enhancing cation-exchange capacity, and stimulating biological activity. The dynamics of soil organic matter decomposition in the tropics depend on the quality of organic matter inputs and the environmental conditions, particularly the soil water regime. Flooding changes the nature and products of the decomposition process, and this has significant implications for international efforts to protect the atmosphere.

In tropical Asia, traditional paddy rice in the lowlands and slash-and-burn agriculture in the uplands respectively, have produced low but sustainable crop yields for millennia. However, recent rapid population growth has led to agricultural intensification which in many areas appears to be unsustainable. This paper reviews recent work to develop improved technologies for the management of soil organic matter, pointing out the socioeconomic issues which affect farmer adoption. At the other end of the spectrum, the relevance of recent strategic research applying modern instrumental methods to study soil organic matter in the tropics is considered.

THE term 'soil organic matter' defines the totality of organic matter in the soil which ranges from the organisms present (the soil biomass) to plant and animal tissues which vary in their state of decomposition (Jenkinson 1988). The term 'humus' is usually used to describe the well-decomposed, dark-coloured organic material in soil. Humus has been much studied but is still not well characterised.

The amounts of organic matter in soils vary appreciably but in spite of the higher turnover of organic matter under tropical climates, there is no intrinsic difference between the organic matter content of tropical and temperate region soils (Sanchez 1976). According to Greenland et al. (1992), the myths of a lower quantity and poor quality of humus in tropical soils have derived from experience with a restricted range of soils in a limited range of environments. These myths have not been exploded but they have been deflated as the information base on the properties and management of tropical soils has developed. What has changed little is the early recognition of the importance of soil organic matter in crop production. This is particularly the case for tropical soils with low-activity clays where moisture and nutrient retention, in particular, are usually low. Maintaining an adequate organic matter level in these soils, by attempting to balance additions and losses is not easy but is a worthwhile objective.

Up until recently, major emphasis has been focused on the direct and indirect effects of soil organic matter on soil fertility and crop nutrition, but there is now increasing interest in losses of carbon (C) from soil to the atmosphere and sequestration of C by soil from the atmosphere. The need for an improved understanding of the dynamics of soil organic matter has been given added thrust by Chapter 9 of Agenda 21 'Protecting the Atmosphere'. The development of alternatives to slash-and-burn agriculture and the reclamation of degraded lands have major implications to climate change, as well as to sustainable agriculture (Sanchez 1994).

Lastly, by way of introduction, development of sustainable agricultural systems requires that there be an adequate methodology for evaluation. The recently-developed Framework for Evaluating Sustainable Land Management (Smyth and Dumanski 1993) uses indicators of sustainability in the assessment process. Soil organic matter is emerging as a

* International Board for Soil Research and Management, P.O. Box 9-109, Bangkhen, Bangkok 10900, Thailand.

† Australian Centre for International Agricultural Research, GPO Box 1571, Canberra, ACT 2601, Australia.

key indicator for assessing sustainability (Dumanski 1994).

The purpose of this paper is to briefly review the functions and dynamics of soil organic matter in the context of sustainable agricultural systems and with particular emphasis on management practices and recent research and future requirements.

Functions of Soil Organic Matter

The main functions of soil organic matter are usually considered in terms of effects on soil physical, chemical, and biological properties.

Physical properties

Organic matter binds soil into aggregates, giving rise to soil structure and associated soil porosity, which are important properties in regard to root proliferation, gas exchange, and water retention and movement. The effect of soil structure and its stability on water retention, movement, and uptake by plant roots has been reviewed by Hamblin (1985). Polysaccharides, produced by plant roots and microorganisms in the soil, promote and stabilise microaggregates. It is generally recognised that a balance between the fine water-retentive pores and the coarse transmission pores is required for effective water-holding capacity, water and air permeability, and root penetration. Such favourable physical conditions are possible provided soil organic matter levels can be maintained. A continuing decrease in soil organic matter levels following cultivation, or because of reduced inputs, leads to a subtle deterioration of soil structure which creates difficulties with seedbed preparation, seedling emergence, and root growth (Papendick 1994) because of crusting and compaction.

Crop residues left on the surface of the soil, and the subsequent humification of these materials, have numerous beneficial effects on the soil physical conditions which reduce soil loss through erosion and improve the soil as a medium for plant growth, adding to the protection afforded to the soil. Beneficial effects of surface organic matter include reductions in soil temperatures, splash, slaking, crusting, and compaction (Cassel and Lal 1992). The resulting increased soil strength and improved stable pore structure, often associated with greater faunal activity, lead to more rapid water infiltration and reduced runoff and soil loss (Coughlan 1994). These effects are particularly significant in steep land areas.

A major effect of soil structural decline is that on reduced root proliferation and nutrient uptake. Because of this, continuous organic matter inputs enhance plant nutritional status (Greenland 1988), in addition to directly supplying nutrients, discussed below.

Chemical properties

Soil organic matter arguably exerts its largest effect on chemical properties through direct and indirect effects on nutrient supply. The elemental composition of soil organic matter and specifically the contents of carbon (C), nitrogen (N), phosphorus (P), and sulfur (S) have been studied extensively (see Jenkinson 1988). Briefly, the ratio of organic C to organic N (the 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. Also it appears that organic P is less readily mineralised to plant-available inorganic P, than is organic N and organic S to inorganic forms, probably because a substantial proportion of soil organic P occurs as inositol phosphates, which are quite stable (Tate 1987). The incorporation of N and S into organic forms reduces losses of these elements by leaching. Their slow release and that of P by mineralisation is synchronised to some extent with plant requirements, offering the prospect of developing management practices for improving soil fertility and nutrient supply through soil biological processes.

Indirect effects of soil organic matter on nutrient supply include its positive 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. This is well shown by the work of Willett (1994) who concluded that, for sandy soils in northeast Thailand, soil organic matter was an essential component for the provision of cation-exchange sites and buffering capacity, rather than just a source of nutrients which are produced by its decomposition.

The complexing ability of soil organic matter for certain metals is well established (Jones and Jarvis 1981). Also the ability of added organic matter to reduce exchangeable aluminium (Al) has been demonstrated by Hargrove and Thomas (1981); as has its ability to complex monomeric Al in laboratory studies, thus reducing Al toxicity (Bell and Edwards 1987). The extent to which organic material additions can reduce Al toxicity in acid soils under field conditions is less well established. This is being evaluated in a collaborative ACIAR–IBSRAM project relating to the management of acid upland soils for sustainable food production in Southeast Asia.

A further potentially important effect of soil organic matter in acid soils is that of increasing the efficiency of soil and fertilizer P use by reducing P fixation. If inorganic P can be transformed rapidly into organic compounds which protect the P from chemical fixation by soil components (Tiessen et al. 1992) then this could be particularly useful in acid soils which are invariably P deficient because of an often high P-fixation capacity. This would also require the release of plant-available P by mineralisation at a rate whereby plant roots can compete for it against the process of fixation. The potential of using this approach will be investigated in Phase 2 of the ACIAR–IBSRAM management of acid soils project, referred to above.

Biological properties

Soil organic matter stimulates the activity of fauna and micro-organisms in soil which contribute to nutrient release during the decomposition of plant and animal residues, and to the synthesis of humified compounds, which are important in relation to soil physical and chemical properties, discussed above.

The importance of earthworms in soil fertility is well established but only relatively recently has quantitative work on the mechanisms by which earthworms contribute to enhanced soil fertility and plant growth been undertaken (Syers and Springett 1984). Earthworms can have an important influence on physical and biological effects which interact to affect nutrient supply to plants. Organic matter is vitally important to these processes because it provides a food source for earthworms. Whereas some earthworm species selectively feed on plant residues at the soil surface (e.g. *Lumbricus terrestris* L.) others (e.g. *Octolasion cyaneum* (Sav.)) feed on decomposed organic material in soil (Edwards 1981).

By burrowing through the soil and feeding on and redistributing organic materials, earthworms change the environment of soil micro-organisms and plant roots. In particular, the incorporation of plant residues usually accelerates decomposition by improving aeration and water relations. The importance of faunal activity, stimulated by the addition of organic materials, in promoting aggregation and in enhancing water movement and aeration in soils has been reviewed by Hamblin (1985).

The fact that organic matter inputs can stimulate soil microbial biomass is shown by the work of Saffigna et al. (1989) in Queensland, Australia. Significantly, the return of sorghum residues over a five year period increased biomass C by approximately 15% whereas total organic C increased by only 9%.

The effects of organic matter on soil physical, chemical, and biological properties should not be considered in isolation; they are interactive to a considerable extent.

Dynamics of Soil Organic Matter

The organic matter content of a soil reflects the balance between additions and losses largely due to decomposition. The decomposition process is catalysed by the soil micro- and meso-fauna, and the microflora, which together constitute the soil biomass. The biomass itself constitutes part of the soil organic matter and is its most dynamic pool (Jenkinson 1988). The rate of decomposition of soil organic matter and the size of the soil biomass fluctuate in response to changes in the levels of substrate and in the environmental conditions. In the tropics, soil organic matter usually decomposes rapidly because of the high temperatures. A comprehensive review of the dynamics of soil organic matter is beyond the scope of this paper but some of the major factors affecting the decomposition process are discussed below.

Substrate

The quality of the organic substrate significantly affects the rate of decomposition. Cereal crop residues and grass decompose slowly because of their low N and S contents. Decomposition of these materials will cause net immobilisation of inorganic nutrients in the soil, reducing the availability of nutrients to crops. Recent work in Southeast Asia, with low external input systems on acid soils, showed that unless nutrient deficiencies are addressed, crop yields do not respond to inputs of organic residues (Siem et al. 1994). Phosphorus additions increase plant growth and N fixation by legumes, thus enhancing the quantity and quality of crop residues. Legume residues do not generally immobilise nutrients, because of their higher N contents. Other papers at this workshop elaborate on this point.

Water

The effects of the soil water content on decomposition are complex. Decomposition requires adequate soil moisture to proceed, but excess water restricts access of the oxygen to the decomposition sites and causes major changes in the nature and products of the process (Neue et al. 1994). Anaerobic decomposition or fermentation results in products such as volatile fatty acids, carbon dioxide and methane, depending on the degree of reduction of the soil system. The rate of decomposition is slowed under waterlogged conditions, although Greenland et al. (1992) cite data suggesting that decomposition is sufficiently rapid at temperatures >30°C to prevent organic matter accumulation. Most lowland soils used for rice production in the humid tropics are drained during the dry season when aerobic decomposition can occur. Nevertheless, as mentioned above, prolonged submergence due to the increasingly widespread practice of growing 2 or 3 rice crops per year in irrigated areas, is having deleterious effects on the pattern of nutrient supply.

Water has another major impact on the dynamics of organic matter through the effect of wetting and drying on decomposition. This phenomenon, commonly called the 'Birch effect', can have a significant effect on organic matter dynamics in areas with a pronounced dry season.

The dynamic nature and complexity of the decomposition and nutrient cycling processes in soil can be simplified and captured in mathematical models, such as the Rothamsted carbon model, CENTURY, NTRM, NCSOIL, and others (Young 1994). These models have largely been developed in temperate systems and validated against data from long-term experiments. Such experiments are sadly lacking in the humid tropics, although through the foresight of early IRRI scientists, long-term studies of the effects of intensive rice production were initiated 30 years ago (Cassman et al. 1994).Given the fact that the amounts and quality of soil organic matter in temperate and tropical soils are roughly the same, the models developed to describe turnover in the former (Jenkinson et al. 1987) should be applicable to the latter, although the rate factors, determined essentially by temperature, should vary.

Soil Organic Matter in Sustainable Farming Systems

Soils under native vegetation vary considerably in organic matter content, depending on the type of climax vegetation, climate, parent material, and drainage. In nature, soil organic matter levels represent a dynamic equilibrium between litter fall and root residue inputs on the one hand and the inexorable loss of C due to decomposition on the other. Irrespective of their native organic matter content, soils developed for agriculture inevitably show a decline in organic matter because (i) the inputs of plant C are generally less in agricultural systems than in nature and (ii) tillage and other agricultural practices increase the rate of decomposition of soil organic matter by mixing the surface soil and increasing the number and intensity of wetting and drying cycles. The sustainability of agricultural production systems depends on maintaining the reserves of soil organic matter at the minimum levels necessary to protect the soil and maintain productivity. As discussed below, organic matter maintenance depends on inputs such as labour or fertilizers — there is no free lunch.

Up until 30 years ago, traditional farming systems in Asia produced sufficient food over the last few millennia to support a large population. The population was concentrated in the seasonally flooded lowlands where soil fertility was maintained by silt transported in runoff from the uplands and by inputs from aquatic nitrogen fixers, such as blue-green algae and azolla (Watanabe et al. 1981). The mineralisation of accumulated organic N, and the P made available when the soil was flooded, proved sufficient to produce annual rice crops of 1–2 t/ha *ad infinitum*, i.e., at this yield level the system was sustainable. The relatively small population in the uplands produced maize and upland rice under shifting cultivation in the tropical forests (Sajise and Ganapin 1991). This system, like the traditional lowland rice system described above, was also sustainable because the area of land available permitted periods of bush fallow of 20–30 years which were sufficiently long to restore soil organic matter levels for the next brief cropping period. According to Palm et al. (1994), it takes up to 35 years of bush fallow to restore the 20–30% of soil organic matter lost during a 2-year cropping period.

Population growth in Asia during the past three decades has placed tremendous pressures on the resource base for agriculture. Craswell and Pushparajah (1991) cite data predicting a shift in the ratio of arable land to population from 0.34 ha/caput in 1961 to 0.2 ha/caput in 2000. The population growth has caused changes in the intensity of cropping in most of the farming systems in the region. In the lowlands, population growth led to massive increases in rice production based on large increases in fertilizer use, use of improved varieties, and a greater cropping intensity (Craswell and Karjalainen 1990). Cassman et al. (1994), reviewing data from long-term experiments in the Philippines, found that soil organic matter levels are stable or increase in intensive irrigated rice systems, even when rice crop residues are completely removed from the system. However, they also postulate that the long-term flooding of the soil changes the nature of the soil organic matter by immobilising N. The large rainfed rice-growing areas receive less fertilizer, have lower crop yields, and would be expected to have lower soil organic matter levels.

As a result of population growth and reduced availability of land in the uplands, bush fallow periods have declined and the increased pace of logging of tropical forests has left large areas denuded of vegetation, other than pernicious weeds such as *Imperata cylindrica*. The inherent infertility of the acid soils which dominate the uplands makes the long-term production of food crops a difficult proposition. Consequently, upland farmers cultivating steep land areas for continuous production of food crop expose the land to erosion which accelerates the loss of soil organic matter. Upland farmers have been the neglected clients for agricultural research in Asia and few appropriate technologies are available for sustainable food crop production (Craswell 1987). The region does, however, have sustainable plantation-crop systems which are widely employed by smallholders for the production of acid-tolerant trees such as rubber and oil palm (Zakaria et al. 1987). Land developed for plantation crops is planted with cover crop legumes, such as *Calapogonium* and *Pueraria,* which stabilise the soil surface, fix N, and maintain soil organic matter.

Management of Soil Organic Matter

Over the last decade, national and international research agencies in the region have increasingly turned their attention to the problems of the uplands. IBSRAM and ACIAR have supported national program efforts through networks focused on the sustainable management of acid soils and steep lands. In the irrigated and rainfed lowlands, national programs working with IRRI in the INSURF and other networks and consortia have evaluated technologies for organic matter management, focusing on rainfed areas where the risk factor discourages many farmers from purchasing fertilizers. A central theme of much of the work is to minimise external inputs by utilising N-fixing legumes and maintaining soil fertility through management of organic matter inputs. Table 1 summarises the production systems which are being tested and the organic matter management practices under study.

Table 1 cites many examples of crop and animal sources of organic matter which can be managed to improve the soil in different cropping systems. The benefits of these organic matter inputs in the context of sustainability have been expounded above and will not be repeated here. Nevertheless, commonly, smallholders in Asia have not readily adopted improved practices for organic matter management. In Table 1 we have therefore listed some of the key constraints to the adoption of these practices. Opportunity costs are probably the most important factors influencing farmers' decisions about the management of organic matter (Izac 1994). Farmers must weigh the monetary and non-monetary costs of particular practices in the context of their planning horizon, which for most farmers is short (2–3 years). More on-farm research on organic matter management is clearly needed to assess the economic viability and social acceptability of the technologies proposed by researchers. Furthermore, governments should play a more active role in promoting community programs that introduce farmers to the benefits of sustainable land management.

Soil Organic Matter and Sustainability

It is widely recognised that the maintenance of an adequate level of soil organic matter should be a guiding principle in developing appropriate soil management practices. However, as emphasised by Greenland (1988), just what constitutes an adequate level of soil organic matter varies between soil types, different farming systems, and environmental condi-

Table 1. Summary of options for organic matter management in selected cropping systems.

Production system	Sources of organic matter	Key constraints to adoption
Lowland		
Rice	Azolla	Poor water control, labour, P fertilizer
	Green manure	Labour, seed costs
	Rice straw/compost	Labour
	Food legume rotation	Water, soil physical condition
Upland		
Food crops	Farmyard manure	Alternative uses, labour
	Food legume intercrops	Weed control
	Grass weed residues	Labour
Plantation crops	Cover crop legumes	Establishment cost
	Food crop residues	Fertilizer costs, labour
	Legume/grass pastures	Establishment, management skills
	Mill effluent	Transportation/distribution cost
Hedgerow systems	Shrub legumes	Labour, land tenure

tions. Establishing an optimum level of soil organic matter for a given system is seen to be a logical starting point for establishing practices which aim to manage inputs and depletion to maintain that optimum level.

It is also well established that natural levels of soil organic matter decline following cultivation but that the rate of decline is dependent on management practices and inputs, particularly crop residues, green manures, and animal wastes. Further, if the quantity of soil organic matter is declining then it is usual to find that soil productivity is also declining. Papendick (1994) has described how the organic matter content of many prairie soils in the USA has declined by approximately 30% following 100 years or more of cultivation. Although levels appear to have stabilised, it is not known whether the levels reached are sustainable and will maintain a satisfactory level of productivity in the future.

Increasing commitment to the concept of developing sustainable agricultural systems has focused attention on the need for indicators for assessing sustainability (Syers et al. 1994). In discussing indicators of sustainable land management for the humid tropics and subtropics, a working group at the Lethbridge International Workshop on Sustainable Land Management for the 21st Century concluded that changes in soil organic matter fractions were a useful indicator of sustainable land management (Dumanski 1994). Having established the potential value of soil organic matter as an indicator of sustainability, the difficulty of defining thresholds becomes apparent. Thresholds may be defined as levels of indicators beyond which a system undergoes significant change. In the present context a threshold value provides a baseline against which sustainability can be assessed.

In spite of the considerable literature on changes in soil organic matter levels with changing management practices over time, there is remarkably little information on threshold values. The long-term experiments at Rothamsted have produced much useful information on changes in soil humus content as influenced by management practices (Powlson and Johnston 1994) which has been particularly valuable for model development. But, in reality, little information on threshold values for sustainability assessment has been obtained from these and other long-term experiments up to the present time. With the current increase in interest in evaluating sustainability (Smyth and Dumanski 1993) and the need to develop meaningful indicators and thresholds to facilitate that evaluation (Syers et al. 1994), this is seen to be a limitation and there is an urgent need for detailed investigations of the inter-relationships between soil organic matter levels and key soil physical, chemical, and biological properties that influence sustainable crop growth.

Recent Research and Future Requirements

There is a long history of soil organic matter studies but up until fairly recently there have been very few major advances. Obsession with the search for 'true humus' and its properties has distracted soil scientists from more productive avenues of research. The need to better understand the dynamics of soil organic matter has already been highlighted and this provides the basis for developing predictive ability, particularly with regard to sustainability issues, through the use of models.

Presently perceived research requirements include more sensitive techniques for assessing soil organic matter changes, long-term data sets for crop yield in relation to soil organic matter and other potential indicators, against which sustainability can be assessed, and better information on the dynamics of soil organic matter that can be incorporated into models to provide the basis for improved management practices. These will be discussed briefly.

Microbial biomass C is emerging as a sensitive and reliable indicator for assessing changes in soil organic C. Because of its high turnover rate (Paul 1984), microbial biomass reacts much more quickly to changes in management than does total organic matter content. The larger proportional change in microbial biomass than in soil organic matter (Sparling 1991) makes microbial biomass C a more sensitive indicator of organic matter flux than changes in total or organic carbon. This is particularly useful for monitoring changes in soil organic matter when levels of the latter are low (O'Donnell et al. 1994). The substantial changes in microbial C under different cropping and cultivation regimes, when changes in total organic C were relatively small, reported by Powlson and Johnston (1994), are consistent with this. Microbial C now figures in two recent models of organic matter dynamics (Parton et al. 1988; Jenkinson et al. 1987) which are finding widespread use in understanding accumulation and decomposition processes, and in providing valuable information on the predicted rate of change of soil organic matter, as influenced by management practices. Further evaluation of microbial biomass C as a tool in monitoring and predicting soil organic matter changes is required, particularly in tropical soils where little work has been done.

Long-term experiments are a valuable resource for understanding the effects of management practices on soil organic matter levels and crop yield (Powlson and Johnston 1994). In particular they provide opportunities for model development, testing, and validation. Greenland et al. (1994) have recently commented on the necessity of having a series of long-term experiments in different agroecological zones to experimentally study organic matter dynamics and water use and nutrient flow associated with changes in soil, water, and nutrient management. The implication of this is that key, existing long-term experiments must be continued and new ones started in agroecological zones where data are needed.

Knowledge of soil organic matter dynamics is now at an exciting stage of development with the increasing use of stable isotopes (^{13}C and ^{15}N). The natural abundance of ^{13}C is now being used to investigate the turnover of soil organic matter resulting from changes in the photosynthetic pathway of organic material inputs (e.g. Martin et al. 1990; Cerri et al. 1991). For example, soil studies of organic matter dynamics following deforestation and long-term cultivation (Cerri et al. 1991) have shown that it is possible to quantify the losses of humus derived from native vegetation and the carbon input from crop residues. This is important work and the potential of using ^{13}C and ^{15}N to monitor the effects of climate change, in particular, on organic matter dynamics is an exciting one.

Increasingly, work on soil organic matter will require a more holistic and integrated approach if it is to fulfill its full potential in assisting with the development of sustainable agricultural systems. In particular, component technologies involving organic matter management must be assessed in terms of economic viability, environmental, and social acceptability. Recent developments in methodology for such assessments and the recognition of the importance of soil organic matter to sustainable agriculture and to the evaluation of sustainability bode well for the future of soil organic matter research.

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The Role of Mulches and Terracing in Crop Production and Water, Soil and Nutrient Management in East Java, Indonesia

Sutrisno*, Y.A. Arifandi*, A.R. Till†, Nursasongko*, S. Winarso* and G.J. Blair†

Abstract

Loss of topsoil and nutrients represents a loss of capital from agricultural systems and water conservation is important both on and off site.

A field experiment was conducted at Pakel, E. Java in which crop yield and soil, water and nutrient dynamics were monitored over one season in runoff plots. The treatments consisted of non-terraced (15° slope) and terraced (4 terraces/20 m) slopes. Mulches (zero, rice straw, *Flemingia macrophylla* leaf applied at 2t/ha) were applied in factorial combination at the time of interplanting rice and corn.

Terracing resulted in a reduced yield of corn due to less plants per lot because of terracing. Rice grain and straw yield was higher in the terraced plots.

The application of Flemingia mulch reduced runoff from 13% of incident rainfall in the control to 3% and soil loss from 15–8 t/ha to 1.0 t/ha. Rice straw mulch increased water infiltration under low intensity rainfall but increased runoff above the control under high intensity rainfall.

Using current fertilizer prices Flemingia mulch resulted in a reduction in the fertilizer-equivalent value K and P from US$2.14 to US$0.02/ha.

These findings have important offsite and onsite consequences and the effects are anticipated to compound in later years.

THE island of Java has been subjected to human activities since approximately 500 000 B.C. In the last 140 years the population of Java has risen from 10 million to 130 million in 1990 (Donner 1987). This increasing population pressure, which has been accompanied by forest clearing and an increased area and intensity of cultivation, has resulted in increased erosion. Hollerwöger (1966) estimates that the Bodi River delta in Central Java expanded in area at 0.128 km^2/year from 1864 to 1910 and that this rate of expansion increased to 0.422 km^2/year from 1910 to 1946 as population pressures increased.

Stoddart (1969) reported that soil loss from the Brantas and Konto river catchments in Java amounted to 22.8 t/ha/year. This value is compared with the estimated losses of 73.1 t/ha/year transport by the Lo River tributary of the Yellow River in China, and 2.14 t/ha/year transported by the Mekong River in Laos.

Coster (1938) summarised numerous studies from small plots in Java and found that runoff, expressed as a percentage of annual rainfall, was from 25–55% from bare soil, 2.0–16.2% for dry-land farming, 0.28–5.4% from Imperata grassland and 1.3–6.2% from rainforest. Such soil and water losses leads to high river flows during periods of rainfall and depletion of soil and nutrient reserves in upland areas of the catchments. Degradation of the soil resources means that increasing rates of fertilizer are required to maintain production and that increased flooding, deposition of poorer soil, and blocked irrigation systems are negative consequences for downstream areas.

The experiment reported here was undertaken to examine the effects of terracing and mulching on crop production and soil, water and nutrient losses in an upland area of E. Java, Indonesia.

* Environmental Studies Unit, Department of Soil Science, Jember University, Jember, East Java, Indonesia.

† Department of Agronomy and Soil Science, University of New England, Armidale, NSW 2351, Australia.

Materials and Methods

A series of 24 runoff plots was established in October 1993 on a Alfisol soil 10 km NW of Bondowoso in E. Java. The slope is approximately fifteen degrees, and when dry the soil develops wide cracks down to an apparent hard pan at 20 cm. Some of the other physical and chemical properties of the soil are presented in Table 1. The 20 m long × 3 m wide plots were laid out in 4 randomised blocks, the longitudinal axis was upslope and the individual plots were separated by 60 cm high sheet metal partitions set 20 cm into the soil. Silt and water traps were installed at the lowest point of each plot and the whole area was protected from unusually high surface flows by drains around the high (uphill) ends and sides. The treatments used included two slope managements, unchanged and mini-terraced, and three ground cover methods, bare soil, rice straw at 2 t/ha or Flemingia leaf litter at 2 t/ha were used. There were four replicates.

The terraces, each 5 m long, were constructed within the appropriate plots and seedlings of *Flemingia macrophylla*, which had been grown in a nursery at approximately 2 cm spacings for two months, were transplanted into the lip of the terrace. Because the transplanting took place prior to the commencement of the wet season the seedlings were watered to ensure establishment. The plots were interplanted to rice and maize (4 rows of rice and 1 row of maize) on November 19, 1993. After the commencement of the wet season the rice straw or Flemingia leaves, equivalent to 2 t/ha, were applied. Rice (local variety Kloner) was sown in rows 20 cm apart with 5 cm between seeds. Maize seed (local variety) was sown 2 per hill, with 20 cm between hills, in rows 1m apart across the slope. In the non-terraced treatments there were 19 rows per plot. Because of the risers in the terraced plots only 16 rows were sown in these plots.

At planting the mulch was pushed back from the planting row and a small slot made across the slope. Fertilizers were applied into the slot at 150 kg/ha of triple superphosphate and 50 kg/ha of urea and the seed planted. Approximately 50 days after planting the plots were topdressed with urea at 25 kg/ha.

Sticks of cassava were planted at 50 cm spacings within the rows of maize on January 31, 1994 but competition from the established rice plants resulted in poor growth. Mid-way through the experiment the Flemingia was cut to 25 cm and the cut material returned to each of the terraced plots irrespective of the leaf mulch treatment at the start of the experiment. In the terraced control, and terraced rice straw plots the Flemingia prunings were removed from the plots.

Maize was harvested at maturity (February 19, 1994). At harvest the cobs plus husks were removed and the plants cut near ground level and similarly removed from the plot. Rice was also harvested at maturity (April 2, 1994) and grain and straw separated and removed from the plot.

Data from the experiment were analysed as a randomised block design having 2 terrace (nil, terraced) × 3 mulch (0, rice straw, Flemingia) × 4 replicate factorial.

Rainfall was measured adjacent to the site in a recording rainguage. Runoff water and sediment were collected once each day when rainfall occurred. Runoff was calculated from depth measurements in both the collection box and the overflow drum which collected a pre-determined proportion of the overflow. The water and sediment were thoroughly mixed and a subsample taken from the containers for the determination of sediment load and for chemical analysis. Samples were filtered adjacent to the site and transported to Jember University for analysis. Soil sediment samples were dried at 105°C for 24 hours prior to analysis.

Table 1. **Physical and chemical properities of the soil at the experimental site.**

Physical		Chemical	
Sand	31.1%	pH $_{H2O}$	5.87
Silt	19.3%	pH $_{KCl}$	4.5
Clay	50.6%	Bray-2 P	3.5 µg/g
Permeability	2.7 cm/hour	Exchangeable K	12 µg/g
Bulk density	1.36 g /cm^3	Ca	59 µg/g
Total porosity	41.1%	Mg	27 µg/g
Infiltration rate	1.13 cm/hour	CEC	14.8 meq/100
		Base/saturation	78%

The Ca and Mg concentration in the filtered runoff water was measured by atomic absorption spectroscopy and the K and Na on a flame photometer. P was measured colorimetrically. Exchangeable cations (K, Ca, Mg and Na) were removed from the dried sediment sample by ammonium acetate and measured as for the plant samples. P was extracted from the sediment using the Bray-2 method. Organic matter was determined by the Wakley-Black procedure. Plant samples were ground, digested in a sealed chamber, and analysed by ICP–AES.

Results

Crop yields

There was no significant effect of mulch on grain or crop residue yields in either the maize or rice crops. Terracing however resulted in both lower grain and residue yields in maize and a higher grain yield in rice (Table 2). Terracing did not affect rice straw yields.

The lower maize yield in the terraced treatments was due to a lower plant density in these plots. Terracing meant that only 16 rows of maize could be planted in these plots compared to 19 in the non-terraced plots.

Water runoff and sediment loss

There was a significant terracing × mulch interaction in both water runoff and sediment loss. Water runoff was significantly higher in the non-terraced than the terraced plots within each mulch treatment (Table 3). In the non-terraced plots water runoff was in the order rice straw>control>Flemingia whereas on the terraced plots the order was control= rice straw> Flemingia.

Water loss from the plots ranged from a high of 22.2% of rainfall in the non-terraced, rice straw-mulched plots down to 0.3% in the terraced Flemingia treatment (Table 3). There was a significant linear relationship of the form Y = a + bX between Y = daily water runoff (L/plot) and X = rainfall (mm) for

Table 2. Maize and rice grain, residue and total yields (kg/plot) on terraced and non-terraced plots.

Treatment	Terrace	Non-terrace
Maize grain	9.90 a*	8.17 b
Maize cob + husk	16.74 a	13.87 b
Maize stover	13.81 a	10.23 b
Maize total	40.45 a	32.27 b
Rice grain	4.45 b	5.90 a
Rice straw	14.0 a	12.55 a
Rice total	18.46 a	18.45 a

*Numbers within a row followed by the same letter are not significantly different (P<0.05) according to Duncan's Multiple Range Test.

Table 3. **Total water runoff and % of incident rainfall lost in runoff, and soil loss in sediment over the 110-day experimental period.**

Treatment		Runoff		Soil loss	
Terrace	Mulch	L/plot	% of rainfall	kg/plot	t/ha
Non	0	8756 b*	13.0	95 a	15.83
	Rice straw	14905 a	22.2	78 b	13.00
	Flemingia	2101 c	3.1	6 c	1.00
Terraced	0	2706 c	4.0	8 c	1.33
	Rice straw	2057 c	3.2	4 c	0.67
	Flemingia	198 d	0.3	1 c	0.16

*Numbers within a column followed by the same letter are not significantly different.

the 55 rainfall events which occurred throughout the experiment. The a, b, and r^2 values for the relationships varied and these are presented in Table 4. The relationships varied between treatments with the highest runoff per mm rainfall in the non-terraced rice straw-mulched treatment (Table 4). More rainfall was also required to commence runoff in this treatment.

Soil loss was highest in the non-terraced control plots (Table 2) . Soil loss did not differ between the terraced treatments and the non-terraced Flemingia plots. When expressed as loss per ha the loss from the control plots amounted to 15.833 t/ha over the 110-day period. This was reduced to 0.167 t/ha in the terraced, Flemingia treatment.

Nutrient loss in runoff water

Nutrient loss in runoff water was determined for 3 × 20-day periods (0–20, 41–60, 81–90 days). As for the whole experiment runoff in this 60-day period was highest in the non-terraced, rice straw treatment and lowest in the terraced, Flemingia-mulched, treatment (Table 5).

Nutrient loss in runoff and sediment

There were significant differences between treatments for all measured nutrients lost in runoff (Table 5). Loss of K, Ca, Mg and Na was highest in the non-terraced control and rice straw-mulched treatments. Averaged over all treatments, the ratio of nutrient loss in runoff water was 6.0 K: 3.2 Na : 3.0 Mg : 1.6 Ca : 1.0 P. Exchangeable cation and Bray-2 P loss in sediment was also highest in the control and lowest in the terraced Flemingia plots (Table 6). Over the 60-day period when measurements were made sediment losses were 102.9 kg/plot and exchangeable cation and Bray-2 P losses totalled 201.2 g/plot in the control treatment. No sediment was lost from the terraced Flemingia plots (Table 6).

Table 4. Linear relationship (Y = a + bX) between Y= water runoff (L/plot) and X = daily rainfall (mm) for the 55 rainfall events over the 110-day experimental period.

Treatment		a	b	r^2
Terrace	Mulch			
Non	0	–26.95	9.48	0.67
	Rice straw	–65.63	15.71	0.78
	Flemingia	–30.87	4.95	0.60
Terraced	0	–27.14	3.32	0.31
	Rice straw	–40.72	4.62	0.64
	Flemingia	–10.17	0.68	0.26

Table 5. Runoff and nutrient loss in runoff water over a 60-day period.

Treatment		Runoff	Nutrient loss (g/plot)				
Terrace	Mulch	(L)	K	Ca	Mg	Na	P
Non	0	4100 b*	18.5 a	3.8 a	7.8 a	12.4 a	4.2 a
	Rice straw	6717 a	25.6 a	4.0 a	7.4 a	1.7 a	1.7 b
	Flemingia	933 c	5.2 b	1.0 b	2.1 b	2.3 c	0.7 bc
Terraced	0	1179 c	4.8 b	0.8 b	1.5 c	3.2 b	0.2 c
	Rice straw	703 c	4.0 b	0.9 b	1.2 c	1.7 c	0.0 c
	Flemingia	171 d	1.1 c	0.2 c	0.2 d	0.3 d	0.0 c

*Numbers in a column followed by the same letter are not significantly different.

An estimate has been made of the replacement value of the P and K lost. A total of 13.23 kg K/ha and 1.07 kg P/ha was lost from the control plots over the 60-day measurement period and this was reduced to 0.18 kg K/ha and zero P in the terraced Flemingia treatment. These losses alone are equivalent to US$ 2.14 and US$ 0.02, respectively, in applied fertilizer value (Table 7).

Nutrient removal in crops

There was no significant treatment effect on nutrient removal in grain or in the nutrient content of crop residues.

Discussion

Estimates of soil loss made in the sub-Desa Sampean Hulu (RKLT 1987), in which Pakel is located, indicate that 40% of the area suffers class 1 erosion (<15 t/ha/year), 18% class 2 (15–60 t/ha/year), 26% class 3 (60–180 t/ha/year), and 18% class 4 (180–480 t/ha/year). The soil loss of 15.8 t/ha over 60 days from the control plots in the present study puts this area into class 1 and is of the same order as that reported by Stoddart (1969) for other catchments in Java. Terracing alone reduced this loss to 1.3 t/ha and terracing and the application of Flemingia mulch reduced this to only 167 kg/ha. The reduction in soil loss resulting from conservation practices in this experiment was greater than that found in experiments in N and NE Thailand by Aneckasamphant et al. (1991) when either hillside ditches or grass strips were introduced on sloping land.

Runoff, expressed as a percentage of incident rainfall, amounted to 13.0% in the control treatment which is within the 2.0–16.2% range for dryland cropping reported by Coster (1938). Addition of rice straw mulch increased the amount of rainfall necessary for runoff to commence (coefficient a in Table 4) but also increased the runoff rate once it commenced (b value in Table 4). This is presumably the result of an increased initial infiltration rate due to greater retention of water in the coarse mulch and, in higher rainfall events a 'thatch effect' which sheds water from the surface. Terracing alone was an effective way of reducing runoff and terracing plus Flemingia reduced runoff to only 0.3% of rainfall.

Because of the presence of a flume in the small stream which drains the catchment in which the experiment is located it was possible to examine the relationship between stream flow (Y L/secs) and rainfall (X mm/day) during the period from November 26, 1993 to February 3, 1994. The relationship was found to be $Y = 34.9 + 1.12 X$ ($r^2 = 0.18$, 14 df), indicating that for the whole catchment, which essentially consists of a series of interconnected continuous terraces of differing slope, runoff was lower than that for the single continuous terrace used in this study.

The reduction in soil loss as a result of the introduction of terracing and/or mulch has a positive on-site and off-site benefit. The farmer maintains soil and soil fertility for future cropping and those downstream do not suffer problems of dam and river siltation and/or deposition of poor quality soil onto highly fertile land.

The consequences of greater retention of rainfall resulting from conservation practices on sloping land are more difficult to assess. Higher infiltration rates may mean better soil moisture relationships in soils with high clay content such as that used in the experiment reported here. However, in sandy soils this may mean greater sub-surface flow and higher leaching losses.

Retention of more rainfall in upland areas can also have negative consequences for irrigated agriculture downstream because of reduced flow into dams and

Table 6. Sediment, and nutrient and organic matter loss in sediment over a 60-day period.

Treatment		Sediment	Nutrient loss (g/plot)					O.M.Loss
Terrace	Mulch	Loss (kg)	K	Ca	Mg	Na	P	(g/plot)
Non	0	81.8 a*	60.9 a	86.4 a	33.2 b	17.9 a	2.8 a	4.4 a
	Rice straw	63.4 b	42.6 b	93.4 a	52.0 a	17.1 a	1.7 b	3.3 a
	Flemingia	5.6 b	4.2 c	6.6 b	4.5 c	0.9 b	0.1 c	0.2 b
Terraced	0	6.6 c	4.8 c	11.4 b	6.1 c	1.6 b	0.2 c	0.2 b
	Rice straw	2.4 c	5.4 c	0.5 c	1.0 d	2.3 b	0.0 c	0.2 b
	Flemingia	0.0 d	0.0 d	0.0 c	0.0 d	0.0 b	0.0 c	0.0 b

*Numbers in a column followed by the same letter are not significantly different.

Table 7. Quantity (kg/ha) and value ($US/ha) of nutrients lost in runoff water and sediment in 60 days from diverse treatments of the Pakel cropping systems experiment.

Nutrient loss in:	K		P	
	Control	Terraced Flemingia	Control	Terraced Flemingia
Runoff (kg/ha)	3.08	0.18	0.70	0.0
Sediment (kg/ha)	10.15	0.0	0.47	0.0
Total loss	13.23	0.18	1.07	0.0
Value of nutrients loss ($US/ha)*				
Runoff	0.31	0.02	0.49	0.0
Sediment	1.01	0.0	0.33	0.0
Total	1.32	0.02	0.82	0.0

*KCl Rp400/kg, TSP Rp350/kg, $US = Rp2100

reservoirs. Increasingly farmers in upland areas are adopting the attitude of 'the best use of rainfall is on my land where it falls'.

This experiment has demonstrated the impact of terracing and mulch type on crop growth, and soil and water dynamics. Although the impact of these treatments was not evident in crop yield in the first year of the experiment it is anticipated that crop responses will become evident in the second and subsequent years as the impacts of soil and nutrient loss accumulate.

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Organic Matter Management in Upland Systems in Thailand

Samnao Phetchawee* and Waree Chaitep†

Abstract

The practice of agriculture in the tropics generally results in significant reductions in soil organic matter, which in turn results in reductions in the chemical, physical and biological fertility of the soil. Attempts have been made to restore or maintain soil fertility by the introduction of well adapted legumes into the cropping systems in Thailand. For corn–legume cropping on sandy soils, high corn yields have been obtained by intercropping corn with verano (*Stylosanthes hamata*) with minimum tillage and fertilisation. Corn–rice–bean intercropping has proved to be feasible on clay soils. High cassava production has been obtained with cassava–cowpea+pigeon pea and cassava–mungbean+pigeon pea cropping systems. Additional advantages have been obtained from the long-term incorporation of cassava leaves and stems.

AGRICULTURAL products form a major part of Thailand's economy. Nearly 80% of the population is engaged in agriculture. As a result of increased population, significant areas of forests have been converted into cultivated land, with forest lands decreasing to 28% of the total land of the country in 1990 (Agriculture Statistics of Thailand 1990/91). This is lower than the 40% forest cover suggested as necessary to maintain the natural environment. The current government policy to restrict the further destruction of reserved forest means that the productivity of cultivated land needs to be increased by introduction of appropriate technologies, including new improved varieties, effective control of weeds, pests and diseases and improved soil management.

The conversion of forests to cultivated land generally coincides with a large reduction in soil fertility as a result of a decline in soil organic matter. Soil organic matter is a reserve of nutrients in the soil, and is exploited rapidly when farmed under tropical conditions. The importance of organic matter in crop production has been recognised in many countries together with a growing interest in sustainable agriculture and recognition that continued use of chemical fertilizers may result in deterioration of soils.

* Soil Science Division, Department of Agriculture, Ngamwongwan Road, Chatuchak, Bangkok 10900, Thailand.

† Sanpathong Rice Experiment Station, Amphoc Sanpathong, 501200 Chiang Mai, Thailand.

Functions of Organic Matter in Soil

Soil organic matter plays a number of very important roles and the amount of organic matter is often used as a direct index of soil fertility. Soil organic matter derives from plant tissues and animal residues in the soil. The formation of humus occurs after the organic matter is decomposed in association with microbial activity. Organic matter plays an important role in the improvement of soil physical properties, such as the promotion of soil aggregation, improved permeability and aeration of clay soils, increased moisture holding capacity, aggregation of sandy soil and improved nutrient holding capacity (Hsieh and Hsieh 1990). In regard to chemical properties, organic matter often accounts for at least half the cation exchange and buffering capacity of the soil. The decomposition of organic matter releases many nutrients, such as nitrogen, phosphorus, potassium and sulfur, as well as many secondary and micro nutrients (Hsieh and Hsieh 1990). In regard to biological properties, soil organic matter increases the population of beneficial soil microorganisms.

Distribution of Soil Organic Matter

During cultivation of land for agriculture, the soil organic matter supplies plant nutrients to crops until the native soil fertility is exhausted. It was estimated in 1989 that soils across 30% of the total area of Thailand contained less than 1.5% soil organic matter (Table 1). A survey of 244 upland soil types in Thailand indicated that the median value of organic matter varied with region, from a high of 2.03% in the Central Plain to a low of 0.74% in the Northeast (Table 2). In terms of land form, the survey showed that the surface of lowland soils contained a median value of 1.74% organic matter, while the upland surface soils contained 1.34% organic matter. Over all soil types in the country the soil organic matter is considered to be low.

The low soil organic matter means a reduced potential for high crop yield, especially because many poor farmers have grown crops with no fertilizer for much of the last two decades. Currently farmers are applying increasing amounts of chemical fertilizers. The consumption of chemical fertilizers has increased by nearly 70-fold in the 33 years from 1957 to 1990 (Table 3). The importation of chemical fertilizers to Thailand amounted to 0.04 million t in 1975, with consumption reaching 2.7 million t in 1990. It is suggested that the current practice of long-term application of fairly limited amounts of NPK fertilizers has resulted in a deterioration in many soil properties, leading to a decline in crop yield. We believe that this trend will be reversed only by application of a combination of organic and chemical fertilizers.

Table 1. Soil organic matter content in Thai soils as estimated in 1980.

Soil organic matter (%)	Area (million ha)	Percent of area
0–1.5	15.798	30.8
1.5–3.5	17.543	34.2
3.5–5.0	1.605	3.1
5.0–7.0	0.504	1.0
>20	0.080	0.2
Others	15.782	30.8
Total	51.312	100

Source: Anandhana (1989).

Table 2. Distribution of organic matter in upland surface soil of various regions of Thailand.

Region	No. of samples	Organic matter (%)[a]
Central	43	2.03
Southern	88	1.60
Northern	24	1.47
Eastern	34	0.84
Northeast	55	0.74
Total	244	

Source: Sathien (1994).
[a]Median value.

Source of Organic Materials

There are eight major sources of organic materials in Thailand: i) crop residues, ii) green manure, iii) compost, iv) residues from agro-industrial wastes, v) cattle manure, vi) swine manure, vii) poultry manure and viii) municipal compost. Dhanyadee (1987) reported on the source, quantity and chemical characteristic of organic materials which can be used as fertilizer for crops in Thailand (Table 4).

The total quantity of organic materials in the country contain a huge amount of plant nutrients, which can be used to reduce the use of imported chemical fertilizers. The bulky nature of these materials means that many farmers avoid using them, but organic materials have been found to be practical in vegetable farms, field crops and perennials, provided the materials are available near the farms or can be easily transported.

Table 3. Use of chemical fertilizers in Thailand.

Year	Amount ('000 t)
1957	39.9
1967	217.9
1977	870.6
1982	959.8
1987	1722.2
1988	2087.1
1989	2506.8
1990	2724.7

Source: Center for Agricultural Statistics (1992).

Organic matter management in upland systems

As mentioned, upland soils are generally of low fertility, with low organic matter content, especially in the coarse textured soils which occur widely in all regions. Since these soils have deteriorated through the inappropriate management systems applied for a long time, there is a need to develop sustainable agricultural systems in order to return the soils to a productive state closer to their natural condition

Table 4. Quantity and chemical characteristics of organic materials produced in Thailand

Source	Quantity ('000 t/year)	Chemical characteristics pH	C/N	N	P (%)	K
Crop residues	**34 300**					
Rice straw	27 000	8.2	89	0.55	0.04	1.98
Corn residues	1 000	8.2	62	0.53	0.06	1.83
Soy and mungbean residues	500	8.1	16	3.34	0.42	2.10
Water hyacinth	5 800	7.8	34	1.27	0.29	4.02
Agro-industrial wastes	**11 760**					
Bagasse	6 700	6.0	146	0.40	0.06	0.37
Sawdust	30	5.4	496	0.32	0.06	2.45
Coconut dust	30	6.1	167	0.36	0.01	2.07
Rice hull	5 000	6.1	152	0.36	0.04	0.90
Municipal wastes	**15 000**					
Municipal wastes	3 000	5.9	39	1.20	0.64	8.58
Night soil	12 000	–	–	0.57	0.02	0.60
Animal wastes	**21 000**					
Cattle manure	16 000	8.3	–	1.58	0.03	1.34
Swine manure	3 000	6.8	–	2.71	1.37	0.81
Poultry manure	2 000	7.2	–	1.23	0.87	1.31
Total	82 060					

Source: Dhanyadee (1987).

prior to clearing. Due to the nature of the soils and the farming population, low input technologies need to be adopted using improved organic matter management. These systems are likely to include stubble mulching, the use of well adapted legumes in intercropping or rotation systems and the use of minimum tillage. These practices have proved profitable in corn, sorghum, cassava and kenaf production.

Neiro (1992) reported on a number of promising tropical legume species and management systems which are well adapted to sandy soils.

Green manuring crops. Neiro (1992) investigated a number of tropical legumes for their potential as green manuring crops (Table 5). Sunhemp (*Crotalarea juncea*) produced the maximum biomass, with 15 t/ha, then jack bean (*Canavalia ensiformis*), at 12 t/ha, followed by two cultivars of cowpea (*Vigna unguiculata* white and black forms) and mungbean (*Vigna radiata*).

Cover crops. Promising cover crops included siratro (*Macroptilium atropurpurium*), which produced a maximum of 20 t/ha of fresh material, verano (*Stylosanthes hamata*), at 17 t/ha, *Calopogonium mucunoides*, at 17 t/ha, *Alysicarpus vaginalis*, at 16 t/ha and *Mucuna pruriens*, at 14 t/ha (Table 5).

Phetchawee et al. (unpublished data) initiated a long term corn production experiment on sandy soil in Ubon Ratchathani in 1987. The treatments were changed slightly in 1991 and now the experiment consists of five combinations of corn–legume rotations, including mungbean, cowpea, pigeon pea, sunhemp and jack bean, and two intercropped com-

Table 5. Fresh weight of biomass of green manure and cover crops (kg/ha) grown at Ubon Ratchathani.

Green manures	Fresh wt. (kg/ha)	Cover crops	Fresh wt. (kg/ha)
Sunhemp (*Crotalarea juncea*)	15 388	Siratro (*Macroptilium atropurpurium*)	20 667
Canavalia ensiformis	11 986	Stylo (*Stylosanthes hamata*, verano)	16 806
Cowpea, white form (*Vigna unguiculata*)	7 567	Calopo (*Calopogonium mucunoides*)	16 528
Cowpea, black form (*Vigna unguiculata*)	6 917	Alysi (*Alysicarpus vaginalis*)	16 222
Mungbean (*Vigna radiata*)	3 806	Mucuna (*Mucuna pruriens*)	14 028
Sesbania rostrata	3 222	Pueraria (*Pueraria phaseoloides*)	5 111
Rice bean (*Vigna umbellata*)	2 361	Centro (*Centrosema pubescens*)	4 444
Bonavista bean (*Lablab purpureus*)	2 250	Mimosa (*Mimosa invisa*)	3 556
Pigeon pea (*Cajanus cajan*)	1 736	*Clitoria ternatea*	2 000
Sesbania cannabina	394		

Source: Neiro (1992)

binations, of corn with verano and native cowpea. The biomass of dry crop residues collected in 1991 was highest with the verano, as was the corn grain yield when it was intercropped with verano (Table 6). The soil organic matter measured in 1991 and 1993 was highest in the plots where corn was intercropped with verano (Table 7).

Phetchawee et al. (1986) also carried out a long term corn production experiment on a clay soil in Lopburi in 1980–1985. The management systems included rice straw mulch, sunhemp mulch, rice bean mulch, mimosa mulch and incorporated compost. Corn yield increased two-fold after receiving legume mulches such as rice bean and mimosa for five years (Table 8). Moreover, the soil organic matter was significantly increased as a result of these treatments (Table 9).

Organic matter management in cassava

Sittibusaya et al. (1984) carried out a long term cassava production experiment during 1975–1984. The treatments included i) continuous cassava without fertilizer ii) continuous cassava with fertilizer, iii) cassava–legume rotation with peanut and pigeon pea and iv) cassava with mungbean and pigeon pea. The cassava legume rotations increased cassava yield in the 9th year of cropping only in the case of

Table 6. Dry biomass of crop residues (t/ha) collected in 1991 prior to sowing corn and corn grain yield at Ubon Ratchathani.

Legumes		Corn grain yield (kg/ha)	
	Residue biomass (t/ha)	Average 1991–1993	Relative yield
Fallow	6.1 b	478	100
Mungbean	5.4 b	521	109
Cowpea	5.5 b	499	104
Pigeon pea	5.4 b	475	99
Sunhemp	5.4 b	659	138
Jack bean	6.6 b	507	106
Verano	11.5 a	1002	210
Native cowpea	7.2 b	751	157

Table 7. Effect of continuous corn–legume cropping on soil organic matter at Ubon Ratchathani in 1991 and 1993.

Legumes	Organic matter (%)	
	1991	1993
Fallow	0.72	0.71
Mungbean	0.78	0.64
Cowpea	0.81	0.80
Pigeon pea	0.76	0.79
Sun hemp	0.74	0.77
Jack bean	0.78	0.67
Verano	1.00	0.86
Native cowpea	0.76	0.87

Table 8. Corn grain yield under long-term mulching with plant residues and compost at Lopburi.

Management	Mean corn grain yield (t/ha)			
	1980		1985	
	– Fert.	+ Fert.	– Fert.	+ Fert.
No mulch	2.5	3.2	2.8	4.2
Rice straw mulch	2.9	4.0	4.3	7.6
Sunhemp mulch	2.6	3.0	3.9	5.5
Rice bean mulch	2.2	3.5	5.9	7.6
Compost	3.3	3.9	5.9	8.2
Mimosa mulch	1.9	3.9	7.5	7.6
LSD 5%	0.48		1.4	

Remarks: Fertilizer rate: 62.5 kg N/ha and 62.5 kg P_2O_5/ha.
Compost application: 20 t/ha municipal compost.

Table 9. Soil organic matter under long-term mulching and compost applications at Lopburi.

Management	Organic matter content in soil (%)			
	1980		1985	
	– Fert.	+ Fert.	– Fert.	+ Fert.
No mulch	0.83	0.91	1.10	1.33
Rice straw mulch	1.15	1.09	1.63	1.86
Sunhemp mulch	0.92	1.11	1.51	1.52
Rice bean mulch	0.87	1.05	1.64	1.80
Compost	1.10	1.14	2.57	2.91
Mimosa mulch	1.05	1.02	2.83	2.45

the Yasothon and Huai Pong soils (Table 10). Incorporation of legume residue did not prevent a decrease in soil organic matter content with cropping in most soils, but did tend to maintain a higher level of organic matter and a better nutrient status (Table 11). The cassava–peanut rotation was more effective than the cassava–mungbean rotation.

The results presented above clearly demonstrate the potential for improved soil management, and increased crop yield, by the careful selection of appropriate cropping systems for the upland soils of Thailand. The most appropriate cropping systems will generally include return of crop residues, the inclusion of an appropriate legume in a rotation or as an intercrop, some degree of minimum or conservation tillage and the judicious use of appropriate chemical fertilizers.

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Table 10. Effect of annual application of fertilizers crop rotation on the yield of cassava and the soil organic matter content after 9 years of cropping in three soil series in Thailand, 1975–1984.

Cropping system	Soil series			Soil series		
	Yasothon	Korat	Huai Pong	Yasothon	Korat	Huai Pong
	Cassava yield (t/ha)			Organic matter (%)[a]		
Continuous cassava:						
without fertilizers	11.8	28.2	20.0	0.62	0.80	1.41
with fertilizers[b]	19.8	20.7	25.1	0.60	1.14	1.68
Cassava/legume rotation[c]:						
peanut+pigeonpea	27.8	27.8	29.9	0.68	1.41	2.10
mungbean+pigeonpea	22.5	26.2	23.2	0.63	1.14	1.68

[a] Initial (1975) OM contents were: Yasothon 0.87%, Korat 1.24%, Huai Pong 2.10%.
[b] Annual application of 50 kg N/ha, 20 kg P/ha, and 42 kg K/ha.
[c] No fertilizer applied; cassava and two consecutive legumes crop were grown in alternate years.
Source: Sittibusaya et al. (1984).

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Table 11. Changes in soil fertility status after 10 years of continuous cassava monocropping without fertilisation on Huai Pong soil in Southeast Thailand.

Soil test[a]	1975–Initial	1984–after 10 years	Percent change
pH	4.8	4.7	2
Organic matter(%)	1.90	1.14	40
Bray 2 –P (ppm)	28	17	39
Exch. K (ppm)	45	12	73

[a] Data from surface soil samples taken before planting.

Management of Crop Residues in Sugarcane and Cotton Systems in Brazil

T. Muraoka, J. O. Filho, A. E. Boaretto and E. Ambrozano*

Abstract

Filter cake and vinasse, the residues of sugarcane refining and the ethanol industry, are intensively utilised in soils under sugarcane cultivation in Brazil. During the replanting of the sugarcane crop, green manure or grain legume cultivation has become a routine technique. Green manure has also been used as an alternative means of compensating soil organic matter reduction as a consequence of the burning of residues after harvest in cotton cultivation.

Reference is made to the experimental results on management of a) filter cake and vinasse in sugarcane plantations and b) green manure in sugarcane and cotton cultivation.

BRAZIL, the world's largest sugarcane producer, will harvest, in 1994, 240 million t of cane from the 4.3 million ha planted to this crop, producing 9.5 million t of sugar and 12000 million litres of alcohol. Both the sugar and alcohol industries produce, along with their main products, considerable amounts of residues: filter cake, molasses and bagasse in sugar mills, and bagasse and vinasse in alcohol distilleries.

The intensive utilisation of vinasse and filter cake in soils under sugarcane cultivation has become a routine practice among sugar–alcohol producing units in Brazil, because they have a high fertilizer value, and the vinasse also has a high biochemical oxygen demand (BOD) which causes great damage if it is discharged into waterways.

Cotton, although not the second most important crop, has a significant place in the country's agriculture. Brazil is expected to produce around 439900 t of cotton fibre this year (55% of its domestic needs) the balance being imported. Clearly there is a need to increase cotton production, which may be accomplished only by increasing yields as there is no opportunity to expand the planted area.

Both crops present a common feature. They have been cultivated intensively in the same area over many years, and little residue is left after harvest, as the cane leaves are burnt prior to cane cutting and cotton plant residues are also burnt for disease and insect control. Data on changes in the quantity of soil C derived from the original forest material and C derived from previous sugarcane crops, in a subtropical cane plantation cultivated for 12–50 years, have been obtained by Cerri (1986). The quantity of total C in the forest ecosystem was found to be 71.9 t C/ha. After 12 years of cultivation the content has decreased to 44.6 t C/ha and after 50 years to 38.5 t/ha. Isotopic (^{13}C) data indicated that 45% of the total organic carbon of the cultivated soil was introduced by residues of the crop itself and 55% is the remnant from the original ecosystem as stable humus, which contributes little to the soil biological processes.

Therefore, although sugarcane and cotton are relatively well fertilised crops in Brazil, the soils in which they are cultivated have decreased in soil organic matter (SOM) content over the years. Better residue management or the introduction of green manure crops into the cropping system needs to be explored to restore SOM levels.

This paper deals with the management in Brazil of a) sugarcane industry residue application in sugarcane cultivation, and b) green manure in sugarcane and cotton systems.

* Center for Nuclear Energy in Agriculture, Caixa Postal 96CEP, 13400-970 Piracicaba SP, Brazil.

Sugarcane Industry Residues Management

Filter cake

Filter cake is a residual material of the juice clarification process in the sugar mill. For each tonne of cane processed 110 kg sugar is produced, and 35 kg of filter cake, 125 kg bagasse, and 40 kg molasses result as residues.

Filter cake has a high concentration of C (32.6%), P (1.06%) and Ca (3.6%) and to a lesser degree, others: K (0.22%), Mg (0.32%), S (1.18%), Fe (2.5%), Mn (624 ppm), Cu (65 ppm), Zn (89 ppm), Mo (0.6 ppm) and Co (1.4 ppm) (Gloria et al. 1974). These analyses indicate that filter cake could be a useful fertilizer amendment for use on sugarcane crops with the material adding organic matter to the soil.

Some effects may be easily inferred, according to Orlando Filho et al. 1991:

i) The high P level in filter cake permits partial or total substitution of P fertilizer;
ii) Filter cake applied to sugarcane crops adds high amounts of organic matter, and
iii) Consequently the nitrogen requirement is altered due to changes in the soil carbon–nitrogen relationships.

Several systems of application have been adopted in Brazil. In plant cane, filter cake is applied in furrows at 20 t/ha or broadcast at 100 t/ha. In ratoon crops, the residue is applied in the interrow space during tillage operations at 50 t/ha.

Orlando Filho et al. (1991) reported the results of a series of experiments showing the beneficial effects of filter cake, and concluded:

i) Applying 100 t/ha, resulted in an increase in cane yield from 160 to 174 t/ha in one farm and 92 to 126 t/ha in another.
ii) Application in planting furrows resulted in maximum yield when applied at 10 t/ha. There was no additional gain from the 20 t/ha rate (56, 72 and 73 t/ha of cane, respectively for control, 10 and 20 t/ha filter cake applied).
iii) Ratoon cane productivity was also enhanced by filter cake application, obtaining maximum yield with 40 t/ha (70 t cane/ha, against 60 t cane/ha, control). They concluded that the beneficial effects were probably due to the improvement of soil physical and chemical characteristics, since ratoon crops usually react to P fertilizer only after fourth or fifth harvest.
iv) The application of filter cake at 10 t/ha in the cane crop can substitute for P fertilizer in supplying the crop's need for P, equivalent to 31 kg P/ha as fertilizer, confirming the findings of Prassad (1976).
v) Filter cake may also reduce the need for lime because of its high Ca content. A broadcast application at the rate of 100 t/ha, resulted in a cane plant yield increase equivalent to that obtained with 2 t/ha of lime.
vi) There are significant alterations in the chemical properties of the soil (Table 1), raising Ca, P, Mg, organic C content and CEC, while the exchangeable Al was lowered. These alterations persisted

Table 1. Variation in soil chemical properties as a function of time after filter cake application.

Properties	Filter cake (t/ha)		
	0	100	100
		Months after application	
		8	30
pH	5.0	5.2	5.0
P (ppm)	32	188	109
K (ppm)	47	47	39
Ca (ppm)	215	726	631
Mg (ppm)	65	74	69
Al (ppm)	100	23	41
Titratable acidity (meq/100 g)	6.63	5.58	5.72
CEC (meq/100 g)	8.40	10.0	9.53
Effective CEC	2.75	4.62	4.29
Organic C (%)	1.07	1.24	1.21

Source: Orlando Filho et al. 1991

for up to 30 months after application of the filter cake.

It is expected that Brazil will produce 9.5 million t of sugar this year resulting in 3.5 million t of filter cake being available as a good substitute for fertilizer and lime and also SOM amendment material.

Vinasse

From one tonne of cane, 80 L of alcohol, 125 kg of bagasse and 1040 L of vinasse are produced. The estimated Brazilian 1994 production of vinasse is 156 000 million L. Vinasse is a highly polluting agent when discharged into waterways. However, being primarily an organic residue, containing considerable amounts of nutrients, it has substituted, total or partially, as a mineral fertilizer in some sugarcane plantations.

The chemical composition of vinasse depends on various factors, the most important of which is the nature and origin of the raw material, as well as the type and operation of the distillation equipment (Gloria 1976).

Table 2 shows the chemical composition of vinasse for the different cane-growing regions of Brazil. It can be observed that, irrespective of the origin, O.M. is the main component of vinasse, and it also contains a high amount of K and Ca. Based on the data of Table 2 Orlando Filho et al. (1983) estimated the equivalence between 1 m^3 of vinasse and most common mineral fertilizers in kilograms as follows: 0.89 urea, 0.60 triple superphosphate and 4.47 KCl, for juice must, and 0.65 urea, 0.49 triple superphosphate and 2.55 KCl, for mixed must.

Most research into the effects of vinasse applications on sugarcane yields in Brazil has been carried out in the central–southern region of the country, specifically in State of Sao Paulo. In most cases, the vinasse applied was sufficient to replace normal mineral fertilizer. For instance Gloria and Magro (1976) obtained a 17.5% increase in yield compared to the usual NPK-fertilised plot and Stupiello et al. (1977) 16%.

However, some studies have indicated the need to complement with N fertilizer (Serra 197); Silva et al. 1980) or P fertilizer (Sobral et al. 1981).

The beneficial effects of vinasse addition to the soil are attributed mainly to its high OM content as indicated by Orlando Filho et al. 1983: increase in soil

Table 2. Chemical composition of vinasse from the different canegrowing regions of Brazil.

Element	Mixed must				Juice must			
	Sao Paulo[a]	Rio de Janeiro[b]	Alagoas[c]	Paradba[d]	Sao Paulo[a]	Rio de Janeiro[b]	Alagoas[c]	Paradba[d]
kg/m^3								
N	0.48	0.43	0.36	0.33	0.28	0.35	0.26	0.25
P	0.04	0.06	0.27	0.11	0.04	0.05	0.21	0.08
K	2.77	2.17	2.15	1.81	1.07	0.95	1.42	1.61
Ca	0.95	1.04	0.41	0.60	0.09	0.54	0.12	0.40
Mg	0.34	0.31	0.32	0.20	0.12	0.18	0.24	0.20
S	–	–	1.07	–	–	–	1.35	–
O.M.	29.0	45.1	31.7	19.1	22.3	34.7	25.2	15.3
ppm								
Fe	–	130	47	57	–	110	51	45
Cu	–	57	2	4	–	18	1	1
Zn	–	50	3	4	–	2	2	3
Mn	–	5	6	6	–	10	6	5
pH	4.4	3.8	4.0	3.6	–	3.7	3.6	3.5

[a] Rodella et al. (1980)
[b] Bolsanello and Vieira (1979)
[c] Vasconcellos and Oliveira (1981)
[d] including Pemambuco and Rio Grande do Norte (Medeiros 1981)

pH, available nutrients, CEC, water retention capacity, microbial activity and improving soil structure. There is a considerable increase in some cations, mainly K and Ca (Gloria and Magro 1976; Copersucar 1978).

Green Manure

Sugarcane system

There are three sugarcane systems using legume crops as green manure in Brazil:

i) Green manure crops in rotation with sugarcane. This system has the disadvantage of losing one cropping year for sugarcane.
ii) Green manure cultivation during cane crop reform, i.e. the legume is sown after the last ratoon cane harvest and cultivated until new cane planting (short period).
iii) Grain legume crop cultivation during cane crop reform. This is similar to (ii) except that a grain legume crop of economic importance is cultivated instead of a green manure. Usually soybean, common bean or peanut are the legumes used in this system, and they are sown in October (at the beginning of the rainy season) and grains are harvested in February prior to the new cane planting period. The net income in grain produced covers 50% of the cane reform cost.

The study of green manures in sugarcane in Brazil was first conducted in 1956 by Cardoso, who selected *Crotolaria juncea*, *Stilozobium aterrimum*, *Cajanus cajan*, and *Dolichos lab lab* and a few other lesser known legume crops, from the 120 species compared, as the most promising for sugarcane green manuring. The selection of the most appropriate species depends on its adaptability to the local conditions and as there is a great diversity in environmental conditions in the country, yields vary considerably (Table 3).

The chemical composition of the different legumes also varies considerably. The nutrient content of *Crotolaria juncea* has been found to range as follows—N: 1.6–3.4%; P: 0.18–0.38%; K: 1.1–2.9%; Ca: 0.21–1.20%; Mg: 0.20–0.49%; C: 35.0–39.1 and C:N ratio: 17.3–24.5 (Azeredo and Malhpies 1983).

Campos (1977) reported that the increment on plant cane yield credited to green manure (*Crotolaria juncea* or *Dolichos lab lab)* ranged from 3.3 to 103.6% in a survey of sugarcane farms in Rio de Janeiro State. The effect of green manure incorporation on cane yield was clear in the 1st (5.6–150% increase) and 2nd ratoon crop (10.0–174.0% increase).

In Sao Paulo, Mascarenhas et al. (1994) compared the effect of *Crotolaria juncea*, *Stilozobium aterrimum* (mucuna) and soybean on succeeding sugarcane crops. The green manure crops promoted an increase in the cane yield of 27 and 25 t/ha (mean values of 3 harvests) respectively for *Crotolaria* and mucuna, over the control treatment. Soybean resulted in a negligible increment, due probably to a smaller amount of OM residue left compared to other legumes. However, the authors emphasised that the soybean system was economically more favourable due to the extra income obtained from sale of the soybean seed.

Cotton

Cotton was one of the earliest crops considered in green manure research with studies starting in 1936. Since then several studies have been carried out and mucuna (*Stilozobium aterrimum*) is the legume which has been adopted most widely by cotton growers. Bulisani et al. (1987) recommended a system in which mucuna is sown between the rows of the already developing maize plants which are sown prior to the cotton crop. This legume grows vigorously during February to June, covering the surface completely and then grows up the dried maize plants, producing a large amount of biomass. During the flowering stage, or after the mucuna seed harvest (when seed production is desired) the green manure is incorporated into the soil and the cotton is sown. Ferraz, (1965) using this system, obtained better results (2610 kg/ha) compared to cotton cultivated after *Crotolaria spectabilis* (2475 kg/ha) or non-green manured cotton (1870 kg/ha).

Analysing several data sets on research prior to 1980, when most of the studies on green manure were carried out, the general conclusion is that the green manure, in most studies, promoted a considerable increase in cotton yield (up to 51%) compared to the control treatment. However, the residual effect of green manure seems shorter than in the sugarcane system, as in the 2nd year crop, the increase obtained was small. In later work, Miyasaka et al. (1983), observed that with green manure (crotolaria and mucuna), the cotton productivity increased 25% over a six year period. Pereira et al. (1988) reported that cotton grown in rotation with soybean did not require N fertilizer.

Table 3. Range in the biomass productivity of several green manure legumes.

Legume	Biomass (t/ha)
Crotolaria juncea	17.5–54.2
Slitozobium aterrimum	26.4–32.1
Cajanus cajan	22.8–33.4
Dolichos lab lab	10.7–39.6

Source: Azeredo and Malhães 1983.

Conclusion

Vinasse, the main residue of the sugar cane industry and a highly polluting agent when discharged into waterways, has been successfully utilised on the Brazilian sugarcane crop, increasing productivity, mainly as a consequence of restoring SOM content and some nutrients.

Filter cake which is produced during sugar cane juice clarification, has also been shown to have beneficial effects, due to its high OM content and some nutrients. The maximum economical distance however to transport the materials for reutilisation is limited to around 30 km from the factory. Because of this it is highly possible that the SOM content has declined in soils under sugarcane beyond this distance due to the intensive cultivation and burning of cane residues.

The SOM has also declined in soils under cotton cultivation in Brazil due to the burning of the residues after harvest.

Utilisation of rotation crops with some legume, as green manure in the cotton system and green manure or some green legume crop, in the sugarcane system, have been shown to be able to restore SOM in these intensively utilised soils. Most available data to support this are based on yield data only and do not consider the effect of residues on soil chemical conditions. Investigations of SOM under both crops is therefore needed.

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Management of Crop Residues in Temperate and Subtropical Cropping Systems of Australia

W.M. Strong* and R.D.B. Lefroy†

Abstract

Crop residue management in any cropping system will be influenced principally by the nature and quantity of residues available and the immediate and future land use but it is also affected by other constraints. Among these are the need to protect the soil surface to conserve soil and water, the nature of crop and/or pasture rotation, the availability of labour (and resources) and the alternative uses for crop residues within the farming system.

The nature of crop residues and the type of land use practices differ considerably in the northern summer dominant rainfall region of Australia from those of the Mediterranean climate of southern Australia. Continuous cropping, predominantly with cereal crops is the most common land use where crop residues are returned in northern Australia. In southern Australia where grazing (sheep) and cereal cropping are integrated a good deal of residues of forage legume is produced. In this system recycling of N from legume residues following legume pasture leys may be a substantial proportion of the N required by cereal crops grown following the pasture ley.

This paper focuses on the effects crop residue retention may promote in relation to: combating soil erosion, increasing water infiltration, influencing crop nutrition, affecting the soil biota and the control of diseases and pests, and other processes, which may impact on the sustainability of these cropping systems. Examples are drawn from cropping systems of subtropical and temperate Australia.

MANAGEMENT of crop residues in any cropping system will be influenced principally by the nature and quantity of residues available and the immediate and future land use but it is also affected by many other constraints. Among these are the need to protect the soil surface to conserve soil and water, the nature of crop and/or pasture rotation, the availability of labour and resources and the alternative uses for crop residues within the farming system.

In many cropping systems the extent and nature of tillage practices will also impact upon the residue management option. For the purpose of this paper effects of tillage per se are not addressed except where tillage is integral to the residue management practice in question. For example, surface mulching of crop residues requires use of special tillage equipment designed to avoid incorporating crop residues on the soil surface.

The nature of crop residues and the type of land use practice differ considerably in the northern summer dominant rainfall region of Australia from those of the Mediterranean climate of southern Australia. Continuous cropping, predominantly with cereal crops, is the most common land use where crop residues are produce in northern Australia. Very small areas of legume crops are grown. Until the mid 1970s much crop residue was burnt for the convenience of sowing the next cereal. This practice is now uncommon. Cereal residues are now highly valued as an effective soil erosion control measure.

In southern Australia where grazing (sheep) and cereal cropping are integrated a good deal of residue of forage legume is produced. In this system recycling of N from legume residues following legume pasture leys may provide a substantial proportion of the N required by cereal crops grown following the pasture ley.

* Queensland Wheat Research Institute, Department of Primary Industries, Toowoomba, Queensland 4350, Australia.

† Department of Agronomy and Soil Science, University of New England, Armidale, NSW 2351, Australia.

This paper focuses on the effects crop residue retention may promote in relation to: combating soil erosion, increasing water infiltration, influencing crop nutrition, affecting the soil biota and the control of diseases and pests, and other processes which may impact on the sustainability of these cropping systems. Examples are drawn from cropping systems of subtropical and temperate Australia.

Role of Residues in Soil and Water Conservation

Soil erosion caused by wind or water is directly related to land management practices. Tillage and removal of vegetative cover predispose soil to erosion by reducing structural stability and increasing runoff. Rosewell and Marston (1978) compared some land management practices common to the summer rainfall region of northern Australia (Table 1). Their results highlight the importance of crop residue retention in combating erosion of soils of the region.

The quantity of residues required to reduce soil loss to an acceptable level depends on soil type, nature and distribution of residues, rainfall duration and intensity, length and steepness of slope and the land management practices used. Wingate-Hill and Marston (1980) estimated the quantities of residues of wheat and sorghum needed to reduce soil loss to 12 t/ha/year (Table 2).

Table 1. Effect of land management practice on relative soil loss at Gunnedah Research Centre, New South Wales (Rosewell and Marston 1978).

Management practice	Relative soil loss (%)
Wheat–long fallow, residues burnt	100
Annual wheat, residues burnt	40
Annual wheat, residues retained	14
Permanent pasture	1

Table 2. Residue quantities needed to reduce erosion to less than 12 t/ha/year on land of 8% slope in northern New South Wales (Wingate-Hill and Marston 1980).

Soil type	Quantity of flattened residue needed (kg/ha)	
	Wheat	Sorghum
Loamy sand	900	2800
Silt	1500	4300
Clay	2000	5400

The desirable level of crop residues should be maintained during October to March, the period in which high intensity rainfall is most likely, (Felton et al. 1987). For 90% effectiveness of raindrop interception, approximately 2500 kg/ha of residues of closely spaced crops (wheat and barley) or 4000 kg/ha of tall or widely spaced crops (grain sorghum) are required. Where residue quantity is 1000 kg/ha or less both types of crops are similarly effective (60%) in reducing water erosion.

Standing crop residues are more effective in reducing wind erosion by reducing wind velocity at the surface.

For more detailed reviews of the effects of residues on control of soil erosion see Felton et al. (1987).

Fallow efficiency, the proportion of rain stored in soil during a period of fallow, depends upon the rates of infiltration and evaporation at the soil surface; both are influenced by residue management. Good residue management can increase fallow efficiency by increasing infiltration and in situations where rainfall occurs regularly by reducing evaporation from the soil surface.

Felton et al. (1987) present data for subtropical Australia which indicate that two-thirds of the rainfall over a 4-year period was lost due to evaporation. In this study retaining crop residues increased fallow efficiency from 21% to 29% but the extra stored water was achieved through reduced run-off and thus increased infiltration.

Although the effect of crop residues on total water storage is usually small, residues may extend the time for successful sowing (Radford and Nielsen 1983), due to an increase in the water content of the surface soil.

Felton et al. (1987) present evidence of the increase in water storage due to the retention of crop residues (Fig. 1). The major benefit of crop residues is to increase infiltration by reducing raindrop energy which maintains voids at the soil surface and permits water entry.

As shown in Figure 1 there is an approximately linear relationship between cover and infiltration, but cover becomes less effective as the profile fills. Thus, during summer fallows in subtropical Australia, by the time the residues of the previous crop have decomposed, the beneficial effects of crop residues to increase infiltration are only marginal because this usually coincides with a near-full soil profile.

Role of crop residues in crop nutrition

The impact to crop nutrition of crop residues can be indirect, due to their physical effects to modify the water and temperature regime at the soil surface which in turn affects the soil microenvironment. In this way crop residues may affect microbial and chemical transformations of soil and applied nutrients, as well as root growth and nutrient uptake by plants. The major effects considered here will be those which significantly affect the cycling of nitrogen in soil. Other effects will not be considered in any detail.

Effects on organic matter

Under pasture systems, temperate and tropical, there is a good deal of evidence for the accretion of organic matter (Clarke and Russell 1977; Ladd and Russell 1983). Most attention has been given to the accretion of nitrogen, and for practical purposes nitrogen accretion seems to be mainly affected by the amount of legume growth (Dalal, Strong and Weston, unpublished data).

Few experimental comparisons are available for systems of continuous cropping. Dalal (1989) compared various management practices on a vertisol over 13 years of continuous cropping. The highest concentrations of organic C and total N (0.1 m) occurred with a combination of no-tillage, residues (wheat or barley) retained and N fertilizer applied. Saffigna et al. (1989) also showed an increase (8%) in soil organic C where crop residues (sorghum) were retained rather than removed.

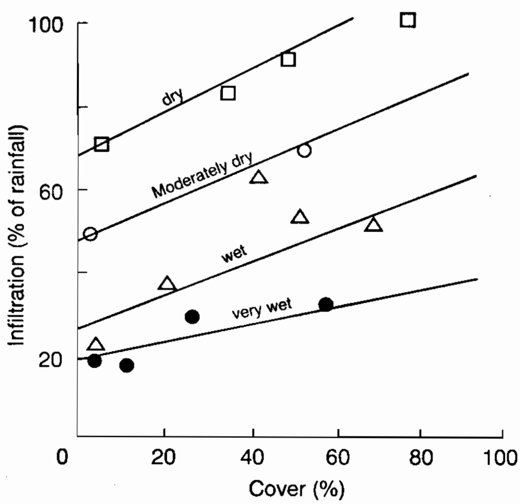

Figure 1. Effect of crop residue cover on infiltration into a vertisol at four moisture contents (from Felton et al. 1987).

Table 3. Nitrogen removal in cereal grain (wheat) in various cropping systems following inputs of cereal and legume residues on a vertisol in subtropical Australia.

Crop rotation	N removal kg/ha/year[a]	N benefit kg/ha/year
Continuous cereal	44	
Chickpea – cereal	58	14
Medic – cereal	62	18
Lucerne – cereal	58	14
3 yr pasture – cereal	66	22

[a] Values are means over period 1987–1990

Cycling of nitrogen

Addition of cereal residues into soil can markedly decrease the availability of nitrogen to plants by increasing immobilisation of soil and fertilizer N (Craswell 1978; Saffigna et al. 1989; Strong et al. 1987), which appears to become available to subsequent crops in very small quantities (White et al. 1986; Strong et al. 1987).

An appreciation of the recycling rate of immobilised N in agricultural soils can be obtained from N fertilizer studies using isotopically labelled fertilizers. Experiments have shown that immobilised fertilizer N in soil may have a very long residence time and becomes only slowly available to subsequent crops (Strong et al. 1994; White et al. 1986).

One practical consequence of cereal residue addition to soil is that burning the residues can have a net beneficial effect on the N supply to subsequent crops. Another practical consequence is that any delay in the addition of N fertilizer, until after the majority of the residues have decomposed, may increase the quantity of the applied N which becomes available to the next crop.

Incorporation of residues of forage or grain legume crops usually results in an increased supply of mineral N for subsequent crops (Ladd et al. 1981; Doughton and MacKenzie 1984; Strong et al. 1986). A variety of rotations of cereal and grain or forage legume crops have been compared as possible N fertility restorative options in a soil with low fertility status at a site in southern Queensland. All legume options increased the supply of N to a subsequent cereal crop as evidenced by the quantities of N removed in cereal grain (Table 3).

Where crop residues are added to soil there is a likelihood that denitrification may be increased following the addition of the energy source. Several researchers have observed these effects of crop residues; Bowman and Focht (1974); Bacon et al. (1989); Avalakki et al. (1994).

Addition of wheat straw (10.5 t/ha) to a vertisol, which contained no visible plant residues from previous crops, more than doubled N losses due to denitrification (Avalakki et al. 1994). In the absence of wheat straw, rates of denitrification and immobilisation were similar in magnitude: 0.97, 0.26 and 0.16 kg/ha/day, at 30°C, 15°C and 5°C respectively. Very rapid losses due to denitrification in the presence of added straw led to decreases in immobilisation, highlighting the potential effects of the much higher maximum rates for denitrification than for immobilisation. Decreasing temperature slowed potential rates of denitrification from ~ 2.5 kg/ha/day at 30°C to 0.8 kg/ha/day at 15°C and 0.4 kg/ha/day at 5°C.

Because of the positive effects crop residues at the soil surface have on infiltration there is potential for mobile nutrients, like nitrate, to be moved to deeper layers in the profile. Dalal (1989) showed the potential leaching effects created by the retention of cereal straw on the surface of vertisol in subtropical Australia (Fig. 2). Although the effects of crop residues on leaching were negligible in a tilled system, their effects were dramatic in a no-till system where the crop residues remained on the surface.

Other effects

The effect of retaining crop residues will almost certainly impact on the availability of almost all nutrients contained within the topsoil. Generally residue retention leads to more favourable soil–plant–water relations, particularly in arid regions. The ability of crop residue retention to favour plant nutrient uptake can be indirect through its effect on water infiltration, particularly for mobile nutrients, or through its effect on microbial and/or plant processes.

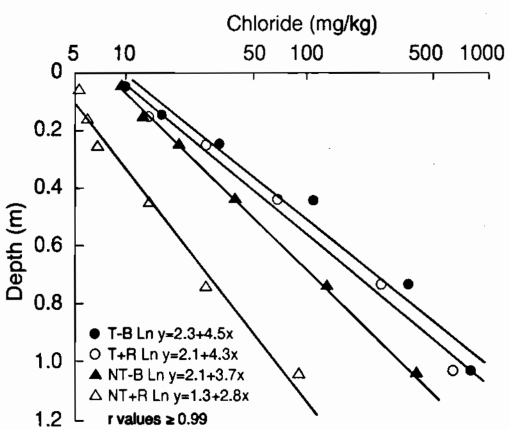

Figure 2. Effects of tillage (T) and no-tillage (NT), crop residue burnt (–B) or retained (+R) on chloride distribution in the soil profile (from Dalal 1989).

In systems in which legumes are grown to supplement N supplies to subsequent cereals, the retention of crop residues may impact upon N supplies through decreasing establishment of the legume. Robson and Taylor (1987) suggest that in temperate Australia the effects of crop residues in reducing crop establishment are largely by decreasing the breakdown of hard seeds of the legume (medic) at lower temperatures, products of decomposition toxic to the growth of the legume and/or physical impedance to the emerging legume seeds.

Retention of cereal residues may increase nitrogen fixation by non-symbiotic micro-organisms as has been indicated by increased rates of acetylene reduction (Roper 1983). It is not yet possible to quantify any gains by non-symbiotic fixation, but they are only likely to be significant in regions of frequent rainfall because of the apparent moisture requirements of the process; the rate of acetylene reduction decreases as the soil dries out (Roper 1983).

Retention of cereal residues may also impact on nutrient transformations in soil because of the effect to generally lower soil pH. Robson and Taylor (1987) suggested that effects of residue management, tillage and crop rotation on soil pH might occur because of the direct effect of the organic addition or indirectly through its effects on nitrogen transformations, relative uptake of cations and anions and relative return of cations and anions in the residues. Organic acids can be formed by microbial decomposition of plant residues, but any effects on soil pH will depend upon the initial soil pH and the degree of dissociation of the organic acids (Ritchie and Dolling 1985).

Effects on Soil Biota

Of the many crop management practices, the management of crop residues would appear to have a major influence on the soil biomass. Soil animals do appear to be much involved in the primary decomposition processes which result in the recycling of nutrients contained in organic materials (Lee 1991). The bulk of the active microbial and grazing faunal biomass operates in the active organic pool usually associated with fresh additions of plant residues (Lee and Pankhurst 1992). Thus, any increase in the return of above or below ground residues within the cropping systems could conceivably increase populations of soil fauna.

In northern Australia some producers perceive that an increase in soil-dwelling pests is a major obstacle to systems where all crop residues are retained. Robertson and Agnew (1991) found that the effect of soil conserving practices, such as residue retention, was to change the species of soil insects, there being no

Table 4. Antecedent nitrate–N (kg/ha/1.2 m) on unfertilised Vertisol and N uptake (kg/ha) from soil and fertilizer by successive wheat crops over the period 1987–90 for two tillage treatments, conventional tillage (CT) and zero tillage (ZT), (Strong et al. 1994).

Wheat crop	Nitrate–N[a]		N uptake[b]		Applied N uptake[c]	
	CT	ZT	CT	ZT	CT	ZT
	kg/ha/1.2 m		kg/ha		% applied	
1987	156[d]	105	123[d]	98	62.9	62.0
1988	54	45	64	54	55.5	57.3
1989	44	49	45	44	68.7	58.1
1990	31	44	55	55	57.4	60.5

[a] Prior to wheat sowing in unfertilised soil
[b] In grain and straw of unfertilised wheat
[c] 75 kg N/ha applied as ^{15}N depleted ammonium nitrate
[d] Significant tillage effects

increase in total number. Further, there was an increase in predatory soil animals in conservation systems providing some potential for a biological control of soil insect pests.

Increasing the quantity of soil microbial substrates by the addition of crop residues may also benefit the soil flora. Dalal et al. (1991) studied the influence of residue management practices over a 20-year period on a vertisol in subtropical Australia. They found that retention of residues of wheat or barley in combination with no-tillage and annual application of N fertilizer (69 kg/ha/year) increased microbial biomass N in the surface layer (0–25 mm), and residues combined with fertilizer had a similar effect in the 0–100 mm layer. Microbial biomass was also affected similarly by the retention of sorghum residues (Saffigna et al. 1989).

Table 5. Potential loss of N applied before wheat sowing following various crop and pasture treatments over two years on a site in subtropical Queensland (Islam 1992).

	1989	1990
	(% applied)	
Continuous wheat (CT)	66	46
Continuous wheat (ZT)	55	
Chickpea–wheat		58
Medic (1 year)		26
Lucerne (1 year)		55
Grass–legume pasture (4 year)		87
Long fallow	12	9
LSD (P<0.05)	11.0	13.6

Root-lesion nematode (*Pratylenchus thornei*) has been identified in the northern cereal region of Australia as a significant pathogen for certain crops including wheat and barley. Results of long-term experiments (Thompson 1991) show that nematodes survive better in the topsoil with no tillage than with mechanical tillage. Also there are fewer nematodes in no tillage where crop residues are retained than where residues are burnt. Thompson (1991) suggests that it is probable that crop residue retention increases the food base for antagonists of the nematode. In this way bacteria, fungi, mites and predacious nematodes that parasitise or prey on nematodes may provide some biological control of nematodes which may be promoted by retention of crop residues.

For a variety of grain crops grown in northern Australia, P and Zn nutrition has been shown to be directly related to root colonisation with VAM fungus (Thompson 1994). Thompson presents evidence to show that soil disturbance of normal agricultural tillage practice in northern Australia may reduce VAM infectivity. The impact of residue management on VAM infectivity could be affected by the management of crop residues through its effects on soil—water relations particularly at the soil surface. The effects of intercropping and soil organic amendment on native VAM populations has been observed elsewhere (Harinikumar et al. 1990).

Effects on Plant Diseases

In northern Australia management practices which have increased the levels and duration of retained crop residues have generally led to increased levels of some diseases. Crown rot, caused by *Fusarium graminearum* Group 1, is a disease of wheat and barley which is in common occurrence throughout cereal growing regions of northern Australia. Hyphae in winter cereal or grass residues are the means by which the organism survives in the absence of a susceptible host (Wildermuth et al. 1992).

Similarly, an important leaf spot disease of wheat, yellow spot caused by *Pyrenophora tritici-repentis*, has risen in its importance in the northern region of Australia, coinciding with the change from burning to retaining wheat residues (Rees 1987).

A Comparison of Some Cropping Systems of Northern Australia

Management options for continuous cropping

Tillage and nitrogen fertilizer application

One major implication of tillage practice is the effect it may have on increasing fallow water storage. In wheat crops grown with conventional (CT) and zero tillage (ZT) during years of below average rainfall, 1992 and 1993, a 20–30 mm greater water storage in ZT than CT resulted in approximately 0.6 t/ha higher grain yield.

Except for one year, 1987, tillage practice appeared to have negligible effect on net N mineralisation during the period 1987–90 or on its utilisation (Table 4). Uptake of applied N by each crop was similarly unaffected by tillage treatment.

Where wheat has been cropped continuously over the period 1987 to 1990 application of fertilizer N has substantially increased grain yields and/or grain protein concentration. In the experiment fertilizer N as urea had been applied at the time of sowing. The efficiency of N applied at sowing in ^{15}N-labelled fertilizer experiments, conducted annually on adjacent microplots, was found to be quite high, 55–69% becoming available to the first crop (Table 4). Estimated retention of applied ^{15}N retained in the soil indicate that, each year, approximately 17% of the ^{15}N applied at wheat sowing is lost from the soil-plant system.

Other experiments have shown that fertilizer N applied more traditionally, 6–12 weeks before wheat sowing, may result in much larger losses of applied N, presumably due to denitrification. Recent studies of gaseous emissions from fertilised soils, saturated after application, confirm that lost ^{15}N can be quantitatively recovered in gas emissions as $^{15}N_2$ and $^{15}N_2O$, the majority being $^{15}N_2$.

Measurements of potential loss of N from soil prior to sowing winter crops suggest that such losses may be large where crops are grown continuously, presumably because of the ready supply of available carbon from crop residues (Table 5).

Grain legumes

Grain yields of wheat crops grown following chickpeas have been considerably higher than for continuous wheat (Table 6). There appear to be two benefits from chickpeas in rotation with the cereal crop. The first, and obvious benefit is the increase in available N following chickpea, evident in soil before sowing the next crop or the actual N recovered by the next crop (Table 6).

Following chickpeas, the quantity of N recovered by the next wheat crop was equivalent to that recovered where wheat was applied between 25 and 50 kg N/ha. Grain yields following chickpeas were higher than those fertilised with 25–50 kg/ha of N. The higher yields following chickpeas are due, in part at least, to a higher subsoil water reserve after chickpea than after wheat.

Management options for rotating pastures with cropping

Increases in the quantities of N taken up by wheat were evident following short-term (1 year) pure swards of lucerne or medic pastures in two years, 1989 and 1990, and following a 4-year grass–legume pasture ley in 1990 (Table 7). Water reserves following pastures impacted significantly on grain yields of subsequent wheat crops. Generally, wheat yields were similar to or higher than yields with continuous wheat cropping, but in one year (1989) grain yield following a pure lucerne sward was decreased, presumably because of a lower water reserve.

Comparisons of various management options

Protecting the soil resource

Soil organic C content following mixed grass–legume pasture maintained for 2 to 4 years increased almost linearly with the pasture period. Organic C content increased by about 650 kg C/ha/year in soil under grass–legume pasture compared with that under conventional cultivation. This is attributed to the continuous addition of C from surface plant materials and roots and nitrogen accretion from legumes. The absence of cultivation may also retard organic matter decomposition.

The rate of increase in soil organic C under grass–legume pasture (Fig. 3) was satisfactorily explained by the equation:

$$OC_t = 1.28 + \left(0.76 - 1.28\exp^{0.1273t}\right) r^2 = 0.99.$$

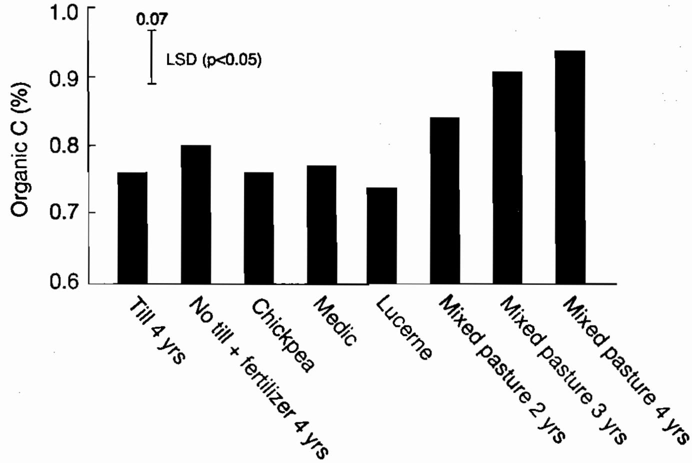

Figure 3. Organic carbon content (0–5 cm) following various cropping systems in subtropical Australia (Dalal et al. 1994).

Table 6. Grain yield and N uptake (in grain and straw) of wheat following chickpeas or N fertilized wheat crops (R.C. Dalal, W.M. Strong, E.J. Weston, unpublished data).

Previous crop/ treatment (kg/ha)	Grain yield (t/ha)			N uptake (kg/ha)[a]		
	1988	1989	1990	1988	1989	1990
Chickpeas	4.62	2.88	3.59	89 (45)	61 (15)	73 (5)
Wheat 0 N	3.08	2.07	2.23	54	34	41
Wheat 25 N	4.39	2.57	2.84	84	50	55
Wheat 50 N	4.83	2.82	3.14	110	64	71
Wheat 75 N	4.65	2.31	3.41	132	76	96

[a] Figures in brackets are amounts of N in residues of previous chickpea crop

Table 7. Grain yield and N uptake (in grain and straw) of wheat following short- or long-term legume pasture leys (R.C. Dalal, W.M. Strong, E.J. Weston, unpublished data).

Previous crop/treatment (kg/ha)	Grain yield (t/ha)			N uptake (kg/ha)		
	1988	1989	1990	1988	1989	1990
Medic (1 yr)	2.94	2.70	3.59	47	81	105
Lucerne (1 yr)	2.84	1.85	3.43	46	66	86
Grass–legume (3.75 yr)	–	–	3.38	–	–	106
Wheat 0 N	3.08	2.07	2.23	54	34	41
Wheat 75 N	4.65	2.31	3.41	132	76	96

In this equation, OC_t is the organic C at time, *t* years. Thus, the rate of organic C accumulation in this Vertisol was relatively rapid initially and it was similar to but opposite in magnitude to that of rate of loss in organic C (–0.09/year) in this soil although the equilibrium value of 1.28% organic C is much lower than the virgin soil organic C content of 2.26%. This demonstrates that the grass–legume pasture system can restore organic C rapidly in fertility degraded soils.

Two-year rotation of lucerne–wheat, medic–wheat and especially chickpea–wheat had relatively small effect on soil organic C content (Fig. 3). It is likely that relatively small inputs and the rapid rate of turnover of added organic C in these short-term legume rotations did not allow organic matter build-up over four years in this soil.

In the longer-term, however, soil total N in the two-year rotations of lucerne–wheat and medic–wheat exceeded that in the chickpea–wheat rotation

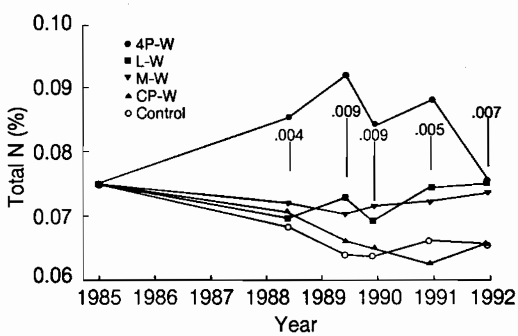

Figure 4. Trends in soil total N under 4-yr grass–legume pasture–wheat (4P–W), lucerne–wheat (L–W), medic–wheat (M–W), chickpea–wheat (CP–W) and conventional-till (CT) wheat (Control), (Dalal et al. 1994)

and continuous conventional till wheat treatment (Fig. 4). Furthermore, soil total N contents approached the initial levels after about 7–8 years and became similar to that in the 4-year grass-legume pasture-3–year wheat treatment. Apparently, forage legumes in rotation with wheat can maintain organic matter in the long-term while chickpea–wheat rotation and continuous conventional till wheat fail to arrest the decline in organic matter under arable cropping especially when the amounts of crop residue returned to soil are low.

In this study, no-till practice generally had a very small effect on organic C and total N in this Vertisol (data not presented). The no-till practice under continuous cereal cropping without N input therefore may not be sustainable in terms of maintaining soil organic matter in soil.

Conclusions

The impact of crop residue retention in Australian cropping systems is likely to differ considerably from the north to the south. Differences in cropping system, and rainfall patterns (summer dominant in the north versus Mediterranean in the south) are such that cereal residues predominate in northern systems while residues of cereal and forage legumes are returned in large quantities in southern systems.

The recent (past 20 years) trend in the north to retain residues to combat soil erosion by water has led to improved infiltration but has impacted upon other management practices. Higher levels of N fertilizers appear to be required in continuous cereal systems and some disease control measures have been necessary to avoid increased levels of foliar and root diseases of winter cereal crops.

The importance of forage legume residues to southern systems has been important in relation to nitrogen cycling to cereals following pasture leys. Recent evidence would suggest that N_2 fixation by forage legumes has declined in some southern systems, bringing into question the ability of legume residues to adequately supply the nutrient requirements of subsequent cereal crops.

The use of grain legumes and short-term forage legume leys may prove valuable in northern systems to provide an increased N supply for subsequent cereals. Evidence so far suggests that these systems will not arrest the serious declines in N fertility evident in most northern cropping systems.

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Fate of Organic Matter and Nutrients in Upland Agricultural Systems

G.J. Blair, A. Conteh and R.D.B. Lefroy*

Abstract

Increasing intensification of agriculture has resulted in increased pressure on soil organic matter. Environmental factors, the chemical composition of the plant litter and the accessibility of the plant litter all affect the breakdown and mineralisation rate and subsequent availability of the nutrients recycled by the litter.

Matching mineralisation rates to crop requirements is easier in temperate environments where cool to cold winter temperatures restrict both mineralisation and crop growth rates. In tropical environments rapid mineralisation can result in a rapid supply of C to micro-organisms which release nutrients into the soil before a crop demand has been established.

The fate of crop residues (returned, removed, burnt) is a major determinant of the long-term fertility of a cropping system. The effects vary between nutrients which in turn are determined by the nutrient harvest index. In a cotton-cropping system the proportion of nutrient removed in product ranged from 62% for S to 7% for Ca.

In this system the fertilizer equivalent value of the nutrients contained in this residue is estimated at $A144/ha. Alternatively if the stubble is burnt the value of nutrients lost is estimated at $A68.42/ha.

Crop residue and/or green manure management therefore is the key to the sustainability of upland cropping systems.

MUCH of agriculture throughout the world has developed by opening up new land to production. Initially productivity is supported through the utilisation of nutrients released from the accumulated soil organic matter (SOM). This high level of SOM is also a contributor to the physical fertility of the soil. The release of nutrients from SOM is largely through microbial activity so a supply of readily useable carbon (C) is essential as it provides the energy source for the microbial population. Much of the world's agricultural area was originally under forest or natural grasslands which had a high SOM content.

Mineralisation of SOM releases nutrients to the soil which are available for plant uptake, conversion to less available forms, lost to the atmosphere, erosion and leaching. The dominance of each process varies with the nutrient and is greatly affected by soil moisture conditions. For all nutrients the increased offtake in product places increased demands on SOM. As the labile SOM is depleted it becomes increasingly difficult to meet the demand of the crop hence the increasing need for inorganic fertilizers. If the labile SOM and inorganic fertilizer cannot meet the need of the crop this places more demands on the non-labile SOM and it will be slowly depleted. This depletion of all SOM not only has implications for the nutrient cycles in the soil but also for soil structure as organic matter is an important determinant of this. An example of nutrient cycling is shown by the carbon and nitrogen cycles in grazing and cropping systems depicted in Figure 1. It is similar for the other nutrients in that if the fertilizer input does not meet the harvest removal requirements, the deficit must be made up by the SOM, thus reducing the size of this pool.

There are important changes in both the C pool size and turnover rate when natural systems, such as grassland, are converted to crop land and when legume green manures are incorporated into the system. In natural grassland systems there is a large pool of C with residues of different ages and quality which are turning over at varying rates. When the land is culti-

* Department of Agronomy and Soil Science, University of New England, Armidale, NSW 2351, Australia.

vated and cropped the rate of breakdown of organic debris is increased and, although the amount of residue returned may be the same as in the grassland it all occurs at the one time and is all of a similar quality with a generally wide C:N ratio and low nutrient concentration. As C is lost from the system the remaining C becomes more resistant to breakdown. When a legume green manure is introduced into the system the residues provide a large amount of easily decomposable C and a ready supply of N for the micro-organisms which results in a rapid breakdown of the organic matter.

Much of world agriculture is intensifying production to meet increasing internal demands and to produce exports to balance trade. This intensification, much of which is occurring on soils relatively low in organic matter and nutrient status and with poor physical properties, is becoming increasingly dependent on inorganic fertilizers. Whilst this in itself is not a problem, it tends to reduce the ability of the small farmer to continue to participate in cash agriculture. It can also result in the lowering of SOM status which results in soils with lower nutrient status and water-holding capacity and in which toxicities of elements such as Al and Mn can become more acute.

In systems where population and/or economic pressures are low the use of legume or non-legume green manure crops provides an opportunity to rehabilitate soil C levels and, in the case of legumes, soil N. However, in many such systems the overall productivity declines because of limitations imposed by nutrients other than N, particularly P.

As population and/or economic pressures increase green manures become increasingly difficult to accommodate in crop rotations as they are seen by farmers as replacing a food crop. If economic circumstances permit, the agricultural system moves towards increasing dependence on inorganic fertilizers. In systems where this is not economically feasible and population pressures are high, farmers generally rely on organic residues transported to the farm from nearby locations and/or human excrement and animal dung and urine inputs. This has been the case in much of Chinese agriculture for centuries. Another approach has been to introduce alley cropping with legume trees into the system.

Technological developments in the production of plant cultivars with shorter growing seasons and increased adaptation to adverse soil and climatic conditions has increased the possibility of growing more

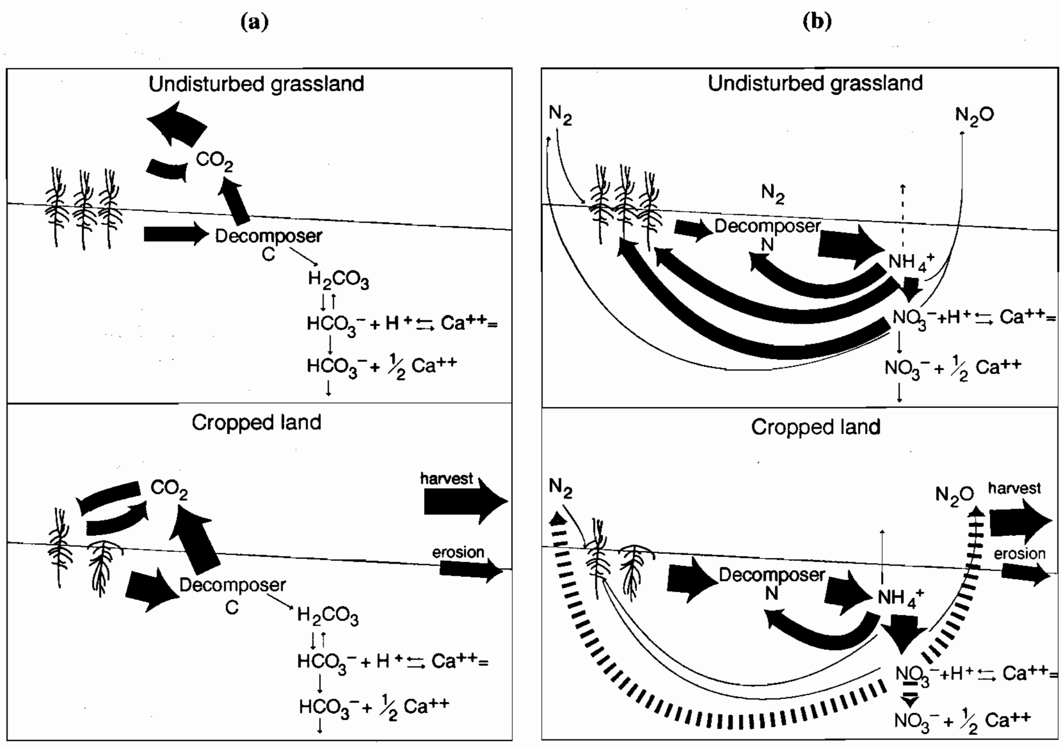

Figure 1. The carbon cycle (a) and the nitrogen cycle (b) in an undisturbed grassland and in cropped land shortly (2–3 years) after cropping.

than one crop per year in many locations. This second crop has often been grown at the expense of a fallow or green manure crop. The other consequence of multiple-cropping systems has been a decline in the retention of crop residues and an increase in burning of such residues. This results in a low return of C to the system and the potential loss of C and nutrients via volatilisation and in smoke, and in greater losses of ash in surface runoff.

Factors Affecting Organic Matter Decomposition

The proportion of total C decomposed in the initial phase of breakdown has been found by Jenkinson (1981) to be similar for a wide range of crop residues. In this study ryegrass roots, ryegrass tops, green maize and mature wheat straw, all lost about two-thirds of their C after one year in the field. Allison et al. (1949) found that 34% of the C in green oats remained in the soil after one year; the corresponding figures were 38% for N-supplemented wheat straw, 28% for whole green soybean plants and 38% for mature maize stalks. The interesting feature of these results is that similar amounts of C remain in the soil from fresh green residues and mature plant material, such as straw, once the initial phase of decomposition is over. The rates of decomposition of different plant materials, however, differ during the initial stages of decomposition (Jenkinson 1981). Thus Waksman and Tenney (1927, as cited by Jenkinson 1981) showed that immature plant material, with a large water-soluble fraction, decomposed more rapidly over a 28-day period than did mature material. With certain exceptions, it is generally reported that most of the crop residue added to the soil is broken down in the first year.

Effects of plant material

The diversity in sources of plant derived organic matter inputs, as well as the complexity of these substrates, results in extreme heterogeneity in the microbial reactions involved in their decomposition (Alexander 1977). Ross (1989) gave three determinants of quality of organic residues:

(i) the amount of fibre or wood,
(ii) the content of C compounds, which provide the energy source for decomposer organisms, and
(iii) the content of nutrients such as nitrogen and phosphorus.

Gray and Williams (1971) likened the decomposition sequence of microorganisms on soil organic substrates to autogenic succession, whereby each wave of decomposition alters the substrate for the next wave, with progressive depletion of the chemical energy sources. Fleshy organic materials decay quickly, rapidly losing water-soluble components, followed by carbohydrates such as starch. These losses account for the bulk of the reduction in dry weight that accompanies decay (Tate 1987). The decay of woody tissues is much slower, and the reduction in dry weight is mainly due to the decomposition of cellulose. Mindermann (1968) presented decomposition curves for a range of litter and soil organic constituents measured in field studies on litter of *Pinus nigra* (Corsican pine), *Pinus sylvestris* (Scots pine) and *Quercus robur* (Sessile oak) and showed the relative resistance to decomposition of phenols, waxes and lignins and the relative ease of decomposition of sugars and hemicellulose.

Attempts have been made to predict the rate and pattern of decomposition of organic substances from a range of organic matter quality parameters such as lignin, fibre, or nitrogen content (the latter usually represented by C:N ratio). Van Cleve (1974) found a negative correlation between lignin content of tundra litter and rate of decomposition, while Latter and Howson (1977) found decomposer bacteria numbers to be negatively correlated with crude fibre content and positively correlated with nitrogen content of organic substrate. When substrates with higher C:N ratios are utilised by soil microbes as an energy source, CO_2 is evolved and nutrients, including nitrogen, are immobilised, thus increasing the nutrient content per unit volume of organic matter and thus lowering the C:N ratio. Availability of inorganic N will be limited until the C:N ratio is reduced to a level where lack of readily decomposable C sources limits microbial demand for nutrients (Martin and Holding 1978).

Effects of moisture

Water is of central importance in the soil ecosystem, governing the overall level of microbial activity and hence the rates and pathways of decomposition. Microbial activity is governed by soil moisture content both directly; by limiting microbial movement and the transport of nutrients in soil solution under drought conditions (Dickinson 1974), and at the other extreme, the build-up of oxygen deficiency with waterlogging; or indirectly by the controlling effects of moisture content on soil temperature (Alexander 1977).

Microbial decomposition processes operate over a wide range of soil moisture conditions from wilting point to saturation (Ross 1989), although optimum conditions, as measured by peak rates of CO_2 evolution (Miller and Johnson 1964) and N mineralisation (Stanford and Epstein 1974), are around field capacity in the range considered as readily available for plant uptake. Some results obtained by Clement and Williams (1962) illustrate the effects of moisture on overall microbial activity. They incubated a sandy loam soil at different water contents and found that there was a rather flat optimal water content at which mineralisation of both nitrogen and C was maximal.

Moisture stress causes death of a proportion of the community of soil organisms (Van Gestel et al. 1993). The extent of the resulting decrease in biomass appears to be determined by properties of the microbial communities, such as their type and activity, and by the previous climatic history of the soil, rather than by soil characteristics (Van Gestel et al. 1993). After rewetting of soils, components of those dead microorganisms and organic carbon from other sources, such as plant residues, are used as substrates for growth by the surviving populations (Jenkinson 1966; Shields et al. 1974).

Amato and Ladd (1980) and Amato et al. (1984) reported enhanced decomposition of plant material in intermittently dried and rewetted soils. Van Veen et al. (1985) observed decreases in biomass C and flushes of mineralisation after desiccation and remoistening of soils, but, for the total incubation period, overall decomposition rates were slightly lower for the dried and rewetted soils, compared to those of soils held continuously moist.

There are both positive and negative effects of alternate wetting and drying cycles on SOM decomposition:

(i) If soil is saturated for long enough on each wetting cycle, the alternation of wetting and drying will be analogous to anaerobic and aerobic conditions, thus slowing the net rate of decomposition;

(ii) Since wetting and drying of soil colloids, particularly the smectite clays, causes expansion and drying causes contraction, the alternation of wetting and drying can cause breakup of aggregates and particles thus increasing the availability of organic matter for decomposition.

Laboratory studies have shown that the periodic wetting and drying of soil increases SOM decomposition (Sorensen 1974). In intermittent wetting and drying experiments, flushes of mineralisation have been noted in the first one or two cycles, with a 'tailing off' in subsequent cycles (Sorensen 1974; Ross and Malcolm 1988). Birch (1958) noted that the magnitude of the initial flush of nutrients increased with increasing length of drying period prior to wetting. Sorensen (1974) demonstrated that addition of straw to periodically dried and rewetted soil curtailed the tailing off in mineralisation and suggested a lack of decomposable substrate as the main reason for reduced nutrient release. Two main hypotheses have been proposed to explain the nutrient flush:

(i) that initial drying and rewetting shatters soil aggregates and exposes previously unavailable organic substrates for decomposition (Haque and Walmsley 1972);

(ii) that micro-organisms, killed by soil drying, are decomposed to release the nutrients immobilised in their tissues (Birch 1960).

Effects of oxygen

Decomposition of organic materials in soil is greatly facilitated by the presence of oxygen because, with only minor exceptions, most soil organisms are aerobes. In the absence of oxygen, anaerobic fermentation takes place, often by facultative anaerobes which can exist either in the presence or absence of oxygen. Where fermentation predominates overall decomposition is slower.

Metabolism in soil is fundamentally altered when oxygen becomes limiting (Yoshida 1975). Not only do large sections of the population become inactive but the facultative anaerobic organisms shift from aerobic respiration to either anaerobic respiration (utilisation of other inorganic compounds as electron acceptors) or fermentation (utilisation of organic compounds as electron acceptors). The mineralisation of added substrate to CO_2 is very much slower under anaerobic than aerobic conditions (Jenkinson 1981). Parr et al. (1970) showed that once aerobic conditions were restored, the evolution of CO_2 rapidly increased, and after a week or so the total amount of CO_2 evolved from an incubation that had previously been anaerobic becomes the same as that from an incubation that had been aerobic throughout.

Effects of temperature

Jenkinson and Ayanaba (1977) compared the rate of decomposition of plant material in tropical rainforest (Southern Nigeria; mean annual temperature 26.1°C) with the rate under cool temperate conditions (Southern England; mean annual temperature 8.9°C). Their results suggest that decomposition of plant material in tropical Nigeria was four times greater than under the temperate conditions of England. Jenkinson and Ladd (1981) also reported that decomposition rates under semi-arid conditions of South Australia were approximately double those reported for the United Kingdom.

Temperature is also reported to be a major factor governing the accumulation of mats in hill pasture (Jenkinson 1981). Floate (1970) found that the time required to mineralise the same amount of C from dead moorland grasses was 1 week at 30°C, 6 weeks at 15°C, and 12 weeks at 10°C.

Effects of pH

A study of the rates of decomposition of ryegrass at three different pH regimes over a period of ten years (Jenkinson 1977) showed that decomposition rates were similar in the soil of pH 6.9 and pH 4.8 throughout the whole period of the experiment. In contrast, initial decomposition was slower in the very acid soil (pH 3.7); after one year, 58% of the added C had been lost, compared with the 69% in the other two soils. However, by the end of five years, this difference had almost disappeared, suggesting that the slowing of decomposition by the acidity was largely confined to the early stages. Acid and alkaline soils differ in their microbial populations (Dickinson 1974) and it is therefore likely that acidity slows down decomposition by restricting the activities of the soil population to a relatively small number of species.

Effects of inorganic fertilizers

The micro-organisms which decompose organic material added to soil usually obtain the necessary inorganic nutrients from two sources; those already present in the soil in available forms and those in the added plant material itself. The inorganic nutrient required in greatest abundance is N and thus is the element that most often becomes the first limiting to microbial activity in soil.

Allison (1965) incubated short-leaf pine sawdust (45% C, 0.13% N) in a soil poor in organic matter (0.84% C) that had previously been leached to remove nitrate. Addition of ammonium nitrate to the incubation increased the rate of oxidation of the sawdust during the first two months, but thereafter the curves for evolution of CO_2 tended to draw together.

It is sometimes found that large additions of organic matter decompose more slowly than small additions, even when factors such as aeration are not limiting (Jenkinson 1981). Nitrogen deficiency is the usual explanation: the soil contains sufficient nitrogen for decomposition of small additions but not for large additions. Thus, when Jenkinson (1966) added straw (C:N = 83) at a rate of 2.5 mg C/g soil to a soil containing 0.1% organic nitrogen, 23% of the straw C was lost in 35 days, whereas the loss from a 10 mg C/g straw addition was only 11%. When the C:N ratio was adjusted to 15 with nitrate, 29% of the C was lost from the small addition of straw in 35 days, 30% from the large addition.

Accessibility

Finely divided organic matter usually decomposes more quickly than coarse organic matter. Thus, Cheshire et al. (1974) incubated finely ground (<53 m) and coarsely ground (<1000 m) rye straw in soil and found that the finely ground material lost 61% of its C in 448 days, but the coarsely ground only 52%. Similar results were obtained by Allison and Cover (1960) using short-leaf pine sawdust.

Coarse organic material is more resistant than fine material because of accessibility; grinding creates extra surface and thus exposes more substrate to microbial attack. Since microbial build-up is more rapid on fine material, the N demand is correspondingly greater; thus, Sims and Frederick (1970), studying the decomposition of plant material of wide C:N ratio in soil, found that fine particles immobilised six times as much inorganic N in the first month as did coarse particles.

Residue decomposition on the soil surface is more subject to greater extremes of temperature and humidity. Thus Parker (1962) and Shields and Paul (1973) found that the rate of decay of plant material on the soil surface was much more subject to environmental factors than when incorporated in the soil. However, under conditions of uniform moisture and temperature these placement effects are less important (Jenkinson 1981). Allison and Cover (1960) found that sawdust kept moist and supplied with adequate nitrogen decomposed as quickly on the surface as when mixed with the underlying soil. When left on the surface as mulch, organic residue often becomes desiccated and decomposes more slowly than when incorporated (Parker 1962; Shields and Paul 1973). Generally, organic residues decompose more rapidly at shallow depths and leave less humus than at lower depths (Schnitzer and Khan 1972).

Matching Mineralisation Rates to Crop Requirements

The basic technology and approach to crop residue management and green manuring has been transferred from temperate to tropical regions. The use of green manure crops with a potentially high breakdown rate is appropriate in regions with cool spring temperatures, which slow the decay rate such that nutrients, particularly N, are released from the green manure at a rate which has some relationship with crop demand. In tropical systems, where mineralisation rates are potentially higher because of high soil temperatures at the beginning of the growing season (Jenkinson and Ayanaba 1977), and potential leaching losses are greater because of higher intensity rainfall, a rapid release of nutrients from the residue is inappropriate. The release of nutrients such as N, K and S can lead to NO_3^-, K^+ and $SO_4^=$, and the associated cation or anion, moving down the soil profile with the wetting front such that the establishing crop does not have ready access to the released nutrients. In soils of high hydraulic conductivity and/or poor nutrient retention capacity such nutrients may be leached below the rooting zone of the crop.

The consequences of the above are the same for soil C as for nutrients. When crop residues or green manure are added to tropical systems, where the turnover rate is high, there is an episodic introduction of C into the system and a rapid depletion of C as mineralisation progresses. This means that soil C levels cannot be rehabilitated back towards their initial values where the C and nutrient pool sizes were large and their turnover rate slow. Such a system results in a release of C and nutrients from the organic matter at a rate consistent with plant demand. Both release rate and demand rate are dependent on soil moisture and temperature.

In addition to the direct effects of crop residues, green manures and fertilizers on nutrient dynamics and crop growth, considerable interactions can occur between them such as 'priming' where the addition of fertilizer can stimulate the release of nutrients from organic matter.

Data from a glasshouse experiment conducted at Armidale demonstrate the difference between crop residues and green manure crops in their effect on crop yield and apparent nutrient recovery (Table 1). The incorporation of 3t/ha of wheat straw reduced yield to below the no residue control in two successive crops and there was an apparent immobilisation of P, K, and S in the first crop. By contrast, there was a substantial increase in yield of the first crop when chickpea trash was incorporated with an apparent mineralisation of all nutrients. Yield response and apparent mineralisation were lower in the second crop. When leaf from the tree legume *Albizia falcataria* was incorporated, which had a similar C:N ratio as chickpea trash, there was a low mineralisation rate of N, P, and K and an immobilisation of S in the first crop which resulted in a low yield. In the second crop mineralisation rates were high and this resulted in a high wheat yield. These data highlight the need for complete nutrient balance in the residues, not just a favourable C:N ratio, and in the C and nutrients in the residues being accessible to microbes.

Table 1. Yield of two wheat crops grown in soil amended with 3t/ha of crop residues or green manure. Yields are relative to a zero residue control.

	Crop	Relative yield	Relative apparent mineralisation rate[a]			
			N	P	K	S
Wheat straw	1[b]	90	0	−1	−16	−24
(C:N 138.3)	2	93	10	7	13	42
Albizia leaf	1	106	37	21	7	−14
(C:N 10.4)	2	196	102	109	129	121
Chickpea trash	1	153	324	51	39	18
(C:N 11.2)	2	137	26	30	49	60

[a] $\frac{\text{Nutrient content of treatment} - \text{nutrient content of control}}{\text{nutrient content of control}}$

[b] Crop 1 = 10 weeks, Crop 2 = 12 weeks

Table 2. S and P balance sheet in a maize cropping system over 3 years at Phra Phuttabat, Thailand.

Input (kg/ha)	S balance				P balance			
Fertilizer	0	16	32	96	0	16	32	96
Rainfall	12	12	12	12	7.2	7.2	7.2	7.2
Total	12	28	44	108	7.2	23.2	39.2	103.9
Uptake (kg/ha)								
Grain	21.0	17.1	23.1	26.6	36.1	41.2	51.4	67.4
Residue	19.0	18.2	23.9	19.6	6.2	9.8	9.7	12.4
Balance (kg/ha)								
Residue returned	−9.0	10.9	20.9	81.4	−28.9	−18.0	−12.2	35.8
Residue removed	−28.0	−7.3	−3.0	61.8	−35.1	−27.8	−21.9	23.4

Table 3. Fate of nutrients (kg/ha) in 1.5 t/ha (6.6 b/ha) cotton crop.

Fate	N	P	K	Ca	Mg	S
Removed in product	110	18	38	8	13	26
Returned at defoliation	48	7	22	47	9	2
Stalk+capsules	73	12	87	51	10	10
Roots	12	3	14	6	4	2
Total	242	40	158	112	35	42
% removed	45	45	24	7	37	62

Table 4. Nutrient ratios in returned parts.

Plant part	C:N	N:S	P:S
Leaves	16.7	4.4	0.7
Stalks	38.5	8.7	1.3
Capsules	41.7	8.0	1.3
Roots	50.1	6.7	1.3

–When C:N >15, so not enough N to use C
–Microbes need 15N:1S, so enough S
–Microbes need P>S, so leaf P low

Crop Residue Management and the Carbon and Nutrient Balance

Because crop residues contain considerable quantities of C and nutrients their management can markedly affect the input/output balance. Because of differential translocation of nutrients to the harvested grain the effect of crop removal and residue management varies between nutrients. Lefroy et al. (1988) calculated a P and S balance sheet over 3 years for a maize cropping system at Phra Phuttabat, Thailand (Table 2). This showed that because of the high translocation of P to the seed, relative to S, the importance of residue management to the nutrient balance varied between the two nutrients.

Blair (1994), in a study with cotton estimated the quantities and value of nutrients contained in seed, lint and trash (Table 3). The amounts of nutrients estimated in a 1.5 t/ha crop range from 35 kg /ha for magnesium (Mg) up to 242 kg/ha for nitrogen (N) with the amounts increasing in the order Mg<P<S<Ca<K<N. The proportion of the nutrients taken up by the crop that is removed from the farm in seed and lint varies markedly between nutrients from 62% for S down to 7% for Ca.

Defoliation of the crop returns considerable amounts of all nutrients in the leaf fall. This source of C and nutrients is readily decomposable by soil micro- and macro-organisms and represents a flush of nutrients into the system at a time when crop demand is low. The fate of these nutrients released is an important determinant of the short- and long-term fertility of the system. For example, if the N mineralised from the leaf fall moves down the soil profile and is denitrified then it represents an important loss to the system. Little can be done to alter the fate of nutrients in leaf fall with the possible exception of selecting for tougher leaf cuticles which would slow the decay rate.

Stalks and capsules represent a significant amount of the C and nutrients taken up by the crop (Table 3) and are the one component of the crop that can be managed on-farm. In the example presented, 44% of the plant C is contained in stalks and capsules. The percentage of nutrients in the whole crop present in these residues are; 30% N, 30% P, 55% K, 46% Ca, 29% Mg, and 24% S.

The estimate made of the nutrient ratios contained in various residue parts (Table 4) suggests that leaves have adequate amounts of N for the microbes to use all of the C that they contain whereas stalks, capsules and roots would consume soil N to break down these residues, resulting in short term immobilisation of N. The N:S ratio suggests that all residues contain sufficient S for mineralisation and the P:S ratio indicates a possible P shortage in leaf residues.

Stalks and capsules represent that portion of the crop residue where management options exist. Maintenance of the residues in the system are essential for the long-term sustainability of the system. Clearly burning or removal from the field for stock feed or ethanol production will hasten the rate of decline in soil C and fertility.

Burning stubble can remove about 50% of most nutrients through volatilisation except Ca which is mostly retained in the ash. The actual amount lost will largely depend on the heat of the burn. Most of the burning stubble is the stalk and capsules and some roots. Based on the above stalk and capsule uptake

Table 5. Value per hectare of nutrients contained in stalks and capsules from a 1.5 t/ha cotton crop and monetary loss on burning (Values based on fertilizer costs at Warren, Australia).

	N	P	K	Ca	Mg	S	Total
Value of nutrient in residue[a]	51.10	22.8	56.55	7.15	5.00	1.40	$A144.00
% loss on burning	50	50	50	0	50	50	
Cost of loss on burning	22.5	11.4	28.28	0	2.5	0.7	$A68.42

[a] If the stalks are removed for stock feed or ethanol production their nutrient replacement value is $A144/ha.

figures (Table 3) this represents 37 kg N; 6 kg P; 44 kg K; 5 kg Mg; and 5 kg S which has been lost in smoke. The value of the nutrients contained in stalks and capsules and their fate when burnt is shown in Table 5. The nutrient value of $A144 contained in the stalks and capsules does not include a value for C. Thus while stubble may be difficult to manage, total removal has a financial cost as well as an agronomic cost. If these nutrients are not replaced through fertilizer then the whole system will eventually run down. If the stalks are removed for stock feed or ethanol production their nutrient replacement value is $144/ha.

Conclusion

Clearly management of crop residues is a major determinant of the long-term sustainability of upland cropping systems. The challenge is to increase the pool size of SOM and to slow the turnover rate so that C supply to micro-organisms is more sustained and nutrient released coincides with crop demand.

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Tree/Shrub Legume Residues in Upland Cropping Systems in the Philippines

A.S. Almendras and R.C. Serohijos*

Abstract

Decline in soil chemical and physical fertility following clearing of forests and subsequent cropping is a major problem facing Philippine agriculture and the environment.

A field experiment with three successive crops was conducted on a clayey typic Paleudult from July 1992 to May 1994 to examine the difference in legume herbage source, crop residue management and supplemental addition of chemical fertilizer for soil fertility restoration. Except for N and K uptake of maize in the second cropping, no interaction effects of the above factors were observed. Most of the crop attributes examined were affected independently by fertilizer rate, legume herbage sources and crop residue management. In all croppings, high fertilizer rate (58: 12: 23 kg N, P and K/ha) increased grain yield. Application of *Gliricida sepium* at 2 t/ha was more effective in increasing grain yield than using *Acacia auriculiformis* in the first cropping only. Further croppings did not result in significant gain from addition of legume litter regardless of herbage source and regardless of fertilizer and crop residue treatment. Returning of maize stover and cobs led to taller plant stature and higher LAI values but did not significantly affect the grain yield. Soil organic carbon level at all depths (0–5, 5–10, 10–20, 20–40 and 40–60 cm) was not significantly affected by fertilizer, legume herbage, crop residue or by the interaction of these factors.

Soil productivity is strongly linked to soil organic matter (SOM) through its influence on soil physical properties and nutrient supply. There is a great deal of evidence that the decline in crop yield with continued production in many areas in the tropics is correlated with decline in SOM. As SOM declines, yield can only be maintained by significant inputs of fertilizers. Manipulation of SOM could be achieved through crop selection, appropriate tillage practices, green manuring, residue management and addition of chemical fertilizers (Parton et al. 1987; Paustran et al. 1992).

In the Philippines, there is an increasing interest in using legume residues for improving soil productivity. The legumes, either tree or shrub, have been used in initial tree planting programs, thus encouraging agroforestry in the uplands. This is done to restore soil productivity. Also, agricultural intercrops within the limited confines of reforested areas offer income to the farmers.

One of the popular techniques used to restore upland productivity is alley cropping where agricultural crops are grown in between wide rows of leguminous trees/shrubs. The branches of the legume are regularly pruned at 3 to 6 monthly intervals depending on coppicing ability. The pruned branches are used as mulch or green manure for food crops growing between the rows. In other instances, prunings from other areas are brought to the crop planting site and scattered around the field to augment soil nutrition and improve water conservation in the area.

The benefits of applying legume residue depends on their rate of decomposition. Rapidly decomposing legume residues can result in large short-term benefits through speedy mineralisation but negligible long-term benefits in terms of increasing SOM level. On the other hand, legume residues that breakdown slowly result in a slow rate of nutrient release and may cause short-term nutrient deficits but are likely to have long-term benefits of restoring SOM level (Palm and Sanchez 1990; Gutteridge 1992). Thus to increase the SOM level and to promote synchrony in

* Department of Agronomy and Soil Science, Visayas State College of Agriculture, Baybay, Leyte, Philippines 6521-A.

the release of nutrients from slow decomposing residues with plant growth demand, judicious application of chemical fertilizer maybe necessary.

Materials and Methods

The experiment was conducted in Matalom, Leyte, Philippines from July 1992 to May 1994. Matalom has an average annual rainfall of 2000 mm with maximum rainfall occurring during July to December and with a short dry period from August to September.

The soil of the experimental site is classified as clayey typic Paleudult and its salient characteristics relevant to this study are presented in Table 1. Before the experiment, the land was mainly under grass fallow (*Imperata cylindrica*) for about six years.

The experiment was laid out in a randomised complete block design with three replications for each treatment. There were 16 treatment combinations composed of four legume residues [control, *Gliricidia sepium* (fast decomposing), *Acacia auriculiformis* (slow decomposing), and 50:50 mix *G. sepium* and *A. auriculiformis* (referred to later as 50:50 G/A mix)], two fertilizer rates (58: 12: 23 and 14.5: 3:6 kg N, P and K/ha), and two crop residue managements (crop residue removed and returned).

Maize (cv. Improved Tiniguib in first and third cropping and cv. VM2 in the second cropping) seeds were planted in 3 m × 3.5 m plots with 70 cm between rows and 50 cm between hills. Two plants per hill were maintained.

Three croppings of maize were accomplished. For each cropping, legume herbage collected away from the experimental site were applied in the furrow four weeks before planting for the first and third croppings and two weeks before planting for the second cropping at a rate of 2 mg/ha. Nutrient analyses of the herbage used in every cropping are present in Table 2.

The high-rate fertilised plots received 200 kg/ha complete fertilizer (14: 14: 14) at planting and 30 kg N/ha as urea one month after planting. For the low fertilizer rate, 50 kg/ha of complete fertilizer was applied at planting and 7.5 kg N/ha as urea one month after planting.

To compare the effects of returning crop residues against removal, the maize stover and husk were returned to the plots at harvest.

The grain and crop residue yields and nutrient contents were analysed in every cropping. The plant height and leaf area index (LAI) at tasselling were only determined in the second and third cropping.

Before incorporation of legume residue for each cropping, soil samples were collected with a core sampler. In the second cropping, samples were collected from three depths (0–5, 5–10, 10–20 cm) within each treatment plot while in the third cropping

Table 2. Nutrient content of legume residue used in the study.

Legume residue	Nutrient N (mg/g)	P (mg/g)	K (mg/g)
	First cropping		
G. sepium	2.96	0.15	1.19
A. auriculiformis	2.19	0.10	0.68
	Second cropping		
G. sepium	3.11	0.16	1.25
A. auriculiformis	2.38	0.10	0.60
	Third cropping		
G. sepium	2.09	0.17	0.73
A. auriculiformis	1.03	0.11	0.37

Table 1. Soil properties of the experimental site before the first cropping.

Sampling depth cm	pH (1 : 1) H_2O	pH (1 : 1) 0.01M $CaCl_2$	Org. C (mg/g)	Total N (mg/g)	Ext. P (mg/kg)	Exch. K[a] (cmol(+)/kg)
0–5	5.2	4.7	2.00	0.13	2.03	0.22
5–10	5.1	4.5	1.66	0.11	0.11	0.19
10–20	5.0	4.4	1.34	0.09	0.09	0.16
20–40	5.0	4.5	1.21	0.08	0.08	0.17
40–60	5.0	4.6	0.97	0.08	0.08	0.13

[a] Neutral, 1N ammonium acetate extraction

samples were collected from five depths (0–5, 5–10, 10–20, 20–40, 40–60 cm). Within the harvestable area of each treatment plot, two cores were collected within the planted row and combined with two from the interrow area and analysed for organic carbon using the modified Walkley–Black method.

Results and Discussion

Crop performance

First cropping. Generally, there was no inorganic fertilisation × source of legume herbage interaction in the crop attributes measured, thus only the main effects are presented. Fertilisation at the high rate approximately doubled the yield and nutrient content of maize (Table 3). This indicates the need for supplemental addition of N, P and K to increase crop yield.

Application of *G. sepium* herbage resulted in a 30 and 35% increase in ear and grain yield respectively, over that of the control (Table 3). On the other hand, application of *A. auriculiformis* resulted in only 6% and 7% yield increase for ear and grain weight respectively, over the control. The yield obtained from plots with a 50:50 G/A mix was intermediate between these two treatments reflecting the consequence of mixed decomposition rate i.e. rapid and slow decomposition. There was no significant difference in nutrient uptake between legume herbage treatments (Table 3). This implies that only the timing of nutrient availability affected yield and plant development. The tough cuticle of *A. auriculiformis* herbage appeared to reduce the rate of decomposition. Some undecomposed or partially decomposed litter of *A. auriculiformis* remained in the furrow after one month while only small amounts of decomposed litter of *G. sepium* were observed. Thus, with slower rate of decomposition, a slower rate of mineralisation would be expected. Betonio (1992) observed that *A. auriculiformis* had slower rate of nitrogen (N) mineralisation that *G. sepium*.

Second cropping. Generally, the rate of fertilizer application significantly affected most of the dependent variables measured. From Table 4, it could be noted that plant height, LAI values, stover, cob, ear and grain yield were improved by high rate of fertilization. This again, indicates the importance of chemical fertilizer application in enhancing maize yield in marginal areas like the site used in this experiment.

Fertilisation affected P uptake (Table 5) which was expected considering the extremely low extractable P

Table 3. Yield and nutrient uptake of maize during the first cropping as affected by fertilizer rate and different legume residues.

Treatment	Yield (t/ha)				Nutrient uptake (kg/ha)		
	Stover	Cob	Ear	Grain[a]	N	P	K
Fertilizer rate[b]							
Low	1.93	0.20	0.93	0.59	32.07	3.10	5.36
High	3.34	0.27	2.00	1.40	59.45	6.59	9.87
$LSD_{0.05}$	0.18	0.04	0.21	0.24	3.25	0.56	0.93
Legume residue[c]							
Control	2.61	0.27	1.29	0.86	41.37	4.59	6.56
A. aurculiformis	2.52	0.28	1.37	0.92	44.65	4.72	7.32
G. sepium	2.75	0.31	1.68	1.16	49.52	5.20	8.26
50:50 (G+A)[d]	2.67	0.29	1.52	1.03	47.48	4.88	8.30
$LSD_{0.05}$	ns	ns	0.30	0.22	ns	ns	ns

[a] Yield at 15% moisture content
[b] High–58:12:23 kg N,P and K/ha; Low–14.5:3:6 kg N, P, and K/ha.
[c] 2 t/ha
[d] 50:50 mix of *G. sepium* and *A. auriculiformis*

Table 4. Plant height, LAI, and yield of maize during the second cropping as affected by fertilizer rate[a].

Fertilizer rate	Plant height cm	LAI cm^2	Yield t/ha			
			Stover	Cob	Ear	Grain[b]
Low	196.6	2.41	2.18	0.17	0.52	0.57
High	238.7	3.39	4.00	0.37	1.24	1.66
$LSD_{0.05}$	12.3	0.35	0.31	0.13	0.51	0.28

[a] LAI and plant height at tasseling
[b] Yield at 15% moisture content

present in this soil. A three-factor interaction was detected for both N and K uptake (Table 6), with the high rate of fertilisation increases N and K uptake.

With a high fertility rate, N uptake was generally improved with the return of crop residue in plots with 50:50 G/A mix and in the control. Moreover, maize in plots with 50:50 G/A mix was able to efficiently take up N, with the return of crop residues. There appeared to be an increase in N availability in the plots which received the 50:50 G/A mix with the return of crop residues as compared to the other residue treatments. This suggests that the nutrient release from the 50:50 G/A mix was subsequently complemented by nutrients from the crop residue added. In contrast, the plots with *G. sepium* had much better N uptake when crop residue was removed than returned which is similar to N uptake by maize grown with *A. auriculiformis* herbage and with crop residues removed.

Table 5. Effect of fertilizer rate on P uptake of maize during the second cropping

Fertilizer rate	P uptake kg/ha
Low	3.32
High	8.28
$LSD_{0.05}$	2.32

With a low fertilizer rate, the N uptake was high with *G. sepium* herbage and residue returned and low when crop residues were removed. Nitrogen uptake was not significantly affected by residue management for the two other legume sources (*A. auriculiformis* and the 50:50 G/A mix) and the control. This suggests that with a low fertility regime, maize growing in plots with *A. auriculiformsis*, 50:50 G/A mix or no legume, had an equal N uptake whether crop residue was removed or returned.

Similarly, K uptake of maize was significantly influenced by the three factors (Table 6). Higher K uptake was recorded in maize grown in a high fertility regime than with a low fertilizer rate. At the high fertility rate, K uptake tended to increase when crop residue was returned to the plots with *A. auriculiformis*, 50:50 G/A mix or the control. By contrast, in the *G. sepium* plots, the maize's K uptake was higher when residues were removed than when crop residues were returned. There was no significant difference in K uptake between *G. sepium* and the control treatments indicating that *G. sepium* failed to influence K uptake. When crop residues were removed all legume sources increased K uptake.

When the fertility regime was low, the K uptake had a different pattern. Both *G. sepium* and control plots had a similar trend, where returning crop residues resulted in higher K uptake than when they were removed. On the other hand, *A. auriculiformis* and 50:50 G/A mix tended to enhance K uptake when crop residues were removed.

Third cropping. Plant height, and LAI of maize were affected independently by fertilizer rate (Table 7) and residue management only (Table 8). No interaction effects were observed. High fertilizer rate increased plant height and promoted large leaf resulting in high LAI values (Table 7).With the residue management, removal of crop residues led to short plant stature and reduced LAI.

As in second cropping, stover, cob, ear and grain yield were higher in plots with high fertility regime than in low fertility regime (Table 8).

Organic carbon

Analysis of the soil samples taken after harvest of maize in the first and second cropping revealed that the treatments did not significantly affect the organic carbon level.

From the results of this study, it is evident that application of chemical fertilizer significantly improved crop performance. Thus, under the conditions of this experiment, application of nutrients such as N, P and K is necessary to provide an acceptable crop. However, dependence on chemical fertilizer

Table 6. Nitrogen and potassium uptake of maize during the second cropping as affected by legume, fertilizer rate and residue management.

Treatment	Nutrient uptake (kg/ha)	
	N	K
Low fertilizer rate		
Crop residue returned		
Legume residue		
Control	14.2	6.59
A. auriculiformis	14.0	6.27
G. sepium	19.3	6.88
50:50 (G+A)	13.1	5.44
Crop residue removed		
Legume residue		
Control	16.2	5.60
A. auriculiformis	13.6	6.91
G sepium	12.6	5.01
50:50 (G+A)	14.3	6.31
High fertilizer rate		
Crop residue returned		
Legume residue		
Control	33.0	11.73
A. auriculiformis	33.2	14.56
G. sepium	29.0	11.67
50:50 (G+A)	43.8	14.89
Crop residue removed		
Legume residue		
Control	23.7	9.64
A. auriculiformis	35.2	11.41
G. sepium	38.3	13.66
50:50 (G+A)	23.9	11.41
$LSD_{0.05}$	3.9	7.82

maybe minimised with appropriate legume and crop residue management.

Although there are some indications in this study that crop performance (i.e. N and K uptake) can be improved with legume application and crop residue addition complemented with inorganic fertilisation, an observation period longer than three years will be necessary to measure the impact of these three factors on crop yield and soil organic carbon level. Removal of crop residue will ultimately reduce levels of soil organic carbon. In the relatively short period of this study, however, there was no significant difference between residue treatments.

Table 7. Plant height and LAI of maize during the third cropping as affected by fertilizer rate[a].

Fertilizer rate	Plant height cm	LAI
Low	163.1	1.41
High	190.4	1.89
$LSD_{0.05}$	6.1	0.16

[a] LAI and plant height at tasseling.

Table 8. Plant height and LAI of maize during the third cropping as affected by residue management[a].

Residue management	Plant Height cm	LAI
Returned	180.2	1.76
Removed	173.2	1.54
$LSD_{0.05}$	6.0	0.15

[a] LAI and plant height at tasseling.

Table 9. Maize yield during the third cropping as affected by fertilizer rate.

Fertilizer rate	Stover	Yield (t/ha^{-1})		
		Cob	Ear	Grain[a]
Low	1.93	0.16	0.63	0.50
High	3.22	0.41	1.81	1.59
$LSD_{0.05}$	0.36	0.03	0.24	0.18

[a] Yield at 15% moisture content

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Management of Nutrients and Residues in Perennial Tree Crop Systems of Malaysia

A.R. Anuar*, Othman Yaacob* and E. Pushparajah†

Abstract

Legume cover crops have long been an important part of soil management for plantation crops in Malaysia. Initially, they were used to provide effective cover against soil erosion in newly planted or replanted crops on steep terrain, and later to supply additional N. The non-shade cover crops can contribute about 226 to 353 kg/ha over a period of five years, while for shade tolerant crops it can be as high as 694 kg/ha from the third to the eighth year of growth.

The recycling of agro-wastes in plantation crops has proven to be beneficial such that almost all the wastes from oil palm, rubber and cocoa are utilised. Together with the use of inorganic fertilizers where necessary, the use of agricultural wastes has enabled the plantation sector to be more profitable, competitive, prevent pollution, and above all make the industry environmentally friendly and sustainable.

GEOMORPHOLOGICALLY, Peninsular Malaysia consists of a central core of granite mountains running from north to south, with major flood plains running along the coast and in between hilly, well-drained uplands. The mountains and most of the hilly uplands are at present still under natural forests.

The flood plains on the west coast of the peninsula are much more productive than those on the east. The alluvial plains on the west coast are fringed by large mangrove swamps, and are still largely underdeveloped.

The plantation tree crops cover vast areas of the interior upland. The widespread use of superior, high-yielding planting materials since the beginning of this century has led to an increased use of commercial fertilizers. Since Malaysia's even temperatures permit year-round growth, there is also the possibility of a rapid decline in inherent soil fertility through erosion and nutrient loss unless there is a careful soil management program. The use of ground covers and a nutrient budget are the basic methods in the management of soils and fertilizers for sustained production of plantation tree crops in Malaysia.

This paper examines various methods of managing nutrients currently being used in Malaysia to sustain the three main plantations crop production systems—rubber, oil palm and cocoa.

Distribution of Soils and Agricultural Systems

For operational purposes, the soils of Malaysia can be divided into three broad categories: soils under forest in the mountains of the interior; upland soils under plantation crops, rainfed field crops and forests in the interior uplands; and soils on the alluvial plains. Pedogenetically, soils in the mountains are young, shallow and have an efficient nutrient cycle. Inland soils on the undulating upland terrain are deeply weathered, acidic and highly leached, with a low to moderate inherent fertility related to the natural forest covers and the parent rocks. They are mainly Oxisols and Ultisols, and occupy some 24 million ha or 72% of the total land area of the country. Although such soils have a good physical make-up, they are devoid of most nutrients, and have a low CEC, a low base saturation and a high aluminium saturation with values often exceeding 80% (Tessens and Shamshuddin 1983).

* Department of Soil Science, Universiti Pertanian Malaysia, 43400 Serdang, Selangor, Malaysia.

† IBSRAM, P.O. Box 9–109, Bangkhen, Bangkok 10900, Thailand.

In contrast, soils on the flood plains are strongly gleyed, contain a relatively high CEC and varying levels of organic matter, and are predominantly silty clay loams or clay loams. The various properties of arable soils and the crops normally grown on them are presented in Table 1.

Management of Nutrients and Nutrient Cycling in Plantation Crops

Rubber

The existing recommendations for immature rubber in Malaysia (Table 2) seem to be adequate. For mature rubber, the plantation and smallholdings base their fertilizer recommendations on soil and foliar analyses.

Early plantations of rubber were established on land cleared from virgin forest, and the trees thrived on the high inherent fertility from organic matter reserves built up over a long period. Land clearing, however, could result in serious erosion. Even with some conservation measures, the surface layer of the soil is often eroded away within two years (Soepadmo 1979) due to the intense rainfall and reduction of the rain-interception capacity by clearing. Even cultivated tree crops show 15–20% reduction in rain-inception capacity. This results in an increase in run-off by 10 to 15%, which leads to increased soil erosion from about 30 to 100 kg/ha/year to over 2800 kg/ha/year. Such erosion leads to reduction in the inherent fertility status. With land clearing and burning there is an increase in the nutrients in the surface soil but these drop to relatively low levels within the first eight months (Andriesse 1980). Allowing the land to fallow for a period of 20 years did not enhance the fertility although such fallows can possibly allow organic-matter build up.

Table 1. The distribution of economic crops on the inland and coastal soils of Peninsular Malaysia.

Terrain	Soil properties limiting crop production	Suitable crop
Upland		
Oxisols, Ultisols	Deep profile, low moisture retention	Rubber, oil palm, cocoa, mixed orchard
	Al toxicity, acidic	
Coastal		
Marine clays, Inceptisols, Entisols	Gleyed, often with poor drainage	Oil palm, coconut, cocoa, rice
Riverine	Waterlogging, clay	Rice
Sandy	Low moisture content, poor in nutrients	Cashew nut
Peat	Shrinkage, acidic, low nutrient level	Oil palm, pineapple

Table 2. General fertilizer schedule for immature rubber trees in Malaysia[a].

Situation	Nutrients (kg/ha from Yr 1 to Yr 6)			
	N	P_2O_5	K_2O	M_gO
Low K, no legumes	640	250	170	50
Low K, mixed legumes	225	250	170	50
Low K, pure legume stand	30	250	170	50
High K, no legumes	660	260	90	50
High K, mixed legumes	225	260	90	50
High K, pure legume stand	30	260	90	50

Source: Pushparajah 1984
[a] 450 trees/ha; period of 66–72 months

When a primary or virgin forest is cleared for agriculture, there is a rapid loss of carbon and nitrogen. The dramatic reduction in organic carbon observed after land clearing was seen to persist even after seven years of cultivation (Uexkull 1984): the depletion of organic carbon was evident to a depth of more than 50 cm. In Ultisols and Oxisols CEC is more related to carbon content; hence, with a depletion of the percentage of carbon, there is also a rapid decline in CEC. Such changes would lead to reduction in crop productivity, so the need to maintain the organic-matter content is critical.

Legume cover crops have long been an important part of soil management for rubber. Initially they were used to provide effective cover against soil erosion in newly planted or replanted rubber on steep terrain, and later to supply additional nitrogen. Over the years, field experiments have shown that the amount of fertilizer, especially N, required by young rubber trees can be reduced after the third or fourth year from planting if a good legume cover is maintained. However, regular topdressing with rock phosphate during the first few years is required to establish and maintain the legume cover. With good management of the cover crop and fertilizer, trees can be brought into production at only four or five years, reducing the immature, unproductive period by one or two years. Cover crops also protect the soil, and at the same time maintain or even increase its overall fertility.

An early evaluation by Watson et al. (1964) showed that legume interrow covers return considerable amounts of leaf litter. After two years of established mixed legumes (*Pueraria phaseoloides, Centrosema pubescens* and *Calopogonium mucunoides*) the total above ground dry matter was about 8500 kg/ha and the soil nutrient content was 226 kg N, 18 kg P, 53 kg K, 16 kg Mg and 138 kg Ca. Tan et al. (1976) showed that about 20% of the original quantity of *Pueraria* litter remained after eight months of decomposition but it was higher with *Calopogonium caeruleum* litter (40%). They also showed that about 70 to 80% of K in the litter was released within the first five weeks while the release of N, P, Ca and Mg followed the trend in the rate of litter decomposition.

An assessment was made by Soong and Yap (1976) on the residual effect of different covers on soil conditions 14 to 15 years after establishment in rubber. Clean cultivation led to deterioration of soil by reducing the percentage aggregation of finer soil particles, decreasing aggregate size, and increasing bulk density. In the absence of covers, even with leaf litter turnover (estimated at about 2–3 t/ha/year from rubber) crust formation on the soil surface was evident. Thus there was also a reduction in infiltration. The effects of covers in six trials on Ultisols and Oxisols showed a highly significant correlation between organic carbon and some soil properties. These were percentage of aggregation, mean weight diameter and bulk density. This clearly implies that the beneficial effects of covers on physical properties was through the large returns of organic residues, which in turn increased the soil organic-carbon content.

The effects of covers on nutrient status of soils over a long-term period showed that by the third year of cover establishment the legume covers led to an increase in percentage of carbon in relation to level after burning. By the sixteenth year, the carbon content had dropped to 1.3% but this was a higher percentage than that observed under clean cultivation. Similar beneficial long-term effects on percentage of N and on exchangeable Ca, Mg and K were also evident. A sampling at four years after establishment clearly demonstrated that the lower level of N observed under clean cultivation was due to the nitrate being leached away to lower depths beyond the rooting zone. An early study showed that application of rock phosphate to legume cover and its cycling to the trees through the litter return was more beneficial to tree growth than application directly to the trees (Pushparajah and Cellapah 1969). Later, it was demonstrated that the application of fertilizers to covers enhanced N return (from the covers) and similar beneficial effects were obtained when K and Mg were applied to the covers (Tajuddin et al. 1980). This implies that cycling P, K and Mg through interrow covers is desirable.

Various workers had shown that the legumes enhanced the vigour and performance of rubber. The beneficial effects of the legumes on the yield of rubber continue to persist beyond 12–13 years after establishment (Pushparajah and Tan 1979). The beneficial effect is due mainly to nitrogen contribution.

During the early growth stages, up to five years from planting, trees under legumes did not respond to nitrogen application, whereas trees under a non-legume cover, for example grasses, responded well to N (Pushparajah and Chellapah 1969). To obtain growth of rubber with a non-legume cover equivalent to that obtained with a legume cover, an additional 330 kg N/ha had to be applied to the trees under non-legume cover during the first five years. The nitrogen returns from a mixture of non-shade types over a period of five years have been estimated to be in the range 226 to 353 kg (Watson et al. 1964). When a shade-tolerant legume cover (*Calopogonium caeruleum*) was introduced a total N return was as high as 694 kg/ha from the third to eighth year, while in the first two years the N return amounted to

284 kg/ha. In addition, the cover returned about 35 t of organic matter (Tan et al. 1976).

Oil palm

In contrast to the conventional clean clearing and burning system, the current trend is towards no burning. In this system the tree is felled, shredded into smaller pieces, stacked in predetermined avenues and left to decompose in the field. Legume cover is established as quickly as possible to expedite the rate of decomposition and minimise weed infestation. Full decomposition is obtained after about one year. This technique is environmental friendly, replenishes soil organic matter, improves soil physical properties and contributes relatively large quantities of plant nutrients.

Oil palm needs soils with a high inherent fertility. Studies have shown that oil palm, is a more nutrient demanding crop than rubber, both for early growth and for mature production (Table 3). While N can be partially supplemented through the use of a legume cover crop, particularly on upland soils previously under rubber, the high demand for K has to be met by fertilizers, except on soil with high K reserves.

Oil palms on soils with high K reserves give higher yields and do not respond to K fertilizer, unlike those on soils with low K reserves. From the point of view of the nutrient budget for the crop at various growth stages, oil palm shows a sharp rise in its uptake of major nutrients, particularly K and N, from the second year after planting. This uptake levels off after 5–6 years of growth. It is thus of critical importance to provide adequate nutrition through appropriate management of fertilizer and cover crops while the palms are immature, if early harvests are to be large and rapid increases in yields to be sustained. If nutrient budget data are compared with the ability of soils to supply these nutrients, fertilizer requirements can be determined to give economic production levels. Soils with a low K content, mainly upland Ultisols and Oxisols, require earlier and heavier application of K than those with high K reserves. Mg is also important, particularly on the highly weathered and leached soils found in some inland areas. N is the most expensive nutrient per unit applied. Palms on heavy inland soils formerly planted to rubber require good, early legume cover if maximum early growth of the crop is to be sustained. The value of legume crops to oil palm production, both as groundcover and as a source of N, has been demonstrated.

Research has shown that cover legumes enhanced the yield of fresh fruit bunch of oil palm, the yield increase being about 6% on coastal soils (Tan and Ng 1972). The beneficial effects of legumes have persisted up to at least 10 years after establishment of oil palm and legumes (Yeow et al. 1981). The symbiotic N fixation of legume cover crops can be exploited even more effectively if low cost pre-emergence herbicides are used. The bank of nutrients obtained from the soil and from applied fertilizer by all vegetative cover–legume crops and natural ground cover can be utilised by grazing with sheep or cattle. This further benefits the nutrient budget and nutrient cycling on oil palm plantations.

Proper nutrient management is needed to balance the inputs and losses of the different nutrients. This is particularly important with N:K and K:Mg ratios, and also with micronutrients on certain soils such as peat. On soil with low K content, a good K–N fertilizer balance can give improved yields even from mature palms on sandy soils. An increased supply of N and K without an adequate supply of Mg on soils with low Mg status can lead to the development of Orange Frond symptoms in younger palms, a nutritional disorder which later depresses growth and eventually yields.

Cocoa

When cocoa is grown under mature coconut, this dual crop combination has special nutrient requirements. Both crops have an extensive surface root system. When cocoa is planted in the shade provided by mature coconut, balanced nutrient management is essential to satisfy its high nutrient requirements dur-

Table 3. Estimated annual nutrient uptake by 6–8-year-old palms.

Plant (palm) part	N	P	K	Mg
		(kg/ha)		
Fresh fruit bunches (25 t)	73.3	11.6	93.4	20.8
Vegetative organic matter	108.1	12.0	141.9	33.9
Male flowers	11.2	2.4	16.2	6.6
Total	192.6	26.0	251.5	61.3

ing early growth and yield. The nutrient uptake by cocoa is high and on less fertile inland soils, fertilizers are needed in large quantities. Some of these requirements have been met through the appropriate use of nutrient-rich oil palm residues, coconut husks and other agricultural wastes. Mycorrhizal root associations, such as vesicular–arbuscular mycorrhizal inoculation or VAM have also been successfully exploited to give efficient use of limited amounts of P in highly weathered soils.

Use of Agricultural Wastes for Plantation Crops in Malaysia

Rubber wastes

The main wastes are from rubber factories and include block rubber effluent, sheet rubber effluent, crepe rubber effluent and concentrate latex effluent. The composition of these rubber effluents is shown in Table 4.

Rubber factory effluents must be treated to reduce the biological oxygen demand (BOD) level before it can be discharged. The most popular treatment system is ponding, though other systems are available such as anaerobic/facultative and ditch oxidation treatments (Yeow 1984). Rubber effluents can be used in both rubber and oil palm plantations, but it is only economical to apply them to oil palm plantations because of the high fertilizer requirement of oil palm compared to rubber. Experiments have shown that a fresh fruit bunch (FFB) yield increase of 20% can be obtained from the application of mixed concentrate latex effluent. Normally, land application of rubber effluent is by furrow/gravity flow system. In the production of latex concentrate, bowl sludge is produced which contains high amounts of magnesium and phosphate and to a lesser extent nitrogen (Table 5). Dried bowl sludge has been shown to be a good organic fertilizer source for pasture and cover crops (Lowe 1968).

Oil palm wastes

Large amounts of waste are produced from oil palm factories and the disposal can be a problem to the industry and the environment. The land application of nutrient-rich wastes from oil palm factories has been tested on a large scale and found to be an efficient means of nutrient recycling. These may ultimately produce systems of fertilizer management which are economical and environmentally acceptable for large-scale plantations in the humid tropics.

Irrespective of the treatment methods this treated palm oil mill effluent (POME) can be used as organic fertilizer, and partially substitute the inorganic fertilizer normally used. The difference in treatment will result in different types of POME, which can be used as organic fertilizers which include ditch sludge, digested effluent, digested sludge from biomass production, digested sludge from tank digestion, sludge cake and palm oil cake. The nutrient content in these effluents differ, with nitrogen ranging from 0.03 to 4.5%, P from 0.004 to 0.8%, K from 0.16 to 2.9% and Mg from 0.03 to 0.8% (Yeow 1984).

Instead of discharging these effluents into waterways, the plantation sector utilises them as a substitute to normal inorganic fertilizers. Effluents are mainly utilised for fertilising oil palm plantations, though some are sold for use on other crops such as fruits and annuals, including vegetables.

Several methods have been developed for using POME in fields including flat/long beds, furrow/gravity flow, sprinkler/pipe irrigation and tractor/tanker

Table 4. Composition of rubber effluents[a].

Parameter	Block	Sheet	Crepe	Concentrate
pH	5.5	5.0	6.0	4.8
BOD	1769	1322	305	3524
Chemical Oxygen Demand (COD)	2899	2427	846	4849
Total solids	1961	1976	546	–
Volatile suspended solids	1245	–	–	818
Suspended solids	322	–	–	–
Ammonium – N	68	73	6	466
Total – N	141	143	75	602

[a] Results expressed in µg/g except for pH
Source: Yeow (1984)

Table 5. Analyses of bowl sludge before and after processing.

Constituents	Wet sludge (%)	Dry powdered sludge (%)
Rubber	35	5
Moisture	26	1.7
Mg	6.0	15.2
Ca +K	1	2.2
PO_4	26.4	67.0
NH_4	3.8	8.5
Residues	1.8	0.4

Source: Lowe (1968)

discharge. Each of these systems have their own advantages and disadvantages, and different cost. The sprinkler system is the most expensive, while the tractor–tanker system is the cheapest.

Currently sludge cake is being utilised in manuring of cocoa and oil palm seedlings, soil management in fruit cultivation on sandy soils and annual crops including vegetables.

Application of empty fruit bunch (EFB) is best done at the time of planting where application at the rate of 37.5 t/ha/year together with normal inorganic fertilizer can increase yield by 75% while an application at the onset of maturity only showed a slight increase in yield which is not significant (Lim and Chan 1989). Besides the increase in yield, application of EFB at the time of field planting has the benefit of reducing the period of immaturity by several months. The practice of utilising EFB is now extensively adopted by all sectors, including oil palm, fruits and even rubber growers.

In the case of pruned fronds, they are stacked in palm interrows to act as an erosion control measure as well as providing nutrients and conserving moisture.

The amount of prune fronds is estimated to be 11.7 t/ha/year (Chan et al. 1980). These fronds contribute quite high levels of nutrient to the palms since they contain relatively high concentrations of macro and micro nutrients. Palm fronds contribute 107.9 kg N, 10.0 kg P, 139.4 kg K, 17.2 kg Mg and 25.6 kg Ca/ha/year (Yeow 1984).

Cocoa wastes

Currently, not much work has been carried out on the utilisation of cocoa waste as organic fertilizer. But it has been the practice of cocoa growers to recycle the cocoa pod husk back to the soil. The contribution of nutrients (e.g. phosphate) is very small (Yew and Chee 1992) as the phosphate content in cocoa pod husk is only 1.9 g/plant (Ling and Mainstone 1982). However, its recycling to the soil has enriched the soil organic matter.

Summary

The fertility of soils under major plantation crops of Malaysia is being sustained through the use of ground covers and sound soil and fertilizer management. The recycling of agro-wastes reduces the need for chemical fertilizer and has enabled the plantation sectors to be more profitable and, at the same time, reduces environmental problems.

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Agroforestry in the Food Production Systems in the South Pacific

V.T. Manu and S. Halavatau*

Abstract

The developing South Pacific countries consist of Papua New Guinea and 21 small island states with a combined land area of 550 777 km^2 and a population of about 6.5 million. Except PNG, these countries exist basically as multitudes of small islands, with an oceanic maritime climate, high island to low coral atoll topography, distinct or mixed volcanic and coral limestone soil types and isolated by large ocean distance between islands within and between countries.

The two main types of agroforestry practiced in the region are shifting cultivation and perennial tree-crop based agroforestry mainly with coconut and breadfruit. The main producing sector of the region is the smallholder with a traditional crop production system of integrated cultivation of annual root crops/perennial fruit and tree crops. The tree crops are planted and preserved by the shifting cultivator, hence, as shifting cultivation is phased out by overpopulation, these perennial tree crops become a permanent feature of the smallholder production system. The diversity of the production system is an insurance against climatic risk and the isolation of these remote island countries.

The relatively small amount of agroforestry research in the region is concentrated on the evaluation of the association between subsistence root crops and exotic perennial legumes. Results from experiments show insignificant or depressed yields of root crops in the hedgerow alley relative to non-hedgerow control. Future research should focus on: first, the synchronisation of hedgerow management to alley crop growth, nutrient uptake, etc.; secondly, an increase in the range of crops screened for specific hedgerow alley situations.

Perennial legumes in the region are mainly used as shade trees for coffee and cacao cultivation. Further, where coconut and breadfruit does not thrive, *Casuarina* spp. are grown by the PNG highland farmers as fallow species. Therefore, the future of the adoption of perennial legumes by farmers in the region depends mainly on the alley crop's ability to convert all the input benefits from the hedgerow into real dollars in the farmer's hand.

THE South Pacific countries (SPC) consist of Papua New Guinea (PNG) and 21 small island states, that lie between 141°E and 157°W and 5°N to 23°S. There is a total of at least 3000 islands in the region with a combined land area of 550 772 km^2 scattered in 30 569 000 km^2 of sea. From Table 1, it is apparent the region is dominated by Papua New Guinea with 84% of the total land area and 62% of the total population 6.5 million people. The rest of the countries exist basically as numerous widely distributed small islands in the South Pacific ocean.

The topography ranges from high islands with volcanic hills, with altitudes as high as 2300 m in PNG, to the flat coral atoll or reef islands such as Tuvalu and Kiribati with elevations of only 3 m above sea level. The volcanic soils are much more fertile relative to the soils from coral limestone whose development is minimal due to predominance of calcium carbonate resulting in high pH, and hence depressed availability of plant nutrients. Because of the great variability imposed by the oceanic maritime influence, the small island countries such as Tuvalu, with an annual rainfall of 700 mm are very susceptible to drought. In contrast, countries such as PNG have orographic rainfall of about 4500 mm annually. The cyclone belt encompasses Solomon Islands, Vanuatu, Fiji and Tonga with a frequency of one or more cyclones annually. Cook Island, and the two Samoa have less cyclones but do experience the occasional heavy intensive rainfall.

The food production system of the SPCs has been classified by Yen (1980a) as: integral subsistence sys-

* Plant Nutrition, Soil and Water Section, Vaini Research Station, MAF, P.O. Box 14, Kingdom of Tonga.

tems; mixed subsistence–cash cropping systems; and plantation systems. The first two systems consist of production of traditional annual root crops (*Ipomoea batatas*, etc.) integrated with various perennial fruit and tree crops (*Cocos nucifera*, etc.), poultry and pig husbandry and fishing with the latter system differing in the inclusion of cash crops (*Coffea* spp., etc.). These are the two basic production modes of the smallholder sector which is the main food producing sector of the SPCs. The plantation system is a fully commercial operation for production of commodities such as coconut, sugarcane, coffee, cocoa, rice, oil palm, pigs, cattle and fish.

Traditional Agroforestry in the South Pacific

The role and potential of agroforestry in agricultural development in the South Pacific countries has been discussed (Shrimer 1984; Rogers et al. 1992). Vegara

Table 1. The South Pacific countries: population, total land area, density, forest and permanent crop area, and predominate geology.

South Pacific Countries (SPCs)	Estimated population (mid-1992)	Total land area (km^2)	Arable land (ha) per person	Forest & woodland (% area)	Permanent crops area (ha)	Predominant geology
Papua New Guinea	4056000	462243	0.10	83	360000	volcanic
Fiji	753000	18272	0.32	65	88000	volcanic
Solomon Islands	337000	27556	0.17	91	17000	volcanic
French Polynesia	205800	3521	0.13	31	22000	volcanic
New Caledonia	176900	19103	0.11	38	10000	volcanic
Western Samoa	163000	2935	0.75	47	67000	volcanic
Vanuatu	156500	12190	0.92	75	124000	volcanic
Guam	140100	541	0.09	18	6000	mixed
Federal state of Micronesia	114800	701	n/a	n/a	n/a	mixed
Tonga	97400	747	0.64	11	31000	volcanic
Kiribati	75200	810	0.49	3	37000	atoll
North Mariana Island	54000	471	n/a	n/a	n/a	n/a
American Samoa	50900	200	0.09	70	2000	volcanic
Marshall Islands	50000	181	n/.a	n/a	n/a	atoll
Cook Islands	17800	237	0.34	0	4000	mixed
Palaa	15900	488	n/a	n/a	n/a	volcanic
Wallis & Futuna	14100	255	0.35	0	4000	atoll
Nauru	9800	21	0.00	0	0	coral atoll
Tuvalu	9300	26	0.00	0	0	atoll
Niue	2200	259	3.18	19	2000	coral outcrop
Pitcairn	100	5	n/a	n/a	n/a	n/a

Source: South Pacific Economies 1993: Statistical Summary. Statistics section,South Pacific Commission, Noumea, New Caledonia, 1993.
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and Nair (1985) reviewed and classified the agroforestry systems practiced in the South Pacific in accordance with Combe (1982). A technical meeting on agroforestry in the South Pacific (Clement 1987) documented that the two main kinds of indigenous agroforestry systems in terms of area and the number of countries are shifting cultivation and perennial tree-crop based agroforestry. In the coral atoll island countries (Table 1), with almost no arable land or forest and woodland, only the perennial tree-crop based agroforestry system is found.

Shifting cultivation

The practice of shifting cultivation in the South Pacific is limited to countries with relatively large land areas such as Papua New Guinea down to Vanuatu and American Samoa. These countries have 31% to 91% of their total land area still under forest and woodland which means that they still have the space for shifting cultivation to be practised to a large extent. Shifting cultivation in the SPCs consists of slash-and-burn of forest followed by a multi-storey cultivation as crop rotation or mixed cropping of annual root crops such as *I. batatas* in the lowest strata and inter-cropping or relay-cropping with *Musa* spp., etc., in the middle strata and also perennial tree crops such as coconut, in the top strata. After a number of seasons or the completion of the crop rotation of the annuals, the perennial tree crops are left to grow with the invading weeds hence the bush regenerates during the fallow period. Therefore, through time, these tree crops are progressively incorporated into the fallow species composition. On the next rotation of the shifting cultivation, these tree crops are often preserved into the next phase of the fallow period.

The periodical rotation of the bush fallow and crops allows the soil fertility, regenerated by the trees and other vegetation, to be utilised by the subsequent cultivation of crops. The degree to which the bush fallow regenerates the soil productivity and the removal of weeds depends on the woody species composition, soil characteristics and the duration of the fallow period (Nye and Greenland 1960). In the SPCs, improvement of the composition of the fallow species with perennial legumes by traditional farmers, hence reducing the effective fallow period, has been reported. The inter-planting of *Casuarina oligodon* with crops by PNG highland farmers (Watt 1980; Thiagalingam 1983) or the inter-cropping of *Erythrina subumbrans* and *C. esculenta* in W. Samoa (Vegara and Nair 1985), which is left behind in the fallow period, and consequently, increases nitrogen input into the soil via N-fixation. The natural occurrence of *Leucaena leucocephala* in Tonga and PNG features to a lesser degree as a bush fallow species but is still significant since the arrival of *Heterosophylla cubana* in the 1980s.

The ever increasing population pressure on limited land is indicated by the availability of arable land per capita as shown in Table 1. The ratio is consistently less than 1 ha/person for all the SPCs except Niue, therefore in the last decade cultivation has encroached onto marginal sloping land. Vegara and Nair (1985) reported increasing area under anthropogenic grassland in the PNG highlands, low hills of Solomon Islands, Fiji, Tonga and W. Samoa as a result of frequent burning which prevents re-emergence of trees during the fallow period. However, other factors which favour weed dominance over forest re-emergence, hence conversion to grassland, are: the decrease in fallow period beyond the critical time required for full regeneration of soil fertility until shifting cultivation resumes; prolonged cropping periods; and excessive forest clearance. The suppression of forest tree species re-establishing in the fallow period and the cultivation of the marginal sloping land has made shifting cultivation an unsustainable cultivation system during the last decade in the SPCs.

Perennial tree-crop based agroforestry

As shifting cultivation is phased out as a consequence of population pressure on limited land resources, the perennial tree crops, mainly coconut (*Cocos nucifera)* and breadfruit (*Artocarpus altilis*), have become the permanent component of the subsistence food production system hence the perennial tree crop agroforestry. This is the case in the over-populated, small coral atoll island countries with limited soil resources (Table 1). The cultivation of annuals such as *Cyrtosperma chamissionis* and *C. esculenta* is practiced in man-made organic pits which are dug into the underground freshwater lens. These pits are filled with leaves of *Guettarda, Boerhaavia, Triumfetta* and *Cordia* spp., *Scaecola frutescens, Pisonia grandis* and other species known for their organic mulch quality. Further, the salt tolerant species such as *Calophyllum, Casuarina, Ochrosia* and *Tournefortia* spp. are used for land reclamation because of their high leaf shedding characteristics. At the mid-level *Pandanus* spp., and at the top level coconut and breadfruit feature very strongly.

In the other SPCs the smallholder's traditional crop production system consists of a three-storey cultivation of annual root crops such as *I. batatas, C. esculenta, Manihot esculenta, Dioscorea* spp. and *Xanthosoma saggittifolium* at the bottom level, inter-cropped with non-woody perennials such as *Alocasia macrorrhiza, Musa* spp., *Piper methysticum* and *Carica papaya* at mid-level, and at the top level coconut, breadfruit, *Canarium, Indicum, Barringtonia* spp., *Pomentia pinnata* and *Mangifera indica*. Throughout the South Pacific 6000 km^2 is under coconut which represents 13% of world plantations (Raff 1985). Coconut is commonly grown in every country in the region with the exception of land with altitudes greater than 200 m. The higher yield and better growth of tree crops such as *Coffea* spp., *Theobroma cacao, P. methysticum, Vanilla* spp., under partial shade relative to the exposed cultivation in the SPCs tropical climate, has resulted in these species being interplanted in established coconut plantations.

In the PNG highland where coconut does not thrive, *L. leucocephala, Casuarina oligodon* and *Albizia stipulata* are interplanted as the shade plant for coffee (Watt 1980; Vegara and Nair 1985). In the PNG lowlands and Solomon Islands *L. leucocephala, Gliricidia sepium* are also planted with the coconut as a shade tree for *Coffea* spp. and *T. cacao*. The cultivation of *Vanilla* spp. with its *Ficus* spp. support tree, is often interplanted in established coconut plantations in Tonga and French Polynesia. The cultivation of *P. methysticum* in all SPCs is often found under coconut or other trees for shade. Vegara and Nair (1985) reported pasture spp. (mostly *Panicum maximum*) and coconut or *Pinus* spp. associations for cattle farming in Solomon Islands, Fiji, Tonga, Vanuatu, French Polynesia and the coastal areas and outer islands of PNG.

Therefore, the cultivation of annual root crops in association with perennial fruit and tree crops is the most widely practiced agroforestry system in SPCs. Yen (1980b) suggested that the diversity of this SPCs production system not only enriched the local people's diets with variety but provides a buffer against high climatic risks in the region, such as cyclone, drought, tsunami or intense heavy rainfall. A cyclone would damage the fruit and tree crops first but a drought or tsunami would damage the annual root crops first, hence in any natural disaster food security is at least assured to a certain extent in this tree-crop based agroforestry system across the remote islands of SPCs. However, the existence of this production system with grass fallow will fail once the population exceeds the saturation point of the land resources. Therefore, the incorporation of perennial legumes will play an important role in this production system.

Agroforestry Research in the South Pacific

The major thrust of agroforestry research in the South Pacific countries has been mainly aimed towards subsistence crop production. This is reflected by the large amount of research completed to date which has concentrated on the investigation of beneficial association between root crops (especially *I. batatas* and *C. esculenta*) and exotic perennial legumes. A few pasture—legume association studies have been undertaken, and during the last five years, the scope of agroforestry research has been broadened to include soil erosion control on marginal sloping lands.

Root crop–perennial legumes or trees

The early work of Swift (1981) in PNG reported a higher production of total biomass by *I. batatas–Leucaena* spp. association relative to a monocrop of *L. batatas*. But Brook (1992) reported a highly significant negative correlation between *I. batatas* tuber/vine fresh weight and the amount of hedgerow mulch produced by nine perennial legumes (6 m width) of which seven were below that of the non-hedgerow control. Shading was suggested as the likely cause.

In Tonga trials have found a lower fresh tuber yield of *Fioscorea alata* and the subsequent maize yield of *C. esculenta* that followed in a *L. leucocephala* var. Cunningham alley of 2 m and 3 m spacing relative to the non-hedgerow control. Both root competition and shading were proposed as the likely cause. Further, Halavatau et al. (1993) found no significant response of *C. esculenta* fresh maize yield in alleys of *Gliricidia sepium* and *Flemingia macrophylla* double and single hedgerows at 6 m spacing to that of the non-hedgerow control. The experiment is continuing with *Cucurbita maxima* as the alley crop.

In Solomon Islands, Hancock (1989) reported lower fresh root yield of *Manihot esculenta* and *I. batatas* in *G. sepium* alley. Further alley spacing experiments found *I. batatas* yield to be increasingly depressed with alley spacing of 5m to 6m. In Vanuatu, the evaluation of crop rotation of tuber and root crops with four perennial legume associations is ongoing. Further, a demonstration trial of the taungya system with the timber species and crop association of *C. alliodora* with *I batatas, M. esculenta, D. alata, C. esculenta* and *Piper methysticum* in Pentecost was documented by Clement (1987). In Fiji, various evaluations of root crops and *Zingiber officinalis–Calliandra* and *Gliricidia* spp. associations at different sites are on-going. The importance of minimum space in small islands is demonstrated by the on-going work of Whitesell and Cole (1982) in Marshall Island, where coconut and breadfruit are the hedgerow species and *Citrus* spp. and *Pandanua tertorius* are the alley crop.

In W. Samoa, Kid and Taogaga (1985) reported no direct relationship between *C. esculenta* maize yield and the amount of mulch produced by five perennial legumes of which *Calliandra, Leucaena* and *Gliricidia* spp. were superior. However, rate of growth of *C. esculenta* was faster in the *Calliandra* and *Leucaena* alleys. From W. Samoa also, Rogers et al. (1992) reported results from continuous inter-cropping of *Calliandra* and *Gliricidia* alley at 3, 4 and 5 m width with *C. esculenta* for six seasons. There was no significant difference in the *C. esculenta* fresh maize yield between hedgerow legumes or between different spacing at any of the six harvests. The non-hedgerow control was significantly lower than the hedgerow treatments only in the fifth and sixth harvest. Rogers and Iosefa (1993b,c) reported that ongoing experiments are expanding the number of experimental and on-farm trial sites (including American Samoa) and the increasing emphasis of research on indigenous species such as *Erythrina subumbraus*. Clement (1987) documents various trials in W. Samoa of timber species–root crops association such as *Securinega smoense, Eucalyptus deglupta, Pinus carribea, Cedrela odorata* and *Sweetenia macrophylla* with crops such as *C. esculenta* and *Alocasia macrorrhiza, Coffea*, and pasture species.

In summary, all the experiments report various amounts of biomass generated, nitrogen supplied, soil moisture conserved and all the associated benefits as inputs pass from the hedgerows to the soil and the environment of the alleys. However, these positive benefits are not fully converted by the root crop as indicated by a majority of the results to date with insignificant or depressed fresh maize or tuber yield of the crops in the alley relative to the non-hedgerow control. Shading and root competition from the hedgerow species are the likely factors postulated. From Nigeria, Kang et al. (1989) reported *M. esculenta* yield to be depressed in an alley of *Gmelina arborea* hedgerow as a result of aerial and subterranean root competition but not for *Cassia* and *Acioa* spp. The research of Rogers and Iosefa (1993a) in W. Samoa, found different cultivars of *C esculenta* to have positive and negative yield responses to 50% shade. Further, they proposed that maintaining shade only at planting and during the first few weeks of *C. esculenta* development has the potential to raise maize yields.

After the initial screening phase for adaptation of exotic and indigenous perennial legumes to agro-climatic zones as in PNG by Brook et al. (1992) or resistance to a specific pest by Moxon et al. (1990), screening a wide range of crops in the hedgerow alley for the crop with the highest response should follow. Lastly, there are future research needs in the SPCs to focus on: synchronisation of hedgerow management with crop growth, nutrient uptake patterns, crop physiological tolerance for shade and root competition and crop response to mulch application (Kang et al. 1989).

Erosion control

The SPCs response to the increasing deterioration of the marginal sloping lands due to cultivation has been to increase the number of experiments dealing with soil erosion. The on-going studies of Wayi and Konabe (1993) in the eastern highlands of PNG, Pratap (1993) in W. Samoa and Limalevu et al. (1993) in Fiji are all investigating whether hedgerows of various perennial legumes or tree crops control soil erosion during continuous cultivation of alleys with various food crops. Other countries such as Solomon Islands, Tonga, Cook Islands, etc., are placing emphasis on establishing soil erosion control experiments on sloping land.

The few experiments conducted on perennial legumes–pasture associations is an indication that poultry and pigs are the main subsistence livestock of the SPCs. From Tonga, Murray (1985) reports much better growth of *Bracharia decumbens* in 2 m alleys of *L. leucoephala* var. Cunningham relative to a fertilised *B. decumbens* non-hedgerow plot. Similarly, Raut and Gill (1987) reported from Fiji that more grass was produced in alleys of *Leucaena* than from non-hedgerow grass-only plots. Further, various on-going experiments and demonstration plots of mostly *Calliandra* and *Gliricidia* as fodder for sheep and goats have been established at various sites in Fiji.

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The Fate of Organic Matter and Nutrients in Agroforestry Systems

D.P. Garrity*

Abstract

Agroforestry systems are intermediate between forest ecosystems and agricultural systems, and exhibit some of the nutrient cycling and environmental services of natural systems and a complementarity–competition balance between trees and crops. This paper reviews how the status of nutrients and organic matter are affected by the inclusion of trees in agricultural systems and indicates some focal points for needed research. Nutrient pumping from deeper soil layers, and scavenging leached nutrients through horizontal root development, may significantly increase the overall supply and efficiency of nutrients. But nutrient pumping is limited in humid, strongly acid soils, where the contribution of P by trees usually is far below crop P requirements. Selection of trees with a deep rooting pattern and limited horizontal root development will be enhanced by more convenient methods developed recently based on fractal analysis.

Fallow-rotation hedgerow systems, a variant intermediate between a simultaneous and a sequential agroforestry, hold promise to overcome some of the limitations of continuous alley cropping. Expectations of an increase in soil organic matter content in agroforestry is dependent on the amount, source, and management of the pruning biomass. Crop performance in association with N-fixing tree species often is not superior to that with non-fixing species, suggesting that N-fixation should not be over-overemphasised in relation to characters that reduce competition between trees and crops. On sloping land there is a dramatic redistribution of soil fertility across the alleyways in contour hedgerow systems. This is a serious challenge to the sustainability of yields in these systems. Little effort has been expended in understanding nutrient cycling in the many farmer-developed agroforestry systems employed on millions of hectares. The fate of nutrients and soil organic matter in them is poorly quantified. Recognising the pathways of agroforestry systems evolution in response to the availability of external nutrients may be a useful point of departure for research on the fate of nutrients in a practical context.

AGROFORESTRY systems deliberately combine woody perennials with crops or animals in spatial or sequential arrangements. The tree and crop components experience significant ecological and economic interactions (Nair 1993). Because the structural characteristics of agroforestry systems are intermediate between forest ecosystems and agricultural systems, there are great expectations that they can replicate many of the nutrient cycling and environmental services often associated with natural forests, yet deliver exportable yields equivalent to or exceeding those of conventional agriculture. Testing the validity and limits of this premise is the driving force behind much current research.

Agroforestry encompasses a very wide range of land use systems. Examples of spatial associations of trees and crops include hedgerow intercropping (or alley cropping), trees on the boundaries of crop fields, trees managed in cropland, and mixed perennial systems as in complex agroforests and home gardens. Examples of sequential associations include fallow rotation systems with natural or improved tree components, as occur in shifting cultivation, and tree plantation establishment after cropping with annuals.

Conventionally, trees are viewed as helping to improve nutrient cycling and nutrient retention in agricultural ecosystems by performing a number of functions related to increased resource conservation (Buresh 1994). Among the benefits relevant to the

* Southeast Asia Regional Program, International Center for Research in Agroforestry, Jl. Gunung Batu No. 5, PO Box 161, Bogor 16001, Indonesia.

cycling of nutrients and the maintenance of organic matter are (Young 1989):

1) nutrient pumping from the subsoil by deep-rooted perennials,
2) reduction in leaching losses through capture of mobile nutrients by the well-developed rooting systems of perennials (i.e. nutrient safety net),
3) addition of nitrogen through biological nitrogen fixation by perennials,
4) maintenance of soil organic matter through supply of above- and below-ground litter and prunings from the perennials,
5) better maintenance and improvement of soil physical properties and
6) enhanced protection from soil erosion.

But there are also negative repercussions, and the forces that drive the complementarity-competition balance between trees and crops are complex. A recent approach (Ong and Huxley 1995) is to quantify the overall tree-crop interaction (*I*) by:

$$I = F + P + L - C \pm M$$

where *F* is the benefit of the organic inputs contributed by the trees, *P* is the consequence of changes in soil properties, *L* is the reduction of losses in nutrients or water on sloping land, *C* is the yield reduction due to interspecific competition between the trees and crops for nutrients, water and light. *M* is the consequence of changes in microclimate due to the presence of the trees. All terms are expressed in terms of changes in crop yield compared to open field controls (kg/ha or percentages).

F incorporates the first three benefits listed above: Nutrient pumping (1), the scavenging of leached nutrients (2), and N-fixation (3). *P* includes the benefits of increased organic matter(4) and improved soil physical properties (5), which are also mediated partially by soil organic matter. *L* considers the positive effects of reduced erosion (6). *F* and C are usually the dominant counterbalancing factors, and their magnitude is often closely associated with each other. Although *P*, *L*, and *M* are sometimes large, their effects on crop yield are relatively unimportant in the short term (Akyeampong et al. 1992). The individual factors, particularly *F* and *C*, can be quantified in adequately designed experiments (Ong and Huxley 1995).

This paper reviews how the status of nutrients and organic matter is affected by the inclusion of trees in agricultural systems. Emphasis is placed on the practical significance of these benefits, in light of the associated competitive effects (*C*) that tend to reduce or negate them. The paper concludes with a discussion of the pathways of agroforestry systems evolution in response to a fundamental soil fertility factor: Whether external nutrients are available to the farmer or not.

Nutrient Pumping

Since trees have deeper root systems than annual crops, it has long been suspected that they absorb significant quantities of nutrients from the subsoil, which are deposited on the soil surface via litter, prunings, or decay of shallow roots (Nair 1984; Glover and Beer 1986; Young 1989). This translocation process will increase the stock of nutrients available to the shallower-rooted crops grown in association, thus increasing system yield. This 'nutrient pumping' function is now frequently cited as a promising benefit of the tree component in agroforestry systems (Buresh 1994). The process would be particularly useful in concentrating at the soil surface more of the relatively immobile nutrients such as P and Ca. The cycling of P in organic forms would also be expected to increase its availability.

The practical question is whether nutrient pumping occurs to such an extent that it is economically important? Or is the effect masked by competition for nutrients or water between the deeper and shallower-rooted components?

The idealised system is conceived as a combination of tree and crop genotypes that exploit the growth resources of the soil volume fully, while minimizing competition. Complementarity exists if the trees and crops take up nutrients from different zones of the soil profile.

Trees do have a tendency to root more deeply into the soil profile, and to extract growth resources from below the maximum rooting depth of annual crops. Many tropical trees develop roots extending 4 m deep or more (Jenik 1978). However, in the humid tropics most rooting depth studies (Szott 1995) show relatively shallow rooting depths for the common multipurpose tree species, with a range frequently between 40 to 200 cm. In both agroforestry and natural ecosystems in the humid tropics the majority of tree roots in many cases are found in the top 30 cm of soil (Szott 1995). Lateral root extension in younger trees was found frequently to be between 1 and 4 m.

There are only a few studies that have estimated the locus of nutrient uptake experimentally. Results of ^{32}P studies from various sites (IAEA 1975) on cacao, coffee, and banana show that a large proportion of the uptake of P (30–85%) originated from the superficial zone close to the stem (less than 30 cm depth and less than 100 cm laterally from the base). However, in the case of coconut and oil palm P uptake from this zone was less than 20%. The percentage of P uptake from points farthest from the stem (usually > 45 cm depth and > 1.5 m lateral distance from the stem) was less than 4 % for the majority of the tree crops. Such levels would not make a significant contribution. Further, the proportion of nutrient uptake from zones in competition with crop roots may be reasonably assumed to be considerably higher than this.

There are several key factors working against effective nutrient pumping in humid, strongly acid soils:

1) There is a limited reservoir of nutrients in the subsoil. In the typical ultisol or oxisol, the concentrations of nutrient cations and phosphorus below a 30 cm depth are often low or at trace levels (e.g. Evenson 1989). Even considering the much larger volume of soil explored by the roots, the aggregate quantities of nutrients capable of being extracted are often insubstantial. A countervailing factor, however, is that roots may be capable of converting recalcitrant forms of *P* to extractable forms, and thus increase the exploitable *P* reservoir.
2) There is a distinct tendency for tree roots to grow shallowly in strongly acid soils due to aluminum toxicity in the subsoil caused by Al saturation of the exchange complex, less mechanical impedence in the topsoil compared to the subsoil, and a much greater pool of nutrient availability in topsoil.
3) Ecological theory suggests that below-ground competition tends to increase as soils become more infertile. This is due to a tendency towards increases in the root:shoot ratios, and to an increase in root length as macro-nutrients become limiting (Gillespie 1989).

Alley cropping was envisioned as an agroforestry system particularly suited to capturing the benefits of deep-root nutrient pumping. The circumstantial evidence from studies on acidic soils in the humid tropics is that deep-root pumping does not provide major practical benefits. Phosphorus is usually the most limiting nutrient in these environments. Palm (1988) observed a negative *P* budget in most alley cropping systems studied, but did observe an increase in available *P* in the soil. They attributed this to either *P* pumping or conversion of *P* to more available forms.

A severe practical limitation is that the contribution of *P* in the prunings of the commonly used hedgerow tree species is usually in the range of only 4–10 kg/ha annually (Garrity et al. 1993). This is far below crop *P* requirements. When one considers that a large proportion of this modest amount of *P* is likely to be derived from the crop root zone, it is not likely that the amount of deep-soil pumped *P* exceeds that amount 'robbed' from the crop (Szott et al. 1991).

In alley cropping, reduced crop yields near the hedges are commonly observed (Garrity 1995). Root barrier studies in alley cropping frequently show that about 50% or more of the yield reductions observed close to the hedges are due to below-ground competition, and that competition increases with tree age (Fernandez et al. 1993). This highlights the competition for nutrients created by shallow rooted trees which appear to negate the pumping effect.

Nutrient pumping dynamics are significantly different in subhumid to semiarid situations. In these water-limited environments there is evidence of the extraction by trees of soil water deeper in the profile (Stone and Kalisz 1991). Tree rooting depth tends to be deeper, promoting the survival and resource competitiveness of the trees. During periods when the upper soil profile is dry, nutrient pumping may be more significant, since at such times the tree is totally dependent upon water (and nutrient) extraction from deeper layers. Unfortunately there are no data to confirm this, and the premise has been questioned (Comerford et al. 1984). Common soils of the drier regions (e.g. alfisols, inceptisols) tend to have higher cation exchange capacities at depth than the soils common to the humid tropics, indicating a greater reservoir of extractable nutrients. But as the trees display a major competitive advantage in water and nutrient competition in drought-prone environments, there is quite serious suppression of associated crops during water-limited seasons (Singh et al. 1989; Ong et al. 1991).

Tree-crop systems display varying tendencies for overlap of rooting zones. Trees are likely to effectively operate as nutrient pumps only in situations where they produce deep root systems, and there are substantial nutrient quantities at depth. These conditions are most likely on deep, high base-status soils with good moisture. Care must be taken in selecting the specific tree genotype and crop genotype that exhibit suitable compatability. Van Noordwijk (1989) has emphasisd the selection of trees with a deep rooting pattern and limited horizontal root development. But much more work to document rooting depth profiles and nutrient cycling in agroforestry systems is needed. This may best proceed by quantitative study of the indigenous farmer-developed systems in current use. It will provide more evidence for the robustness of the nutrient pumping phenomenon.

Trees as Nutrient Safety Nets

One of the serious deficiencies of conventional annual cropping systems, particularly in humid environments, is their tendency to exhibit high leaching losses of the mobile nutrients such as nitrogen and potassium. This results in both short-term financial losses to the farmer, and serious off-site environmental nutrient pollution effects. In contrast, forest and perennial-crop systems are known to exhibit more closed nutrient cycles. Table 1 compares leaching losses for four nutrients between a monoculture maize system and a mixed perennial system. Nutrient losses from the root zone varied from three to fifty-one times more than from the maize system.

This has led to the concept that in mixed annual–perennial systems the trees may behave as nutrient safety nets (Van Noordwijk and de Willigen 1991),

Table 1. A comparison of nutrient leaching losses between an annual crop and a mixed perennial system (cacao, plantain, and *C alliodora)* during a 242 day period. Source: Adapted from Seyfried and Rao (1991).

Nutrient	Monocrop maize	Mixed perennials
	(kg/ha)	
Nitrogen	51	1
Potassium	3	1
Magnesium	21	3
Calcium	43	3

reducing leaching losses and recycling the re-captured nutrients. Van Noordwijk et al.(1991) has also postulated that tree roots may play another indirect role in reducing leaching losses: the presence of old root channels may tend to increase the amount of soil water that infiltrates through by-pass flow.

Experimental evidence quantifying the safety-net hypothesis is scarce. Horst et al. (1991) has shown that the presence of *Leucaena leucocephala* hedgerows reduced leaching losses in a hedgerow intercropping system, and attributed this to Leucaena's high root density in the subsoil of the alley-cropped plots.

The safety-net feature of trees is a function of their lateral rooting behaviour. It may be accomplished efficiently without deep rooting, in contrast to nutrient pumping. Lateral rooting strength, however, may increase the tendency for tree-crop root competition. There is evidence, however, of large species differences in rooting patterns, suggesting the utility of selecting species with naturally deep rooting systems. Van Noordwijk et al. (1994) proposed a method for characterising tree root systems based on fractal analysis that simplifies the effort of determining total root length, root diameter' distribution, and root length per unit dry weight. A proportionality factor, or 'index of root competitiveness' can be calculated based on the sums of root diameter squares for roots with a horizontal versus vertical orientation, and used to compare trees growing on the same soil (Van Noordwijk and Garrity 1995).

The research and extension work on alley cropping during the past 20 years was based on the premise that the pruned hedgerows would enable continuous cropping without additional fertilizer. They were conceived as 'simultaneous fallows', constantly producing nutrient supplies for annual crops. In most cases, however, this has proved unrealistic. Yields usually cannot be maintained without supplemental chemical fertilizers (National Research Council 1993). Many farmers practicing hedgerow intercropping eventually discontinue cropping, a realistic reaction to the inability of the hedgerow fields to sustain yields.

Fallowed tree hedgerow systems can rapidly accumulate nutrients in the woody biomass, compared with the performance of the conventional grass fallow succession obtained in many areas. This has stimulated interest in the concept of fallow-rotation hedgerow systems as a variant intermediate between a simultaneous and a sequential agroforestry system. Although little experimental evidence has yet been generated, it is an alternative that deserves serious investigation, as it may fit the practical realities of low-cash flow farmers better than continuously cropped (and fertilised) hedgerow systems.

Trees as N-fixers and Providers

The contribution of biologically fixed nitrogen by the tree component is substantial in many agroforestry systems. Since N is often strongly limiting, the capacity of trees to supplement the supply of N is a highly valued characteristic. Not many measurements exist of the amounts of fixed N actually contributed. Ladha et al. (1993) found 30–60% of the N in the hedgerow prunings of *Gliricidia sepium* was biologically fixed N. The percentage of atmospherically derived N varied seasonally and tended to be higher in the wet season.

Recently, attention has been drawn to the fact that crop performance in association with N-fixing species often is not superior to that with non-fixing species (Garrity and Mercado 1995). In the Philippines, *Senna (Cassia) spectabilis* (non-nodulating legume) supplied 20–30% more N to associated annual crops over a four-year period than *Gliricidia sepium*, with similar yields. *S. specrabilis* also exhibited major advantages over *Leucaena leucocephala* in Machakos, Kenya, due primarily to reduced competition for water (Ong, C. K, pers comm. 1994). Van Noordwijk et al. (1995) reported that the non-fixing *Peltophorum dasyrachis* Kurz.(pterocarpa) outperformed three other leguminous species in stimulating maize performance in Indonesia, with a similar N content in its prunings (Fig. 1). They concluded that reduced canopy shading per unit biomass produced (due to a more compact branching pattern), and the strikingly deep root system of *Pelthophorum* were major contributing characteristics. The causes for the superiority of the non-fixing trees clearly varied among these studies. This emphasizes that N-fixation is only one of a number of critical characters affecting the optimum fit of a tree species in an agroforestry system, and should perhaps not be over-overemphased in place of a more holistic comparison among prospective species.

The synchrony of plant demand with nutrient release from tree litter and prunings is a major issue in current research. The range of pruning-derived N that is utilised by annual crops is usually quite low, varying from 5–30% (Kang et al. 1990). Pruning N from some sources may be mineralised rapidly, and leached or volatilised before crop roots gain access to it during crop establishment. Or it may be mineralised slowly and remain unavailable during the peak demand phase of crop growth. The lignin:N ratio has been considered an important predictor of mineralisation rates, but the content of polyphenolics may also explain part of the variation in N mineralization rates. Handayanto et al. (1994) has shown that the importance of polyphenolic content decreases with higher leaching rates.

In an analysis of alley cropping trials at several locations in Africa, Akyeampong et al. (1992) found a low correlation between relative maize yields and the amount of N applied as prunings. In Maseno, Kenya, for example, leafy biomass production by Calliandra (50 t/ha in 40 months) exceeded that from Leucaena (33 t/ha) and Gliricidia (21.6 t/ha) but resulted in the same accumulated maize yield over six seasons. This corroborates the growing body of evidence indicating that maximum hedgerow leafy biomass, once considered a prime factor in sustainably productive alley cropping, may not be as important as characters that reduce competition between trees and crops. Competitiveness is often best achieved with trees having low biomass production to decrease pressure on below-ground resource pools.

The critical balance between F (pruning effects) and C (tree-crop competition for nutrients, water and light) is highlighted by the relative values calculated from alley cropping studies at six sites in Africa varying in tree species, management, soils and climate (Fig. 2). F ranged from 12 to 60%. Increasing F was closely associated with higher levels of C. These tradeoffs make it particularly difficult to predict the response to organic inputs in agroforestry systems as opposed to those of inorganic inputs such as fertilizers and lime.

Soil Organic Matter Enhancement

In their review of tree crops as soil improvers in the humid tropics, Sanchez et al. (1985) examined trends in soil properties when tree crops and fast-growing tree plantations are established. Lundgren's (1978) model hypothesises that soil organic matter levels will decline substantially after forest clearing and plantation development, recover partially during maximum growth, and then decline again upon felling, and establishment of the second rotation.

Available data sets from Southeast Asia, Africa and Latin America indicated, however, that during the years after forest clearing and establishment of rubber, oil palm, and *Gmelina arborea* or *Pinus caribaea* plantations, soil organic matter and nutrient levels did not tend to decrease significantly, and in some cases

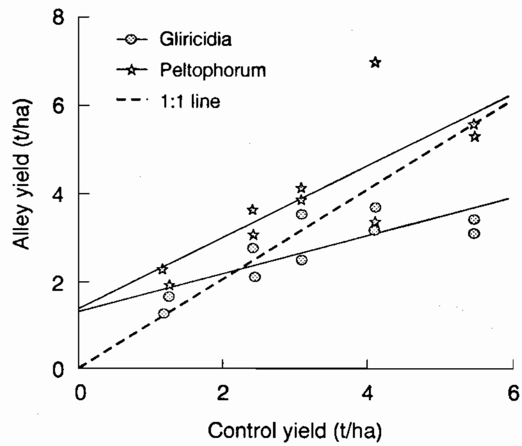

Figure 1 Contrasting tree phenotypes in agroforestry systems: (A) deep roots that complement the crop rooting zone, or (B) shallow, spreading roots that compete for growth resources.

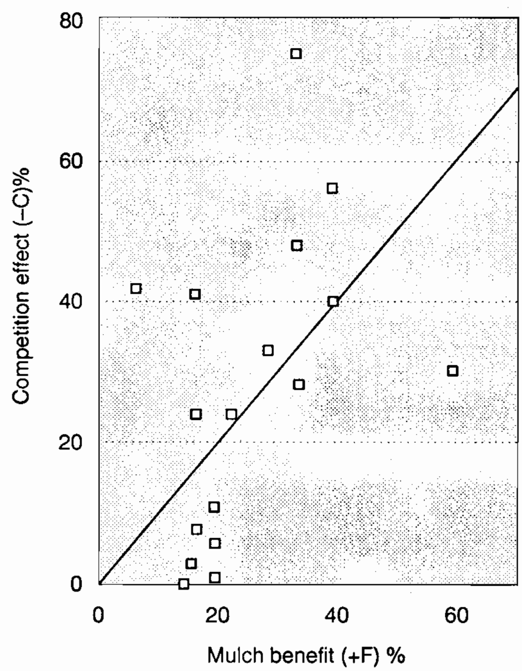

Figure 2 Maize performance in association with hedgerows of the non-N fixing species *Peltophorum dasyrachis Kurz.(pterocarpa)* consistently exceeded that with the N-fixing species *Gliricidium sepium* on an acidic soil in Lampung, Indonesia (adapted from Van Noordwijk et al, 1995).

increased (Sanchez et al. 1985). Toward the end of the productive period, however, there was a declining trend in soil organic carbon in some of the perennial crops.

The relatively small and gradual changes in soil organic carbon in tree crops contrast with the rapid and dramatic reduction in soil organic carbon usually observed when cleared forests are cultivated with annual crops. Do agroforestry systems tend to moderate or reverse the adverse effects of annual cropping systems on soil organic matter? The answer depends on the particular components, environmental conditions, and the management regime.

Tropical home gardens and complex agroforests often resemble natural secondary forest systems in structure and ecology. In Torquebiau's (1992) review of the sustainability indicators of tropical home gardens, he found many indirect sources of evidence that soil fertility levels were maintained over long periods, and hypothesised that organic matter levels generally increase. Unfortunately, datasets are not available to test this contention.

In sequential agroforestry systems, such as shifting cultivation, the land is fallowed after a period of annual cropping. There are numerous beneficial effects attributed to such fallows, whether they are natural or improved fallows. Rebuilding soil organic matter levels is a frequently cited effect.

The case for increased soil organic carbon contents is not so clear-cut with simultaneous agroforestry systems. In parkland systems, where trees are maintained at a low density in the fields (Belsky et al. 1993), or when native forest trees are retained on paddy bunds, as in Northeast Thailand (Vityakon 1993), there is clear evidence that the presence of the trees has a positive influence on soil organic matter levels, at least in the vicinity of the trees.

In hedgerow intercropping systems, several studies have reported increases in soil organic matter (e.g. Yamoah et al.1986) as a consequence of continuous pruning application in such systems. The degree of positive benefits varies with the tree species (in this case the ranking of positive effects was *Cassia (Senna) spectabilis* > *Gliricidia sepium* > *Flamengia congesta*. The decomposition literature has elucidated quite dramatic differences among species in the rate at which litter decomposition and nutrient release occurs (Palm and Sanchez 1990; Miah 1993)

Expectations of an increase in soil organic matter content are dependent on the amount, source, and management of the pruning biomass. Kang et al. (1990) reported a nonsignificant increase in soil organic matter in a Leucaena hedgerow system that produced large amounts of prunings, but had a very rapid litter decomposition rate. Considering the modest hedgerow biomass yields often obtained with practical alley widths and environmental constraints, it is more likely that the presence of hedgerows will decrease the rate of carbon depletion, rather than actually increase organic matter levels.

Many studies have reported that more favorable carbon levels were maintained with hedgerows than in open field systems (Kang et al. 1984; Atta-Krah et al. 1986; Lal. 1989; Evenson 1989). But exceptions are observed: On a strongly acid (pH 4.2) steeply sloping ultisol, Samsuzzaman (1993) found that in the absence of external fertilizer inputs, soil organic matter declined more rapidly in hedgerow treatments than with open field cropping.

Since the soil organic matter benefits of agroforestry accrue gradually, system viability will be strongly dependent on a favorable *F/C* balance in the short run. In analysing and recommending the use of on-farm organic matter sources, the analysis of yield and income per unit of labour expended is often a key, but very neglected, aspect.

Spatial Fertility Redistribution in Developing Terraces

The dramatic reduction in soil loss from sloping fields upon installation of contour hedgerow systems has now been well-documented for a wide range of slopes, soils, and systems (Sajjapongse 1992; Garrity 1995). Contour hedgerows typically reduce soil losses by 50 to 95%. Consequently, they have been promoted as a major option in conservation farming systems in many tropical countries.

Rapid terrace development occurs behind vegetative barriers, particularly when tillage is practiced frequently in the alleyways. Although soil movement off-field is minimised, redistribution downslope within the alleyway is promoted. This removes or 'scours' the topsoil in the upper alley, with sediment accumulation in the lower alley and in the hedgerow. This results in quite striking gradients in soil fertility across the alleys (Garrity et al. 1994; Samsuzzaman 1993; Agus 1993). Organic C and N levels, available P, and exchangeable Ca and K are reduced upslope and enriched downslope in a linear pattern, resulting in dramatically lower crop biomass in the upper alley. Thus, 'scouring' presents a serious challenge to the sustainability of yields in these systems.

There are three ways to cope with this fertility redistribution problem: apply the crop residues, hedgerow prunings, and inorganic fertilizers differentially by zone to alleviate the upper alley depletion; reduce the frequency of tillage to decrease the rate of scouring; or switch to perennials better adapted to scavenging nutrients in the degraded upper alley zone. Unfortunately, there has been almost no research on this problem, although it looms as one of the key nutrient-related issues in the sustainability of contour hedgerow systems.

Smallholder System Pathways

The limitations of pruned tree hedgerows have prompted interest in a wide range of other alternative hedgerow components that perform the same soil conservation functions with less labour and greater economic benefits. The options include fodder grass strips and cash perennials such as coffee, fruit trees, and many others. Although these alternatives are often very effective in erosion control, they do not solve the problem of maintaining soil nutrient balances. Fertilisation with manure, fertilizers, and/or additional plant residues is still required.

Figure 3 illustrates the major pathways available to smallholders to meet their production and income sustainability objectives, particularly on sloping lands. The dichotomy of system choice depends fundamentally on whether an external nutrient supply is available to the farmer.

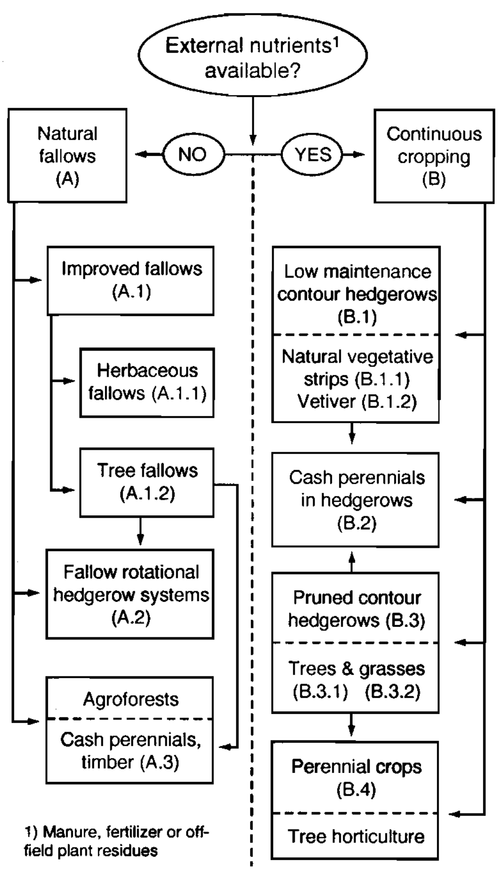

Figure 3 The balance between F (positive fertility effects.

Farmers without access to nutrient inputs must depend on some form of fallowing. To increase productivity they need better ways of accelerating the accumulation of nutrients in the fallow vegetation. The viable options are improved fallows (A1 in Figure 3), fallow-rotation hedgerow systems (A2), and agroforests containing cash-generating perennials (A3).

Farmers begin using external nutrient inputs as markets develop for commodities with a substantial return to fertilizer investment–vegetables, horticultural crops, or cash perennial crops. Credit mechanisms appear as these enterprises develop.

When continuous cropping becomes feasible (B) further evolution is needed to protect investments in soil fertility through some form of conservation farming. Options range from natural vegetative strips (B1), that may be enhanced by value-added perennials (B2), to pruned leguminous tree hedgerows. Further transformation may lead to commercial perennial crops or tree horticulture (B4).

There is a correspondence between the options appearing opposite each other on the left and right pathways in Figure 3. This reflects the potential for a parallel transfer from left-to-right, or right-to-left, depending on changing nutrient availability. Different parcels on the same farm may be managed simultaneously in separate categories on both sides of the diagram.

Conclusion

Although trees possess the potential for deep rooting and nutrient pumping, they also tend to form extensive lateral roots in the topsoil which, although capturing and recycling leached nutrients, also compete with associated crops for nutrients. This competition may often outweigh the benefits due to deep rooting, except perhaps on the more fertile and deep soils. The prospects for exploiting these rooting mechanisms are least in humid, infertile tropical soils.

Because of the strong tradeoff between the fertility enhancement (*F*) functions of trees and competition with crops (*C*) in simultaneous agroforestry systems, the use of pruned tree hedgerows may often be more suitable in a fallow-rotation mode than in continuous cropping situations. More attention should be given to this and other practices intermediate between simultaneous and sequential systems. The inherent opportunities of agroforests or mixed perennial systems as a basis for sustainable low-input farming should also be given much more attention.

There are many agroforestry systems developed by farmers and employed on millions of hectares in the tropics. Unfortunately, little effort has been expended in understanding them as the basis of building improved systems. The fate of nutrients and soil organic matter is poorly quantified in these systems. This presents a major current challenge for agroforestry research and development.

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Organic Matter for Lowland Rice and Upland Wheat Rotation Systems in India

Bijay-Singh*

Abstract

Long-term field experiments have indicated a declining trend in the organic matter content of the soils under rice–wheat rotation in India. This is a matter of concern because the rice–wheat system is not showing sustained productivity in spite of increases in inputs. Application of farmyard manure and green manure along with chemical fertilizers has been shown to increase or maintain soil organic matter levels and achieve yield sustainability in most of the studies carried out so far. However, at some locations, soils could not sustain high productivity because of a drain on soil fertility caused by large removal of nutrients by rice and wheat. Removal of rice and wheat straw from the fields is one major reason for soil organic matter depletion. Even after the introduction of mechanised harvesting, farmers prefer to burn the crop residues left in the fields. Although incorporation of residues into the soil can lead to a build-up of soil organic matter and an improvement in the soil physical environment, sustainable yields of rice and wheat have not been obtained to date. However, when the quality of soil organic matter was improved by incorporating crop residues along with narrow C:N ratio green manures, a significant build-up of soil organic matter was observed, along with sustainable high yields of sequentially grown rice and wheat.

THE rice–wheat system in which a crop of lowland rice is followed by a crop of wheat extends to more than 10 million ha in India (Huke and Huke 1992). During 1960 to 1990, genetic improvements in rice and wheat and improved management strategies resulted in a rapid increase in area under this system. After a dramatic rise in productivity and production during the 1980s, the system is showing signs of fatigue and is no longer exhibiting increased production with increases in input use. In this context, soil organic matter depletion in the rice–wheat system is a matter of great concern although several complex interactions between management of rice and wheat are involved.

In cultivated soils, the particular cropping system and associated cultural practices influence the level at which organic matter will stabilise. When manures and fertilizers are applied to the soil to maintain efficient plant cover, a decline in organic matter is arrested and this in turn leads to sustainable crop yields. Long-term experiments conducted in India have shown that integrated use of organic manures, including green manure and chemical fertilizers, can maintain high productivity and provide sustained stability in crop production. This paper addresses the issue of organic matter management in the rice–wheat system in terms of achieving sustainable production from this system in India.

Organic matter status of the soil

In 1971, long-term field experiments on rice–wheat rotation were initiated at Barrackpore in West Bengal and Pantnagar in Uttar Pradesh. After 16 years of sequentially growing rice and wheat with the recommended application of NPK fertilizers the organic carbon content of the soil was reduced by 30 and 38% of the values at the start of the experiment at Barrackpore and Pantnagar respectively (Table 1).In contrast, in all other systems, organic carbon increased with the balanced use of NPK fertilizers. Data from two maize–wheat systems and a rice–rice system are shown in Table 1. The initial soil organic carbon level was maintained at Pantnagar by combined application of NPK fertilizers and farmyard manure (FYM) but at Barrackpore more than 13% of organic matter

* Department of Soils, Punjab Agricultural University, Ludhana 141 004, India.

was lost. It seems that frequent tillage and alternating wetland (rice) and upland (wheat)conditions lead to rapid decomposition of soil organic matter in the rice–wheat system. Verma et al. (1987) have reported a 16.7% loss of initially present organic carbon in control plots after seven cycles of rice–wheat rotation at Masodha. Depletion of organic carbon was only 2% when 120 kg N + 26 kg P + 33 kg K/ha was applied to both rice and wheat crops.

Gaur et al. (1984) found that the application of FYM or compost was the best strategy for maintaining soil organic matter in Indian soils. Cereal residues were second best. At the end of five cycles of rice–wheat rotation in a Typic Ustipsamment at Ludhiana in, Punjab, Maskina et al. (1988) recorded a marked increase in the organic carbon content of the soil in the FYM amended plots (3.3 g/kg) compared with levels in unamended (2.4 g/kg) plots or at the initiation of the experiment (2.2 g/kg). Due to their succulent nature, narrow C:N ratio and low lignin content, green manures decompose rapidly when incorporated into soil (Yadvinder-Singh et al. 1992) and only a small quantity of carbon is converted into stable soil humus. Boparai et al. (1992) observed that while the organic carbon content of the unamended soil under rice–wheat rotation decreased from 1.9 g/kg to 1.5–1.6 g/kg after three years, green manuring helped to maintain it at the initial level. Bhardwaj et al. (1981), Sharma and Mittra (1988) and Meelu et al. (1991) observed an increase in the soil organic carbon content ranging from 0.4 to 1.0 g/kg due to green manuring of rice in rice–wheat system.

Organic amendments and yield sustainability

In a large number of experiments the effect of applying FYM on the yield of rice, wheat or both was studied when each crop was grown with 100 kg N/ha (Table 2). Except during 1970–71 and 1975–76 at Varanasi and Masodha, there was significant response of both wheat and rice to FYM. In general, yield increases were greater when FYM was applied to both the crops rather than to rice or wheat suggesting a positive role of FYM in achieving yield sustainability in a rice–wheat system in India. In a sub-temperate humid climate at Palampur, Sharma et al. (1987) observed that after four cropping seasons soil organic carbon content was 8.7, 11.7, 12.9 and 16.0 g/kg depending upon whether FYM was not applied, applied to rice, to wheat or to both the crops, respectively. The yield response to FYM application followed the pattern of organic carbon in the soil. It is surmised that FYM plays a role additional to its capacity to contribute NPK. It is well known for improvement in the soil physical environment.

The long-term fertilizer experiments conducted in India during 1885–1985 have shown that neither organic manures nor NPK fertilizers alone can achieve yield sustainability at a high level under modern intensive farming (Nambiar and Abrol 1989).

Table 1. Changes in organic carbon content (g/kg) of soils under different cropping systems as influenced by fertilizer and farmyard manure (FYM) treatments during 1971–1987.

Treatment	Cropping system				
	Rice–wheat–jute	Maize–wheat-cowpea (fodder)	Rice–rice	Rice–wheat–cowpea (fodder)	Maize–wheat
50% NPK[a]	5.0	2.6	5.1	9.7	8.7
100% NPK	4.4	2.6	5.6	10.3	9.4
150% NPK	5.0	2.6	5.0	14.6	9.2
100% NPK + FYM	6.2	4.0	7.0	15.6	13.1
Control	4.2	2.5	4.7	7.0	7.0
Initial status	7.1	2.1	2.7	14.8	7.9
Soil group/ association	Recent alluvium	Alluvial	Lateritic	Foothill	Sub-montane
Texture	Sandy loam	Loamy sand	Sandy loam	Silty clay loam	Silt loam
Location	Barrackpore	Ludhiana	Bhubane shwar	Pantnagar	Palampur

Source: Nambiar et al. (1989)
[a] % refers to % of recommended application rate

The yield data from long-term experiments initiated in 1971 (Table 3) demonstrate the superiority of integrated use of organic manures and chemical fertilizers in providing greater stability in crop production in the rice–wheat system at Pantnagar and in rice–rice or maize–wheat systems at different locations, when compared with chemical fertilizers alone (150% NPK) supplying more NPK than the former. At Barrackpore, however, the 150% NPK treatment yielded more rice and wheat than 100% NPK + FYM, in spite of the fact that FYM checked the loss of soil organic matter. It seems that declining soil organic matter is not the only cause of decreasing yield sustainability; rather large nutrient removals can result in drain on the soil fertility and the soil may not be able to sustain high productivity in the future. In a crop grown after five years of a rice–wheat rotation at Ludhiana, Maskina et al. (1988) found that yields were similar when FYM + N (80 kg/ha) and N (120 kg/ha) alone was applied, although a significant build up of organic carbon content from 2.2 g/kg to 3.3 g/kg was observed in the FYM + N (80 kg/ha) treatment.

Crop residue management in a rice–wheat system

Traditionally, wheat and rice straw have been removed from the fields in India; wheat straw is used for feeding animals whereas rice straw is removed because it adversely affects the yield of the following

Table 2. Direct, residual and cumulative responses (t/ha) (averaged over years) to farmyard manure at 15 t/ha in a rice–wheat rotation in Uttar Pradesh, Madhya Pradesh and West Bengal, India during 1969 to 1976–77

Location		Farmyard manure applied to					
		Rice and wheat		Rice		Wheat	
		Control	Response	Control	Response	Control	Response
		Uttar Pradesh					
Varanasi	Rice	4.89	0.45	4.76	0.41	5.01	0.42
	Wheat	3.63	0.34	3.33	0.36	3.66	0.42
Bichpuri	Rice	2.70	0.27	2.58	0.24	2.70	0.15
	Wheat	3.82	0.63	3.82	0.41	3.90	0.46
Masocha	Rice	3.17	0.42	3.26	0.40	3.29	0.45
	Wheat	2.92	0.70	2.49	0.37	2.81	0.64
Pura farm	Rice	3.65	0.28	3.48	0.23	3.80	0.44
	Wheat	4.74	0.22	4.39	0.21	4.72	0.37
		Madhya Pradesh					
Kathulia	Rice	6.19	0.25	6.17	0.31	5.80	0.19
	Wheat	2.82	0.57	2.59	0.16	2.67	0.25
Raipur	Rice	2.09	0.64	1.98	0.59	1.54	0.74
	Wheat	1.79	0.54	1.23	0.52	1.77	0.55
Jabalpur	Rice	3.02	0.95	2.98	0.83	2.80	0.69
	Wheat	1.94	1.02	1.72	0.88	1.95	0.77
		West Bengal					
Kharagpur	Rice	3.75	0.64	3.71	0.52	3.07	0.27
	Wheat	2.26	0.18	1.75	0.20	2.10	0.23

Source: Gaur et al. (1984)

wheat crop. This is possibly one of the important causes for organic matter depletion in a rice–wheat system. Recently, due to the advent of mechanised harvesting, large quantities of crop residues left in the field are burnt and this practice has important implications on the organic matter content of the soil. Data listed in Table 4 reveals that there is a significant build up of soil organic matter due to incorporation of rice and wheat straw into the soil as compared to when removed or burnt. However there was a trend to lower yields of rice and wheat when residues were incorporated. In residue incorporated treatments, yields were low due to immobilisation of soil and fertilizer N by decomposing crop residues with a wide C:N ratio (Yadvinder-Singh et al. 1988). Nevertheless, in these studies there was a significant improvement in the soil physical environment due to build-up of organic matter by crop residue incorporation.

Table 3. Effect of chemical fertilizers applied alone or together with farmyard manure (FYM) on yield of crops in a rice–wheat system compared with other systems in long-term experiments.

Soil group/location	Crop	Mean grain yield during 1984–87 (t/ha)			Mean grain yield during 1971–87 (t/ha)		
		100% NPK[a]	150% NPK	100% NPK + FYM	100% NPK	150% NPK	100% NPK + FYM
Recent alluvium, Barrackpore	Rice	3.5	4.8	4.4	4.2	4.4	4.3
	Wheat	2.5	3.1	2.8	2.4	3.0	2.5
Alluvial, Ludhiana	Maize	2.2	2.2	3.3	2.5	2.6	3.2
	Wheat	5.2	5.3	5.3	4.7	4.7	4.8
Foothill, Pantnagar	Rice	5.8	6.3	6.8	6.2	6.5	7.0
	Wheat	4.0	4.4	5.3	3.9	4.6	4.7
Submontane, Palampur	Maize	2.4	3.3	4.3	3.2	4.1	4.7
	Wheat	2.8	3.3	4.0	2.6	3.1	3.3

Source: Nambiar et al. (1989)
[a] % refers to % of recommended application rate

Table 4. Effect of crop residue management on soil organic matter content and grain yield of the crops in a rice–wheat rotation in India.

Reference	Duration of study (years)	Residue management	Organic carbon g/kg	Mean grain yield of crop (t/ha)	
				Rice	Wheat
Sidhu and Beri pers comm.	10	Removal	3.8	5.33	4.02
		Burnt	4.3	5.57	4.12
		Incorporated	4.7	4.51	3.72
Sharma et al. (1987)	6	Removal	11.5	2.94[a]	2.65
		Incorporated	13.1	2.96[a]	2.73
Dhillon and Dev (1984)	2	Removal	5.5	6.63	3.26
		Burnt	5.2	6.69	3.06
		Incorporated	5.7	6.21	3.10

[a] Direct seeded upland irrigated rice

Table 5. Effect of crop residue management and green manuring on soil organic matter content and yields of crops in rice–wheat rotation.

Treatment	Grain yield of rice (t/ha)						Grain yield of wheat (t/ha) 1988–89 to 1993–94	Organic carbon after rice 1993 (g/kg)
	1988	1989	1990	1991	1992	1993		
No-N control	4.0	4.6	3.7	4.3	4.1	3.4	4.2	3.5
120 kg N/ha	6.1	6.3	6.2	5.9	5.0	5.3	4.2	3.7
150 kg N/ha	6.3	6.6	6.2	6.5	5.7	5.6	4.2	3.8
Green manure (GM)	6.6	6.5	6.2	6.3	5.8	5.5	4.3	4.1
GM + wheat straw	6.9	6.9	6.4	6.8	5.6	5.5	4.4	4.7
GM + rice straw	6.9	6.9	6.7	7.0	5.9	5.3	4.4	5.0
Wheat straw + 150 kg N/ha	–	6.8	5.8	6.1	5.2	4.8	4.2	4.9
LSD (P=0.05)	0.53	0.59	0.46	0.45	0.32	0.37	–	0.7

Urea was applied to all the GM treatments to make N addition through GM + urea = 150 kg N/ha
Source: O.P. Meelu, Bijay-Singh and Yadvinder-Singh, Department of Soils, Punjab Agricultural University, Ludhiana

In a long-term experiment in progress at Ludhiana (Punjab), it has been shown that the adverse effects of wheat or rice straw residues can be effectively counteracted by combined incorporation of green manure (narrow C:N ratio) and crop residues (wide C:N ratio) into the soil before transplanting of rice (Table 5). The superiority of this practice over applying crop residues or green manure alone is that besides high yields, there is a significant build up of organic matter in the soil which helps to attain sustainable crop production in the rice–wheat system. Green manuring of rice is well known for its role in supplying N (Yadvinder-Singh et al. 1991).

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Studies on Inorganic Nutrients and Organic Residues for Rice-Based Cropping Systems in Bangladesh

N.I. Bhuiyan, P.K. Saha, M. Ishaque and J. Abedin*

Abstract

Agriculture in Bangladesh is essentially rice based. Among many, rice–rice and rice–wheat systems are the two most important ones. High yield goal with higher cropping intensity is the urgent need of the nation today to produce more food from the limited land resources in order to feed the country's ever growing population. More crop production demands more nutrients from the soil. In order to develop appropriate nutrient management practices for improving crop productivity and sustaining soil fertility, a few medium- to long-term field trials have been initiated at the Bangladesh Rice Research Institute (BRRI) and one in a farmer's field under an irrigated environment. Inorganic nutrients of different kinds and organic residues, including green manure, were evaluated in these trials. Results of three such trials with rice–rice system and one with wheat–rice system are discussed in the light of crop productivity, nutrient removal and soil fertility.

BANGLADESH is largely a deltaic plain formed around the Ganges, Brahmaputra and Meghna rivers and lies in the north-eastern part of the South Asian Sub-continent between 20°34′ and 26°38′ north latitude and between 88°01′ and 92°41′ east longitude.

The climate of Bangladesh is favourable for the cultivation of a wide variety of both tropical and temperate crops. Agriculture is the mainstay of the economy, as it contributes about 46% of the gross domestic product and provides employment for about 61% of the labour force (BBS 1990). Although nearly 100 different kinds of crops are presently grown in Bangladesh, rice is the principal one which grows in all the three crop growing seasons of the year and covers about 80% of the net cultivable area of about 9 million ha. Other important crops are wheat, oilseeds, pulses, potato, jute, cotton, sugarcane and vegetables.

Plant nutrients in soil, whether naturally endowed or artificially maintained, are the major determinant of the success or failure of a crop production system. The urgent need of the cropping sector of Bangladesh is to produce more food to feed the country's ever growing population. Targeting high yield with a higher cropping intensity is the most logical way to raise the total production from the country's limited land resources. To achieve this goal, nutrient inputs to and output from the existing farm land must increase accordingly because a two-fold yield increase will remove twice as much nutrient from the soil at harvest. Inorganic, organic and bio-fertilizers are the main sources for replenishing plant nutrients in agricultural soils.

Inorganic fertilizers today hold the key to the success of the crop production systems of Bangladesh agriculture, contributing about 40–50% of the total yield. Although there has been an increasing trend in the consumption of chemical fertilizers, their application appears to be unbalanced since nitrogen alone constitutes about 73% of the total nutrients used in the country, while S use is very low, although about 4 million ha of land are potentially S deficient (BARC 1988).

The positive role of organic residues, including green manures on soils and crops have been well documented (Shaw and Robinson 1960; Russell 1966; Patnaik and Rao 1979). Available reports indicate that most soils of Bangladesh have a low organic matter content (Hoq 1980). About 70% of the net cultivable area in high and medium–high lands has a soil organic matter content less than 2% (Bhuiyan 1991).

* Soil Chemistry Division, Bangladesh Rice Research Institute, Joydebpur, Gazipur 1701, Bangladesh.

This low organic matter content has been considered as one of the main reasons for low productivity of many of our soils. The need for proper soil organic matter management cannot be over-emphasised in view of the low organic matter content of most soils of Bangladesh.

A judicious integration of inorganic fertilizers with organic residues, including green manure, may be a possible option for higher sustainable crop production in Bangladesh. This paper reports the results of some studies on the integrated use of organic residues and inorganic fertilizers for rice-based cropping systems in Bangladesh agriculture.

Nutrient Management for Cropping Systems

A large number of cropping systems are practised in Bangladesh depending on the agroecological conditions and availability of irrigation facilities. These cropping systems are essentially rice-based. Some cropping systems are more intensive and exploitative than others and thereby deplete the soil fertility at a faster rate. Although land type, soil properties, irrigation and rainfall broadly comprises the basic resource base of a cropping system, the ultimate productivity of the system is determined by soil and management factors that directly affect the growth of the crops in a cropping system. Long-term soil fertility monitoring under a specific cropping system will be of great help in determining a better soil fertility management program for sustained productivity at higher level.

Integrated use of organic and inorganic N fertilizer

To develop an integrated organic–inorganic N fertilizer management technique for rice production in a Boro (Dry season)–Fallow–T. Aman (Wet season) cropping system, a long-term experiment was initiated in T. Aman, 1983 at Bangladesh Rice Research Institute farm (silty clay soil). Urea-N at varying rates alone and in combination with rice straw (RS), cowdung (CD) or dhaincha (DH) at the rate of 5 t/ha (dry weight) were used as the treatments. Urea-N was applied to each crop, but organic residues were applied once a year prior to T. Aman planting. The experiment was laid out in a randomised complete block design with three replications. Average grain yield data over the last ten years are presented in Figure 1 which shows that while the application of urea-N alone at the rate of 210 kg/ha/year (120 kg for Boro and 90 kg for T. Aman) gave a yearly grain yield of about 8.8 t/ha on the average, about 9.3 t/ha/year was obtained with a lower dose of N (N_{140}) when organic residues, particularly dhaincha or cow dung was applied. This implies that by integrating organic residues with the fertilisation program, a substantial yearly cost saving on chemical N fertilizer could be made. For example, in the present experiment, what has been achieved with 210 kg N/ha/year without organic residues, was also

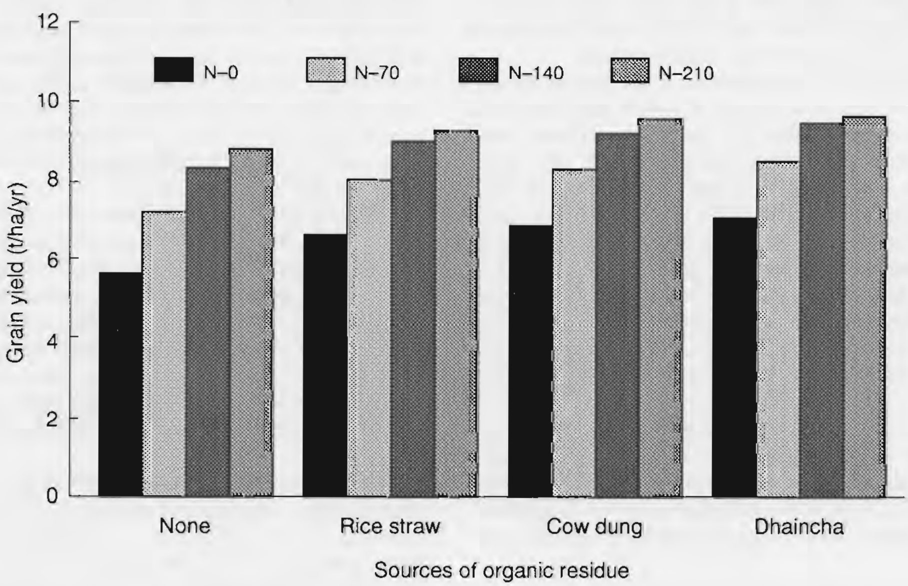

Figure 1. Annual grain yield of MV rices (average of 10 years) as affected by inorganic N fertilizer and organic residues in a Boro–Fallow–T.Aman cropping pattern, BRRI, Joydebpur (1983–93).

obtained with 140 kg N/ha/year with organic residues, which meant a cost saving of 70 kg N/ha/year. Meelu et. al. (1992) also reported an economy of 60 kg N/ha with green manuring to rice.

Integrated use of inorganic N and rice straw N

A four-year duration field experiment was conducted in a permanent layout at BRRI farm (silty clay soil) during the period from T. Aman 1984 to Boro, 1988 to evaluate the relative efficiencies of prilled urea (PU), urea supergranule (USG) and rice straw (RS) as sources of N for wetland rice. Two rice crops, Boro and T. Aman, with a fallow in between have been grown per year for this trial. A total of eight crops were grown until Boro, 1988 within a period of four years. Rice straw (5 t/ha) containing 0.58% N was chopped into 10–12 cm pieces and incorporated into the appropriate plots two weeks before transplanting. Prilled urea was applied in three equal splits: one third basal, one third at active tillering stage and the rest at 5–7 days before panicle initiation stage, USG was applied at 10–12 cm soil depth immediately after seedling establishment. All plots received blanket doses of P, K and S at the rate of 25, 35 and 20 kg/ha, respectively during final land preparation. The experiment was laid out in a randomised complete block design with four replications.

An average of four years' data indicates that USG alone produced considerably higher grain yield (about 0.8 t/ha) than PU in the Boro season but not in the T. Aman season (Fig. 2). The seasonal difference in solar radiation and temperature are the most probable reasons for such differential responses. Grain yield did not improve when a part of inorganic N was substituted by rice straw N during the Boro season. This indicates that rice straw is not an effective partial substitute to inorganic N fertilizer for rice in the Boro season when low temperature retards the mineralisation of organic N and helps in accumulation of organic products. In T. Aman, inorganic N (PU/USG) plus RS-N gave similar yields to those obtained with the corresponding all PU or all-USG treatments indicating that partial substitution of inorganic N by RS-N may be possible in T. Aman. This was obviously due to the higher rate of mineralisation of the RS-N in T. Aman because of higher temperature than in Boro (Fig. 2).

After the harvest of the 8th crop, surface soil samples (0–15 cm) were collected and were analysed for their physical and chemical properties following standard analytical procedures. Results show that the application of rice straw increased the organic carbon content of the soil considerably over the control and the treatments that received only inorganic N fertilizers (Table 1). An average of 0.30% increase in organic carbon and 0.01% increase in total N was recorded following rice straw addition. This 0.3% is equivalent to 6.0 t/ha of organic carbon which obviously was accumulated as a residue from a total of 40.0 t/ha rice straw applied during the 4

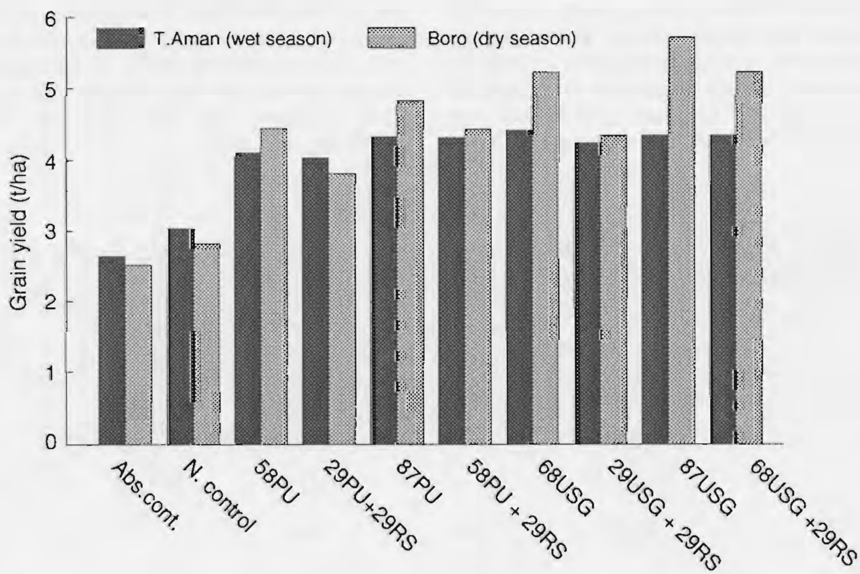

Figure 2. Grain yield of wetland rice (average of 4 years) as affected by inorganic N (PU, USG) and rice straw N in a Boro–Fallow–T.Aman cropping pattern, BRRI, Joydebpur (1984–88).

years. However, such a small increase in organic carbon perhaps was not sufficient to bring about favourable changes in soil physical properties, like bulk density (Table 1).

The prolonged use of inorganic N, P and K fertilizers did not change the total N and exchangeable K contents of the soil, but considerably increased the available P content of the soil. Similar P build up in soil was reported by Kolar and Grewal (1989) when phosphorus was applied to each crop in rice–wheat rotation. The use of rice straw resulted in a significant increase in the soil K content, possibly due to the slow release of K from the decomposition of rice straw which had a large reserve of K. Such an increase in soil K content due to the application of farmyard manure was also reported by Prasad et al. (1982).

Rice straw, although having some beneficial effects on crop productivity and soil properties in the long term, cannot be used in the field because it is the main feed for the cattle and also is used as a roofing material for the houses of the millions of farm population.

Integrated use of inorganic fertilizers, cowdung and ash

To develop a suitable combination of inorganic fertilizers and organic residues for sustaining soil fertility and rice yield under irrigated environments, another long-term study was initiated in 1990 at BRRI farm (silty clay soil) with a Boro–Fallow–T. Aman cropping system. Inorganic nutrients (NPKS) at different levels, cowdung and ash were chosen as the treatments. The descriptions of six treatment combinations used in this study are given in Table 2. Inorganic nutrients as per treatments were used in both the crops of the cropping system, but the organic residues were used once in a year prior to Boro planting. Mean yield data (average of 4 years) presented in Table 3 show that both grain and straw yields were increased progressively with the increasing levels of inorganic nutrients.

The highest grain and straw yields were recorded when cowdung and ash were applied along with the medium level (T_6) of inorganic nutrients (Table 3). Iswaran et. al. (1964) reported that highest yields were obtained when inorganic fertilizers were applied in combination with organic residues. Similarly, cowdung and ash, when applied with a low level (T_5) of inorganic nutrients produced grain and straw yields almost equal to that of the yield produced with the medium level (T_3) of inorganic nutrients (Table 3). Total nutrient uptake (kg/ha/year) was also positively affected by cowdung and ash in combination with low to medium levels of inorganic nutrients (Table 3).

Data on some soil chemical properties presented in Table 4 show that the organic matter content increased considerably in those treatments which received cowdung and ash, but the total N contents remained unchanged irrespective of the treatments. Results in Table 4 further show that available P content decreased in treatments with zero (T_1) and low level of added inorganic nutrients (T_2) whereas it was increased substantially in those treatments which received cowdung and ash along with inorganic nutrients. Similarly exchangeable K, available S and Zn contents of soil decreased slightly in T_1 and T_2 but remained almost unchanged in the other treatments. Considering the yield, nutrient uptake and soil nutrient status, it is apparent that an integration of organic residues, such as cow dung and ash with low to medium levels of inorganic nutrients may be used as an alternative to high level of inorganic nutrients for sustaining soil fertility and increasing rice yield.

Table 1. Effect of inorganic N fertilizer and rice straw on some soil properties after four years of wetland rice–rice cropping, BRRI, Joydebpur, 1984–1988.

Treatments	Bulk density (g/cm^3)	Organic carbon (%)	Total N (%)	Avail. P (ppm)	Exch. K (meq/100 g)
Abs. Control	1.38	1.05	0.11	10	0.32
N–control	1.34	1.04	0.12	15	0.35
N–PU/USG[a]	1.35	1.11	0.13	14	0.29
N–PU/USG+RS[b]	1.33	1.41	0.14	15	0.39
Initial value	–	0.90	0.13	10	0.30

[a] Nitrogen either from prilled urea (PU) or urea supergranule (USG) averaged over rates.
[b] 29 kg N/ha/crop was used from rice straw (RS)

Nutrient Management for Wheat–Rice System

The production environment of wheat, an upland crop and wetland rice is distinctly different, but they are grown on the same piece of land. Nutrient availability to these crops is greatly affected by climatic and management variations. It is expected that some nutrients applied to wheat might have considerable carry-over effect on the following wetland rice crop. Besides, soil tests can be used as an effective tool for efficient nutrient management for a crop or cropping system provided that soil test values are properly correlated with yields.

In view of the above, a long-term field trial with a wheat–rice (T. Aman) cropping system was initiated during the rabi (winter) season of 1992 in a farmers' field (loam soil) in the Thakurgaon Deep Tube Well Project Area in order to develop a sound nutrient management technology. Six treatments, including a check (T_1) and a farmer's nutrient input (T_6) were used (Table 5). Target yields, soil test values and other factors were considered in formulating the other four treatments (T_2 to T_5), the description of which are given in Table 5.

Mean grain yields of wheat and rice (average of 2 years) presented in Table 6 reveal that the treatments T_2 to T_5 produced almost identical yields

Table 2. Description of treatments used.

Treatments	Nutrient levels	Cropping seasons							
		Boro (dry season)				T.Aman (wet season)			
		N	P	K	S	N	P	K	S
		(kg/ha)				(kg/ha)			
T_1	0	0	0	0	0	0	0	0	0
T_2	Low	40	8	12	5	30	6	9	4
T_3	Med.	80	16	24	10	60	12	18	8
T_4	High	120	24	36	15	90	18	27	12
T_5	Low+OR	T_2 + OR[a]				T_2 + residual value of OR			
T_6	Med.+OR	T_3 + OR[a]				T_3 + residual value of OR			

[a] Organic residues (OR) @ 5 t/ha cow dung + 2.5 t/ha ash were applied once in a year prior to Boro planting.

Table 3. Grain and straw yields of and nutrient removal by MV rices (average of 4 years) as affected by levels of inorganic nutrients and organic residues (OR) in a Boro–Fallow–T. Aman cropping pattern, BRRI, Joydebpur, 1990–1993.

Treatments[a]	Nutrient levels	Annual yield (t/ha)		Annual nutrient removal (kg/ha)				
		Grain	Straw	N	P	K	S	Zn
T_1	0	5.6	6.1	93.4	14.2	96.5	7.0	0.41
T_2	Low	6.5	7.2	118.8	18.8	123.4	8.9	0.55
T_3	Med.	7.5	7.9	137.6	23.2	138.8	12.6	0.67
T_4	High	8.0	9.1	157.1	26.7	167.8	14.8	0.82
T_5	Low+OR[b]	7.4	8.1	132.7	21.0	135.8	12.0	0.65
T_6	Med.+OR[b]	8.2	8.9	154.2	25.1	158.8	14.0	0.72

[a] Treatment descriptions are given in Table 2.

which were significantly higher than those produced by T_1 and T_6 treatments. Although T_4 received considerably higher amounts of inorganic nutrients than T_3 and T_5 received organic residue (cow dung) in addition to the inorganic nutrients in T_3, there was no significant improvement in grain yield (Table 6). Perhaps other production factors, either climatic or edaphic which were unknown may have become limiting at this higher level of productivity.

The nutrient removal data presented in Table 6 shows that, except for Zn, higher uptake of nutrients were recorded in the T_4 treatment which received higher amounts of inorganic fertilizers. Zinc uptake on the other hand was maximum in T_2 where Zn fertilizer was applied.

Table 4. Effect of variable levels of inorganic nutrients and organic residues (OR) on some chemical properties of soil after four years of wetland rice–rice cropping, BRRI, Joydebpur, 1990–1993.

Treatments[a]	Nutrient levels	Soil properties						
		pH	O.M. (%)	Total N (%)	Avail. P (ppm)	Exch. K (meq/ 100g)	Avail. S (ppm)	Avail. Zn (ppm)
T_1	0	6.0	2.0	0.09	2.8	0.15	16.0	1.5
T_2	Low	5.9	2.1	0.10	4.6	0.16	22.9	1.5
T_3	Med.	5.9	2.3	0.09	8.0	0.18	25.9	1.5
T_4	High	5.9	2.3	0.10	9.7	0.23	26.5	1.4
T_5	Low+OR	6.0	2.5	0.11	23.7	0.18	25.6	2.0
T_6	Med.+OR	6.1	2.5	0.10	26.1	0.21	31.2	2.0
Initial soil		6.3	1.9	0.10	9.8	0.20	28.9	2.1

[a] Descriptions of treatments are given in Table 2.

Table 5. Treatment descriptions.

Treatments	Crops	Fertilizer nutrients added (kg/ha)					
		N	P	K	S	Zn	Mg
T_1– Check	Wheat	0	0	0	0	0	0
	Rice	0	0	0	0	0	0
T_2–Nutrient rates as per Fertilizer Recommendation Guide for moderate yield goal (3.0–4.0 t/ha)	Wheat	100	40	60	20	3	0
	Rice	70	15	20	0	0	0
T_3–Nutrient rates as per site specific soil analytical data for high yield goal (HYG 4.0–5.0 t/ha)	Wheat	120	45	60	30	0	15
	Rice	90	30	20	10	0	0
T_4–T_3 + other likely nutrients for HYG	Wheat	160	60	90	30	0	15
	Rice	120	40	40	10	0	0
T_5–T_3 + cow dung (3.5 t/ha OD)	Wheat	120	45	60	30	0	15
	Rice	90	30	20	10	0	0
T_6–Farmer's nutrient input	Wheat	45	60	40	0	0	0
	Rice	45	0	0	0	0	0

Data on some soil chemical properties after two years of cropping (4 crops) presented in Table 7 show that organic carbon, available P and available S decreased slightly in those treatments which received no or lesser amounts of those nutrients as inorganic fertilizer. Exchangeable K content on the other hand was increased to some extent in those treatments which received moderate to high levels of K fertilizer. The zinc content in T_2 which received Zn fertilizer was also increased considerably. These results suggest that nutrient status of soil can either be maintained or even improved to some extent if nutrients are recycled through adequate fertilisation.

Table 6. Grain yield of and nutrient removal by wheat–rice cropping system (average of 2 years) as affected by target yield based nutrient management (Farmer's field, Thakurgaon Deep Tube Well Irrigated Project, 1992–1993).

Treatments[a]	Grain yield (t/ha)		Total nutrient removal (kg/ha/year)[b]						
	Wheat	Rice (T.Aman)	N	P	K	Ca	Mg	S	Zn
T_1	1.0	1.8	65.6	13.8	58.7	6.3	11.2	9.7	0.30
T_2	3.1	3.4	156.0	27.4	95.5	12.8	23.3	23.3	0.71
T_3	3.2	3.9	171.0	33.2	101.0	18.4	27.7	30.0	0.53
T_4	3.2	3.9	183.5	32.1	141.7	18.9	29.8	31.9	0.67
T_5	3.3	3.8	179.1	32.4	108.4	16.1	28.0	28.7	0.55
T_6	2.1	3.2	120.9	23.8	90.6	10.2	19.7	14.5	0.35
LSD (5%)	0.4	0.7							
CV (%)	10.1	11.9							

[a] Descriptions of treatments are given in Table 5.
[b] Computed on the basis of grain & straw yields.

Table 7. Effect of cropping system and target yield based nutrient management on some chemical properties of soil after two years of cropping (Farmer's field, Thakurgaon, Deep Tube Well Irrigated Project, 1992–1993).

Trs.[a]	pH (1:2.5)	Org. Matter (%)	Total N (%)	Avail. P[b] (ppm)	Avail. S (ppm)	Exch. K^{+c}	Exch. Ca^{++c}	Exch. Mg^{++c}	Zn[d] (ppm)
						Meq/100 gm soil			
Initial soil	5.4	1.9	0.14	16.0	2.5	0.11	0.88	0.25	0.40
T_1	5.7	1.6	0.11	12.0	1.3	0.10	1.00	0.30	0.45
T_2	5.5	1.7	0.13	12.0	1.3	0.17	0.90	0.20	0.80
T_3	5.2	1.8	0.11	12.0	3.8	0.15	0.83	0.17	0.40
T_4	5.2	1.9	0.12	14.0	3.8	0.15	0.85	0.15	0.40
T_5	5.2	1.9	0.14	16.0	2.5	0.14	1.00	0.18	0.50
T_6	5.6	1.7	0.14	12.0	1.3	0.09	0.83	0.18	0.40

[a] Treatment descriptions are given in Table 5.
[b] Avail. P was determined by modified OLSEN'S method.
[c] Extracted by 1N NH_4OAc pH = 7.0 (1:10).
[d] Extracted by 0.05 NH_4Cl (1:2).
Note:Each value is an average of 2 observations.

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Soil Fertility Management in the Rainfed Lowland Environment of the Lao PDR

P. Lathvilayvong, J.M. Schiller, T. Phommasack and M. Chanphengsay*

Abstract

The rainfed lowland environment of Laos accounts for approximately 66% of the cultivated rice area and 77% of production. Almost 80% of the rainfed lowland rice area is located in the Vientiane plain (Vientiane province and Vientiane municipality) and the provinces of Savannakhet, Champassak, Saravane and Khammouane, in the central and southern agricultural region. A single wet season rice crop predominates in most of this area.

Systematic nutrient response studies commenced in 1990 and have continued with the aim of providing basic information on likely yield response to soil fertility management. Yield responses to nutrient inputs under on-farm conditions often exceed 200%. Phosphate deficiency is widespread and so acute in many areas that it must be alleviated before responses can be obtained to N or other nutrients.

In 1991 studies commenced to evaluate the potential of green manure crops for providing an organic source of N for the wet-season rice crop. *Sesbania rostrata* has shown the greatest potential, with biomass yield after 50–55 days ranging from 5–15 t/ha and rice grain yields the equivalent of inputs of between 60 and 90 kg N/ha. However, in most areas its potential is totally dependent on first alleviating the prevailing P deficiency.

RICE cultivation accounts for about 90% of food crop production and more than 80% of the cultivated area in the Lao PDR. The total cultivated rice area is about 600 000 ha. Rainfed lowland rice accounts for about 66% of the area and 77% of production. Less than 3% (about 15 500 ha in 1992) is dry-season irrigated. The remainder is rainfed upland cultivation largely based on slash-and-burn production systems. Total annual rice production in the Lao PDR averages between 1.5 to 1.6 million t. Most is consumed directly by producers; the amount of rice traded is probably less than 5%. Reported yields vary from between 1.0 to 1.5 t/ha in the rainfed uplands, 2.0 to 3.0 in the rainfed lowlands, and as high as 4.0 t/ha in the irrigated environment. Actual yields are believed to be below those reported, particularly in the rainfed lowland environment. With about 97% of the cultivated area being dependent on rainfed conditions, production is very susceptible to climatic variability; rice deficits are usually a feature of unusually dry years. For instance in 1992 total production dropped by about 18% to 1.25 million t, as a result of drought conditions reducing both area planted and yield, mainly in the rainfed lowland environment. Localised flooding can also be a cause of substantial losses in some years.

Current national policy recognises rice as the most important crop commodity in the country, for which a higher degree of self-sufficiency is the objective of production policy. An annual production target of 2.2 million t by the year 2000 has been set, to be achieved through an increase exceeding 5% (Table 1). Most of this projected increased production is to come from the rainfed lowland environment, through a combination of increased yields and increased cropping area. At the same time it is planned to markedly reduce the amount of rice cultivation in the rainfed upland environment. An increase in the area irrigated and yields is also planned. However, production under irrigation is expected to not exceed about 10% of the total.

* IRRI, Vientiane Office, P.O. Box 4195, Vientiane, Laos.

The Rainfed Lowland Rice-based Ecosystem

The five provinces of Savannakhet, Champassak, Saravane, Khammouane and Vientiane, together with Vientiane Municipality, in the central and southern agricultural regions, account for approximately 77% of the total rainfed lowland rice area. These provinces all border the Mekong River and have similarities to areas of rainfed lowland rice production in northeast Thailand. The topography throughout much of this area comprises a system of low-level terraces with an elevation of about 200 m above sea level.

The climate of the area is tropical and is dominated by the southwest monsoons which bring up to 75% of the annual rainfall between May and October. The annual average rainfall through most of the rainfed lowland area ranges between 1300 and 1500 mm. August and September are the wettest months, when heavy rains can often result in localised flooding, mainly along tributaries of the Mekong River. Temperatures are highest in April and early May (mean daily temperatures in the range 28–30°C) and then fall with the onset of the monsoon rains. From November to February the climate is mostly dry and cool, with mean daily temperatures in the range 21–24°C.

Soils in much of the rainfed lowland area are highly weathered, moderately acid, sandy loams, loams and loamy sands. Classified mainly as Allisols, Acrisols, Camisols and Gleysols, they typically have low levels of N, P and sometimes K; low organic matter and CEC are also usual (Table 2). Soils in about 5% of the area (mainly in Savannakhet province and to a lesser extent Vientiane province) are slightly saline. The only exceptions to the general low level of fertility that prevails are the small areas of river alluvium along the Mekong River and its tributaries and in some of the narrow valleys in the more northern mountainous region.

Current Production Systems

Rice is the predominant crop with a single wet-season crop grown. This usually occupies the whole of the cultivated area. There is no second cropping either before or after the rice crop, apart from small areas of vegetables which are grown near areas of impounded water or creeks that might traverse village land. Seedbed rice is sown in early to mid June, with transplanting about mid July, although the timing of these operations is very dependent on rainfall distribution.

Almost all rainfed lowland rice production in the Lao PDR is of glutinous types, and more than 80% of production is based on the use of traditional photoperiod sensitive varieties. Farmers usually grow between 2 and 4 photoperiod sensitive varieties of varying maturity time. Varieties in the upper parts of the terrace system where water supply is less certain, flower between the end of September to early October and are harvested in late October to early November. Later maturing varieties are usually grown in the lower terraces; these flower between the mid to end of October and are harvested in mid to late November. The traditional varieties have been selected with particular attention to their eating quality rather than exclusively yield potential. Until recently, introduced varieties have originated mainly from Thailand, sometimes through farmer exchange. The most popular varieties have been RD6 and RD8 (glutinous, photoperiod sensitive), RD10 (glutinous, photoperiod non-sensitive), and KDML105 (non-glutinous, photoperiod sensitive). Their adoption has been mainly in farming areas immediately adjacent to the Mekong River where

Table 1. Rice production statistics for 1992 and Lao government policy projections to year 2000.

Rice environment	1992[a]			1995[b]			2000[b]		
	Area (ha)	Yield (t/ha)	Prod'n '000 t	Area (ha)	Yield (t/ha)	Prod'n '000 t	Area (ha)	Yield (t/ha)	Prod'n '000 t
Rainfed lowland	392500	2.94	1153	430000	3.3	1419	500000	3.8	1900
Irrigated	15535	3.56	55	26600	3.8–3.9	102	50000	5.0	250
Rainfed upland	200000	1.44	294	172000	1.04	179	21000	2.4	50
	608035		1502	628600		1700	571000		2200

Sources: [a] Basic statistics about the socioeconomic development in Lao PDR 1992–State Statistical Centre
[b] Policy projections of the Ministry of Agriculture and Forestry for the Lao PDR

farmer-to-farmer contact has been easiest, and in irrigation scheme areas where extension services have been better developed.

However, since 1992 there has been increasing adoption of Lao varieties, the most popular being 'Niaw Thadokkham 1', 'Niaw Thadokkham 2' and 'Phone Ngam 1'; these have all been Lao selections from among IRRI–Thai crosses.

Yields in most areas of wet season rainfed lowland rice cultivation are reported in the range of 2 to 3 t/ha. However, individual farmer yields can be as low as 1 t/ha (Table 3) and fluctuate widely between seasons, reflecting periodic droughts and occasional flooding. Diseases are not regarded by farmers as a production constraint; however, neck and sheath blast are occasionally observed. Gall midge damage is often reported to be serious on a localised basis, particularly in some introduced and improved varieties.

Farm size in most areas does not exceed 2 ha. Inputs into the production system, apart from family labour, are minimal. Organic fertilizer in the form of FYM is used by almost all households in seedbeds. Less than 10% of households use FYM in transplanted rice fields (Table 3). The benefits of the use of FYM are well recognised by farmers but its availability in only limited quantities usually restricts its use to the seedbed. There is only limited use of chemical fertilizer (Table 3). When used in the transplanted rice crop, application rates are often less than 50 kg/ha of the compound fertilizer 16:20:0 or urea. Pesticide application is virtually nil. Weed infestation is not a major problem in most areas, and any weeding is done manually. Labour input for weeding does not usually exceed 10 days of labour/ha The relative insignificance of weeds as a production constraint is believed to reflect the prevailing low level of soil fertility. Herbicides are not used and are not commercially available in areas of rice production in Laos.

Apart from the recent introduction of powered tillers for land preparation and threshing machines, in and near irrigation scheme areas, particularly in Vientiane Municipality and Vientiane Province, the rice production cycle in more than 95% of the Lao PDR remains unmechanised.

Most households in areas of rainfed lowland rice cultivation in Laos do not produce a rice surplus for possible sale; many have a rice deficit even in years of normal rainfall distribution (Table 4).

Table 2. Characteristics of major rainfed lowland rice soils in the Lao PDR.

Soil group	Alisols	Acrisols	Cambisols	Gleysols
Location	Khammouane Savannakhet Champassak Vientiane Plain	Khammouane	Savannakhet Saravane Khammouane	Saravane Vientiane Plain
Soil characteristic	range (median)	range (median)	range (median)	range (median)
pH (H_2O)	3.9–6.5 (5.13)	4.7–5.3 (5.05)	4.2–6.6 (5.40)	4.3–6.4 (4.85)
OM (%)	0.06–5.49 (1.92)	1.94–6.22 (3.03)	0.14–4.41 (2.13)	0.70–7.24 (4.13)
Total N (%)	0.003–0.274 (0.10)	0.097–0.311 (0.15)	0.007–0.220 (0.11)	0.035–0.362 (0.21)
Total P (%)	0.003–0.16 (0.02)	0.023–0.149 (0.05)	0.018–0.4 (0.05)	0.04–0.09 (0.06)
Available P (ppm)	0.05–11.4 (0.56)	0.65–4.15 (0.97)	0.55–33.1 (1.38)	0.57–18.30 (0.85)
Total K (%)	0.02–1.4 (0.36)	0.12–1.84 (0.69)	0.05–1.58 (0.52)	0.01–1.38 (0.82)
Available K (mg/Kg soil)	0.66–56.4 (6.52)	4.00–30.40 (10.08)	2.00–53.2 (7.39)	3.2–64.0 (9.93)
Soil texture	SL – HC (SL)	SL – CL (SL)	S – HC (L)	LS – HC (CL)
% sand	14.56–84.16 (62.10)	25.44–76.68 (52.86)	20.00–89.60 (50.42)	11.80–76.44 (36.72)
% silt	8.90–80.68 (25.80)	3.28–46.0 (27.66)	9.28–58.56 (28.70)	11.32–49.00 (25.87)
% clay	3.84–47.32 (12.10)	7.32–38.56 (19.48)	2.42–41.10 (20.88)	3.00–68.8 (37.41)
CEC (me/100g soil)	1.63–27.91 (3.60)	3.02–21.17 (3.16)	1.16–16.77 (5.20)	2.75–44.7 (11.70)
% Base saturation	1.00–88.26 (65.09)	3.27–60.32 (59.91)	4.89–87.34 (57.89)	7.83–96.09 (65.66)

Table 3. Profile of rice production in selected villages of Vientiane, Champassak and Savannakhet Provinces.

	Vientiane	Champassak	Savannakhet	
	B. Nafay	B. Oupalath	B. Phonesim	B. Phaleng
Area planted/household (ha)	1.00	1.09	1.52	1.65
No. varieties sown/household	2–3		3	4
Glutinous (% area)	>90%	>90%	>95%	>95%
Traditional varieties (% total)	80%	80%	60%	90%
Average yield (kg/ha)	1500	1475	1151	963
Seedbed rice				
Use FYM (% household)	>80%	>80%	>80%	>80%
Application rate FYM	1–2 t/ha	1–2 t/ha	800 kg/ha	500 kg/ha
Pesticide application	occasional	none	none	none
Transplanted rice				
Use FYM (% household)	3–5%	5–10%	none	none
Use inorganic fertilizer				
– % households	<10%	80%	23%	24%
–rate[a]	1–3 bags	1 bag	<1 bag	<1 bag
Insecticide use	none	none	none	none
Fungicide use	none	none	none	none
Herbicide use	none	none	none	none
Use powered implements	threshing, milling	milling	milling	milling

[a] Relates only to those who apply fertilizer, the fertilizer in 50 kg bags of 16:20:0 or urea (46% N)

Table 4. Profile of rice crop production and disposal in selected villages of Vientiane, Champassak and Savannakhet Provinces.

	Vientiane	Champassak	Savannakhet	
	B. Nafay	B. Oupalath	B. Phonesim	B. Phaleng
Mean household production (kg)		3170	1750	1685
Production range (kg)		450–9800	300–4800	350–4800
Household consumption (% production)	> 80		74	78
Payment as tax (%)	-		9.0	10.7
Sold (%)	3.8		1.9	4.5
Kept for seed (%)			4.5	5.6
Paid as land rental			–	–
Payment labour/buffalo hire (%)			10.7	–
% Household self-sufficient in rice	46	42	30	16

Production Constraints in the Rainfed Lowland Rice Environment

A survey of farmers' perceptions of the main production constraints was undertaken in the period September–November 1993. The assessment was made through interviews with 191 farmers in the main areas of rainfed lowland rice production in Vientiane Municipality and the provinces of Vientiane, Sayabouly, Khammouane, Savannakhet, Saravane and Champassak. Farmer respondents were asked to rank the relative importance of the following potential constraints — drought, weeds, insect pests, disease, labour availability, varieties, soil fertility, credit, rodents, crabs/snails and flooding.

In 8 of 9 districts where the surveys were undertaken, drought was nominated as the most important yield constraint. Soil fertility and varieties were never perceived by farmers as being among the three most important factors limiting yield. Among 11 potential constraints these were usually ranked between 5 and 7, with soil fertility usually being ranked before varieties. After drought, the second and third most important factors were perceived as insect pests and weeds. However, in absolute terms these two factors are not particularly significant, as less than 10 labour days/ha is usually devoted to weeding, while separate studies aimed at quantifying yield loss due to insect pests have failed to demonstrate any general economic significance; losses are usually on a localised basis and variable between years.

Research Related Developments in the Rainfed Lowland Environment

Soil classification and soil fertility mapping

For the five provinces and Vientiane Municipality which comprise the main areas of rainfed lowland production, soil fertility mapping commenced in 1990 and is scheduled to be completed in 1995–96. Semi-detailed maps on a scale of 1:50000 are currently available for about 50% of the area. The system being used is based on the Manual of Soil Fertility Mapping of the Russian Soils Institute.

Soil fertility management research

Systematic research on soil fertility management in the rainfed lowland rice environment commenced in 1990 about the same time as the comprehensive soil mapping program. It has continued since that time, mainly in association with the Lao–IRRI Project. The development of the program has been governed by the rate at which the national rice research program has expanded to the provinces and the availability and training of collaborating provincial staff. The following sequence of studies has been initiated and followed:

- Quantifying responses to NPK on the major soil groups in each province through simple omission type studies
- Nutrient rate response studies for those nutrients which have been shown to be deficient, in each region
- Assessment of the potential of selected green manure crops grown at the beginning of the wet season, for providing the N needs of the rice crop
- Assessment of non-N nutrient needs of GM crops in the rainfed lowland environment, and establishment techniques for GM crops.

More than 90% of the above studies have been undertaken under on-farm conditions using farmer management and collaboration. Nutrient management studies have been, and continue to be, undertaken in selected representative areas in association with variety evaluation, integrated pest management (IPM), farming systems and agronomic studies.

Nutrient response studies

Reflecting the inherently infertile nature of the major soil groups in the main areas of rainfed lowland rice cultivation, and a history of very low or no fertilizer inputs over the past 25–30 years, large yield responses are being obtained to the various soil fertility management treatments; however, these responses vary in magnitude and type between regions.

P deficiency is widespread on the loamy sands, loams, and sandy loam soils that prevail in much of the area. In many provinces this P deficiency is so acute that it must be alleviated before responses can be obtained to other nutrients, and before green manure crops can be brought into the system as a potential N source. One exception to this generalisation appears to be in the slightly saline Gleyic Solonetz and Gleyic Solonchack soils found in Savannakhet province; these soils have generally not shown the P responses recorded elsewhere, and rice crops have shown substantial responses to N alone. Reflecting the sandy nature of the soils (and their associated low P fixation capacity), areas of acute P deficiency can usually have their P requirements met through the application of the equivalent of about 12 kg/ha P; an exception to this exists on the Alisol soils in Vientiane province where application rates of at least 18 kg/ha P appear to be required.

All areas of rainfed lowland rice cultivation show substantial responses to N fertilisation (the expression of which is usually first dependent on alleviating the acute P deficiency). For the varieties currently in use the most appropriate N application rate ranges between 60 and 90 kg N/ha, applied as a 2 or 3 way split application (higher application rates are not recommended due to potential losses from flooding, or lack of exploitation due to drought).

Visual differences in vegetative growth in response to K application in the provinces of Vientiane and Champassak, have not been reflected in grain yield. Despite the lack of any measured K response, it has been recommended that where compound fertilizer options include K at no extra cost, they should be used in these provinces.

Pre-rice GM cropping as N source for rice

Studies commenced in the 1991 wet-season within the INSURF Network (International Network on Soil Fertility and Sustainable Rice Farming) and with the formal end of the INSURF Network activities in 1993, have been continued within the Lao national rice research program with Lao–IRRI Project support. Their aim has been to assess the potential of various GM crops for the rainfed lowland environment of Laos, both in terms of their potential as an organic N source and improvements to soil physical and chemical properties. Long-term studies under on-station and on-farm conditions (Vientiane Municipality and Champassak province) are supported by short-term problem-specific studies under on-farm conditions in a number of provinces. Salient results from these studies to date include:

Over three years of studies (1991–1993) in four locations in Vientiane Municipality and Champassak province, to evaluate the potential of *Sesbania rostrata, Crotalaria juncea*, mungbean, blackbean and cowpea as potential sources of organic N for the main wet season rice crop, only *S. rostrata* has shown sufficient consistent performance to be considered under farming conditions. Biomass yield from *S. rostrata* has ranged from 5 to 15 t/ha, with resulting rice grain yields the equivalent of inputs of 60–90 kg N/ha. Although *C. juncea* has performed well in dry years (in 1991 when conditions were dry at the beginning of the wet season, a biomass yield of about 13 t/ha and a resulting rice grain yield exceeding an application of 90 kg N/ha, were recorded), it performs poorly under saturated soil conditions as experienced at the beginning of the wet season for 1992, 1993 and 1994. The performance of mungbean, blackbean and cowpea have also been inconsistent and none have been able to act as a potential GM/cash crop in a pre-rice cropping situation.

On-farm demonstration plots in 1993 and preliminary results from more regulated on-farm experiments in 1994 in Champassak province, have shown that the potential of *S. rostrata* as a GM crop will clearly be determined by the P status of soils on which it is grown. Failure to apply P on soils with acute deficiency will result in almost complete failure of *S. rostrata*.

Initial studies in Savannakhet province have demonstrated that broadcast seeding of *S. rostrata* into a rough seedbed is more likely to result in successful GM crop establishment than dry seeding (dibble planting) into a zero tillage situation. Rough seedbed conditions are also better suited to possible accompanying phosphate fertilisation.

Ongoing studies are being aimed at an examination of a combination of the following issues:

- How to best meet any P requirement of the GM crop on soils with acute P deficiency.
- The ability of P applied to the GM crop to meet the P requirement of the following rice crop: studies commenced in the 1994 wet season.
- The impact of sowing time and growing period on the potential contribution of N from the GM crop. Further examination of GM crop establishment techniques.
- An examination of opportunities for on-farm seed production: Studies commenced in several provinces in the 1994 wet season.
- An assessment of alternative GM crops, particularly species unlikely to act as host for root-parasitic nematodes of rice. This assessment commenced in 1994 and *S. aculeata* is showing promise equal to or greater than *S. rostrata*.

Challenges to Raising Rice Yields in the Rainfed Lowland Environment

Current research initiatives within the Lao national research program are expected to produce a series of technical recommendations which are capable of giving significant yield improvements in the rainfed lowland environment. However, the impact of these recommendations and their adoption by farmers are going to be determined by a number of factors several of which are external to the research effort. Among these are the following:

Lack of extension services

Laos is still without an effective national extension service. Attempts to provide farmers with the technical recommendations currently emanating from research, and to establish on-farm demonstrations of the potential impact of these recommendations will be severely handicapped by this deficiency. Inappropriate advice through commercial sources of agricultural inputs (particularly relating to pesticide and fertilizer use), are likely to create later credibility problems for research and extension efforts. The Lao government is currently trying to attract outside donor support to develop the extension program.

Availability of seed of recommended rice varieties

Current seed production capacity is limited, as is the current seed distribution system; the latter problem is partly related to the lack of development of the extension service. The most effective seed distribution systems are to be found in Vientiane Municipality, and the provinces of Vientiane, Champassak and Savannakhet. However, even in these provinces, farmers in more remote locations have limited access to seed. Farmer-to-farmer distribution of seed will need to be relied on in the short to medium term.

Responsibility for production of seed of potential green manure crops has yet to be addressed

With initial capacity likely to concentrate on the production of seed of rice and cash crops, it can be expected that the adoption of GM crop recommendations by farmers will need to be within the context of seed production by farmers. Effective on-farm seed production and storage techniques have yet to be developed.

Availability and reliability of fertilizer supplies

Even though national policy is to minimise reliance on inorganic fertilizer inputs, commercial fertilizer use will be unavoidable, particularly in areas with acute P deficiency. Currently the main source of fertilizers is from Thailand. Experience by the national rice program and Lao–IRRI Project in 1993 demonstrated serious potential problems in ensuring quality control of imported fertilizers (analysis showed some commercial fertilizers had up to 4% lower nutrient content than stated). Fertilizers are not yet available through commercial outlets outside of most provincial centres.

Poor infrastructure development

Roads even between the major provincial centres are generally poorly developed and movement during the wet season is difficult. At the district and village levels, opportunities for wet season movement of inputs and produce is very limited.

Marketing advice and credit sources are either limited or non-existent

The former can be expected to improve with the development of the extension services. The government is currently attempting to improve opportunities for credit.

Income levels of many farmers are too low to allow them to consider adopting any technical recommendations that involve additional expenditure

The farming systems approach to research currently being followed within the national rice research program aims to help to provide recommendations for raising productivity within a whole farm context. However, without some short-term subsidies for some inputs (particularly fertilizer), a significant number of farming households will probably fail to adopt any of the recommendations for raising productivity due to their small holding size and limited potential for any surplus production for sale.

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Organic Matter Residue Management in Lowland Rice in Northeast Thailand

S. Wonprasaid*, K. Naklang*, S. Khonthasuvon*, S. Mepetch*, B. Hemthanon*, S. Tippayaruk* and R. Lefroy†

Abstract

The Northeast of Thailand has the lowest regional rice yields in Thailand, averaging 1.7 t/ha. Rice production in the Northeast is constrained by the infertility of the acidic sandy soils and the variability in rainfall in the predominantly rainfed cropping systems. Large increases in rice yields have been demonstrated with applications of fertilizer, farmyard manure, rice straw, other rice residues and the use of green manuring technologies, such as *Sesbania rostrata* and *Aeschynomene afraspera*. Generally, these increases are only obtained at unacceptably high costs in terms of cash outlay, the fertility of other regions or labour. A combination of relatively low cost technologies is required to produce increases in yield, long-term restoration and subsequent maintenance of the soil resource base. Two field and one pot experiments were established to investigate the impact of different legume residues, fertilizer, and rice residue management strategies on rice-based cropping systems.

Applications of fertilizer and legume residues which breakdown rapidly had an immediate impact on rice yields. In the first year of the field experiments, there was no impact of the return of rice straw or applications of legume residues which breakdown slowly, but these differences are beginning to become evident in subsequent years. The initial benefit of legume residues appears to be related to both their nutrient content and their breakdown rate. In the field, the initial increase in rice grain yield with shrub legumes was highest with pigeon pea, then *Acacia auriculiformis, Phylianthus taxodifolius* and *Samanea saman*. In a pot experiment, the grain yield increased with applications of legume residues up to 9 t/ha with residues which breakdown slowly, but yield decreased above applications of 3 t/ha with residues which breakdown rapidly, apparently as a result of toxic breakdown products. Careful management of residue quality and quantity, combined with the judicious use of inorganic fertilizers, allows management of organic matter and nutrient dynamics to produce systems that should prove to be more sustainable.

THAILAND is a rice growing country in which 70% of the total population are rice farmers. Thailand presently produces rice in excess of its local consumption and thus is a major exporter of milled rice. Total rice production of the country in 1991/92 is estimated at 20.4 million t (OAE, 1992).

Thailand is divided into four regions: they are the North, Northeast, Central and South. The Northeast is the largest of the four regions, covering about one third of the total land area of the country. The area of land in rice production in the Northeast is also the largest, at approximately 2.7 million ha, however, average rice yields are the lowest in the country. The average rice grain yield of Thailand is 2.2 t/ha. This compares to an average of 1.7 t/ha in the Northeast and 3.0 t/ha in the more fertile Central region. Infertile sandy soils, with some salinity problems, low use of fertilizers and erratic rainfall account for the lower yields achieved by Northeast farmers.

Tropaquepts, Paleaquults, and Natraqualfs are the three main great soil groups used for rice cultivation. The fertility status of NE paddy soils is the lowest in the country, largely as a result of the parent material, and based on three factors: low OM, available P and extractable K. Chantanaparb et al. (1976) collected 253 soil samples from the NE and reported that 65 % of the

* Ubon Rice Research Center, Ubon Ratchatani, 34000 Thailand.

† Department of Agronomy and Soil Science, University of New England, Armidale, NSW 2351 Australia.

soils were acid with pH less than 5.6, 67 % of the soils had OM less than 1.0 %, 85 % of the soils had available P (Bray II) less than 10 μg/g, and 90 % of the soils had extractable K (0.05N HCl) lower than 80 μg/g.

Another constraint to rice production in the Northeast is that 95 % of paddy fields are in rainfed areas. The annual rainfall varies between 1000 and 2000 mm. In addition, and perhaps more critically, the distribution of rainfall varies considerably. Delays in the onset of the rainy season in May and June, dry spells in mid season (late June and July) and short flooding periods later in the season (September and October) can be significant constraints.

In the past, transplanting of rice seedlings was the normal practice, but now direct seeding is gaining in popularity because of the shortage of labour. Land preparation is usually done by animal power or small farm tractors, as soon as there is sufficient moisture. Some farmers apply chemical fertilizers, but a large part of the rice growing area is still cultivated without the application of any fertilizer. The cost of chemical fertilizers in Thailand is relatively high compared to other countries. Even those farmers who use fertilizers apply low amounts; common applications are in order of 40, 11 and 10 kg/ha of N, P, K as 16:16:8 compound fertilizer and urea.

Amelioration of soil fertility

Farmyard manure (FYM) is used by farmers as a source of organic fertilizer. Songmuang et al. (1989) reported that an application of FYM at the rate of 3.1 t/ha gave similar rice yields as a chemical fertilizer application at the rate of 18.7, 6.5 and 6 kg/ha of N, P and K. However, farmers usually have access to relatively small amounts of FYM. At best, FYM can be used to improved the soil fertility of a small area of the farm, with little impact on overall rice production. In areas near rice mills, the residues from the milling operation are used at relatively high rates to improve rice production, but clearly this is of little impact to rice production in the whole region.

A large amount of research in Thailand and other countries in Southeast Asia has demonstrated the effectiveness of green manure on the improvement of lowland rice yields through improved plant nutrition. *Sesbania rostrata* and *Aeschynomene afraspera*, two nitrogen-fixing legumes, appear to be suitable sources of organic matter in Northeast paddy fields (Ragland et al. 1986; Herrera et al. 1989). *S. rostrata* has been shown to result in an average improvement in rice grain yield of approximately 20%, and even more when applied with FYM or chemical fertilizer (Herrera et al. 1989). However, there is no evidence that *S. rostrata* has resulted in long-term improvements in soil fertility in general, and soil OM in particular.

Whilst significant improvements in rice production have been achieved by these green manuring technologies, there are significant problems. The major problems are producing enough biomass at the appropriate time and incorporating the biomass prior to planting rice. *S. rostrata* requires significant inputs of organic or inorganic fertilizer, particularly, P and K, to produce adequate biomass on the infertile soils of the region. In addition, the erratic rainfall at the start of the growing season, and the lack of labour for biomass incorporation, pose significant restrictions on these technologies.

Rice straw incorporated into the soil in the following season is the main source of soil OM in the paddy. Long-term straw incorporation has improved soil fertility and productivity of the soils at the Surin Rice Experiment Station. However, the incorporation of rice straw can only return part of the nutrients into the soil as some of the nutrients are removed with grain harvested. The estimated nutrients removed from the paddy field (average rice grain yield 1.7 t/ha) is about 28, 6.2 and 24 kg/ha/year of N, P and K, respectively. Increases in rice yield of up to 30% to applications up to 25 t/ha of rice straw have been observed (Naklang and Rojanakusol 1992), however, with average straw yields of less than 3 t/ha, these applications can only be made at the expense of the fertility of other areas.

Whilst the use of relatively large applications of FYM, green manuring crop residues, rice straw and/or inorganic fertilizer significantly increase rice production, they are often at unacceptably high costs in terms of the fertility of other areas, cash outlay and/or labour costs. Clearly a suite of strategies are required to increase biomass and nutrient inputs, reduce biomass and nutrient loss and removal, and gradually improve the fertility of degraded soils, or maintain the fertility of less degraded soils, through management of soil organic matter.

The breakdown of plant residues to soil organic matter is controlled by a large number of factors. One factor which affects residue breakdown and associated nutrient release is the quality of the residue. The quality can vary with the total nutrient content and with the chemical and physical form of residues. The application of high quality residues, with high nutrient contents and in forms which are easily broken down by soil biota, are likely to result in rapid release of plant-available nutrients. Conversely, the application of lower quality residues, with low nutrient contents, will release less nutrients and may reduce the availability of certain nutrients to plants, at least in the short-term, due to immobilisation by competing soil biota. Residues from the majority of green manuring crops fall into the former group, whilst rice straw, and other similar products are in the latter group. The application of residues with relatively high nutrient contents, but which breakdown relatively slowly due to chemical and/or physical restrictions, should result in significant inputs of carbon and other nutrients which have significant impact over the medium to long term. Where slow breakdown residues are used, it may be necessary to supply an organic or inorganic source of more available nutrients to avoid the short-term immobilisation of nutrients from residues of low total nutrient content or which breakdown slowly for other reasons.

A number of experiments were conducted to investigate the impact of residues of different quality.

Methods

Two field experiments were started in 1992 at the Ubon Rice Research Center. The experimental site is on an infertile acid sandy soil (Aeric Paleaquult) of the Roi Et series, a widely distributed soil used for rice production in the Northeast of Thailand.

The first field experiment used small amounts of relatively high quality legume residues with different breakdown rates, lower quality rice straw and inorganic fertilizer. The treatments were in a complete factorial design consisting of three rice cropping systems (rice alone, rice with mungbean and rice followed by cowpea), two shrub legume residue rates (0 and 750 kg/ha of *Samanea saman* leaves), two fertilizer rates (18:14:13 and 50:14:13 kg/ha N:P:K) and two crop residue treatments (rice stubble removed and returned), with 3 replications.

In all three rice cropping systems, rice (cv. RD15) was broadcast at the rate of 60 kg/ha. In the rice with mungbean system, the rice and mungbean seeds were broadcast together, with mungbean at a seeding rate of 30 kg/ha. The principle behind this system is that mungbean and rice grow together until the mungbean can no longer tolerate the anaerobic conditions. If the rains fail, the mungbean and rice can grow together, and both can be harvested. The stage at which the mungbean is flooded out will determine the benefit derived by the rice from the mungbean organic matter and, more particularly, fixed nitrogen. In 1993, cowpea (cv. CP4-3-2-1) was used instead of mungbean because it is more tolerant to flooding.

In the rice followed by cowpea system, cowpea was planted at the time the rice was harvested (early November) and grew on the residual soil moisture and any late rains. This system can produce harvestable product or just biomass, depending on the season.

For the slower breakdown legume residue, dry leaves of *Samanea saman* (rain tree) were applied and incorporated into the soil a week before broadcasting.

At planting, chemical fertilizer was applied and incorporated into the soil at the rate of 0:14:13 and 32:14:13 kg/ha N:P:K for low and high nitrogen treatments. At panicle initiation, urea fertilizer was topdressed to all plots at the rate of 18 kg N/ha.

The second field experiment was to more directly compare different legume residues and to rank them with inputs of inorganic fertilizers. The experiment consisted of a complete factorial design with five legume residue treatments (No residue, *Cajanus cajan, Acacia auriculiformis, Samanea saman and Phyllanthus taxodiifolius),* two inorganic fertilizer rates (25:7:7 and 50:14:14 kg/ha of N, P and K) and two rice stubble management (stubble removed and returned), with 3 replications.

Legume residues were applied and incorporated a week before transplanting at the rate of 1.5 t dry weight/ha, except for the pigeon pea (*Cajanus cajan*) in 1992, which was applied at half the rate due to a shortage of material. Thirty-day-old seedlings of rice (cv. KDML105) were transplanted at a spacing of 25 × 25 cm and 3 seedlings per hill. Phosphorus, potassium and half of the nitrogen were applied at transplanting and the balance of the nitrogen was applied at panicle initiation. Four additional fertilizer treatments were included to allow comparison of the effects of three rates of nitrogen (25, 50 and 75 kg/ha) in factorial combination with two of P and K fertilizer (7:7, and 14:14 kg/ha), all applied without legume or rice residues.

A pot experiment was conducted to study the effects of rates of different legume residues on rice yield. The experiment consisted of a complete factorial design with four legume residues (*Phaseolus aureus* (mungbean), *Vigna unguiculata* (cow pea), *Samanea saman* (rain tree), and *Flemingia macrophylla*), five residue rates (0.5, 1, 3, 6 and 9 t/ha) and two chemical fertilizer rates(0:14:14 and 50:14:14 kg/ha of N:P:K), with 3 replications.

An additional three fertilizer treatments were included: 0:0:0, 0:14:14 and 50:14:14 kg/ha of N:P:K, without any residue. Fresh legume leaves were incorporated into pots containing 10 kg of soil three weeks before transplanting. The soil was flooded after the incorporation of the residue and allowed to dry one week before three 28-day-old rice seedling (cv. RD23) were transplanted. Phosphorus, potassium and half of the nitrogen were applied at transplanting and the balance of the nitrogen was applied at panicle initiation. After transplanting all the pots were re-flooded and the floodwater was maintained for the remainder of the experiment.

Results and Discussion

First experiment: In 1992, due to the slightly delayed planting of this experiment and the early rain, the mungbean did not establish very well before the plots were flooded and, consequently, there was little benefit derived from the small amount of organic matter produced. Therefore, rice yield did not respond to the presence of mungbean (Table 1). Rain tree had no effect on rice yield. This was not surprising due to the relatively small amount of material applied (0.75 t/ha) and the slow breakdown rate. Only chemical fertilizer significantly affected grain and straw yield, increasing grain yield by 25 % and straw yield by 36% (Table 1).

The dry matter and grain production of cowpea after rice were not significantly affected by any treatments. The average dry matter and grain production were 489 and 231 kg/ha, respectively.

In 1993, where mungbean was replaced by cowpea in the broadcast rice + legume system, cowpea dry matter responded to the return of stubble and the higher fertilizer application (Table 2).

As in 1992, rice grain and stubble yield in 1993 also increased with the application of fertilizer (Table 1). The rice alone tended to produce less straw and grain yield than the two rice with legume cropping systems. Again, there was no effect of rice stubble management or addition of rain tree on rice grain or straw yield.

Dry matter and grain yield of cowpea grown after rice in 1993 increased when rice stubble was returned (Table 3). Application of rain tree leaf slightly affected cowpea grain and biomass. It appears that the positive affect of rice stubble return, and possibly of rain tree application, may have been due to better soil moisture with these treatments. Maintenance of soil moisture is critical for cowpea grown after rice as, with little rain during this period, the cowpea is growing on a drying soil profile.

Experiment 2: In 1992, rice grain and stubble yields increased with all applications of legume residues (Table 4). The pigeon pea residue, even though applied at only half the rate of the other residues, resulted in the highest grain and stubble yields. This is probably due to the high concentration of nitrogen (Table 4) and the faster breakdown and nutrient release from the pigeon pea residue. Fertilizer also affected the rice grain and stubble yields (Table 4).

In 1993, all legume residues resulted in higher rice grain and stubble yields (Table 5). The pigeon pea residue, now applied at 1.5 t/ha, resulted in the highest yield, but the difference from other residues was smaller than in 1992. This probably indicates that more of the other residues remained from the previous season, due to their slower breakdown rates, and this residual material affected soil fertility.

The response to legume applications in this experiment, when there was no, or little effect of rain tree residue in the first experiment, is probably due to the greater rate of application — 1.5 t/ha compared to 0.75 t/ha. In addition, although the two sites are very close, the soil in the second experiment is of lighter texture, has less of a hard pan, and therefore dries more quickly. During the 1993 growing season, there were periods of significant water shortage late in the season. This particularly affected the second experiment, because of lower water holding capacity of this soil, and because the shortage occurred during a critical stage of plant growth in the later maturing KDML105. It is possible that some of the benefits from legume application are from improved water relation.

Rice yield responded to chemical fertilizer only when legume residue was applied. This reflects the beneficial effect of residue on nutrient utilisation efficiency and may also be related to improved soil moisture when residue was applied.

The removal of rice stubble from the field reduced grain yield in the second year by approximately 9.3%. This may also be related to improved soil moisture when stubble was retained.

Table 1. Rice grain yield (kg/ha) as affected by cropping system and fertilizer.

Fertilizer	Cropping system		
	Rice	Rice+mungbean	Rice/cowpea
1992			
Low	2649a	2662a	2525a
High	3531b	3567b	3552b
1993			
Low	1295a	1379a	1494a
High	1859b	1959b	1973b

$LSD_{(0.5)}$ 2-fertilizer means in 1992 = 156
$LSD_{(0.5)}$ 2-fertilizer means in 1993 = 148
Yields followed by the same letter are not significantly different according to DMRT

Pot experiment

Grain yield was affected by the species and rate of legume residue application. Grain yield increased with the rate of residue application up to 3 t/ha. At higher rates rice yield declined, except in the Flemingia treatment (Fig. 1). The decrease in grain yield at high rates of application was due to the seedlings suffering damage from the decomposition products of the fresh legumes. It is likely that the slow breakdown rate of Flemingia, (Konboon et al. 1994) despite its high nitrogen content resulted in no reduction in rice grain yield when applied at high rates since there was no significant build up of harmful breakdown products.

Grain yield was greater when nitrogen fertilizer was applied, however, the response of grain yield to nitrogen was less at higher rates of legume residue application.

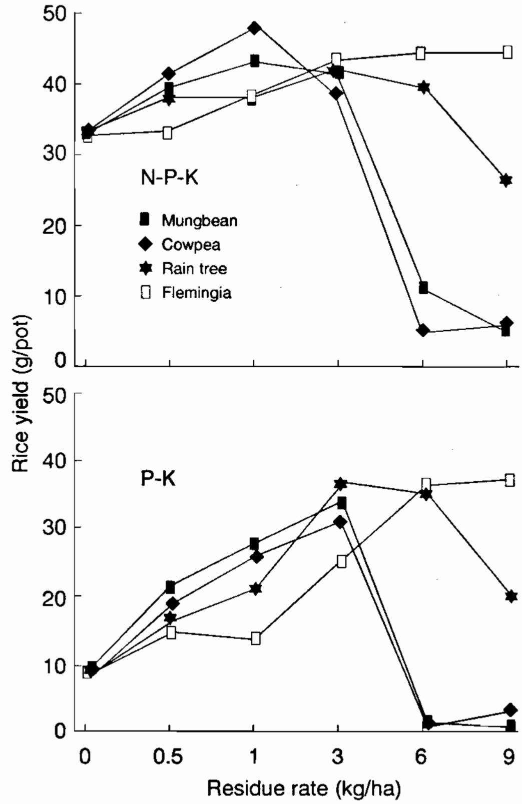

Figure 1. Rice grain yield as affected by legume residue type and rate and fertilizer application.

Table 2. Dry matter of cowpea (kg/ha) grown with rice in 1993.

	Stubble Removed	Stubble Returned
Low fertilizer		
– Rain tree	316	745
+ Rain tree	678	836
High fertilizer		
– Rain tree	1088	1049
+ Rain tree	928	1429

LSD $_{(0.5)}$ for 2 means = 332

Table 3. Effect of rice stubble management on grain and dry matter yield of cowpea (kg/ha) grown after rice in 1993.

	Low Fertilizer		High Fertilizer	
	–RT[a]	+RT	–RT	+RT
Grain yield				
Removed	172	287	89	192
Returned	308	562	448	512
Dry matter				
Removed	424	574	436	726
Returned	879	1164	1272	984

LSD $_{(0.5)}$ for dry matter mean = 209
[a] RT = Rain tree

Table 4. Effect of legume residue and chemical fertilizer on rice grain yield (kg/ha) in 1992.

Residue	Low fertilizer	High fertilizer
None	889 a	999 a
Pigeon pea	1354 c	1783 d
Rain tree	1032 a	1195 b
Acacia	1171 b	1370 c
Phyllanthus	994 a	1324 c

Yields followed by the same letter are not significantly different.

Table 5. Effect of legume, chemical fertilizer and straw management on rice grain yield (kg/ha) in 1993.

	Stubble Returned	Stubble Removed
Low Fertilizer		
None	1440 ab	979 b
Pigeon pea	1667 a	1638 a
Rain tree	1469 ab	1072 b
Acacia	1526 ab	1524 a
Phyllantus	1199 b	1348 ab
High Fertilizer		
None	1279 c	1129 c
Pigeon pea	2035 a	2038 a
Rain tree	1589 bc	1431 bc
Acacia	2035 a	1641 ab
Phyllanthus	1804 ab	1749 ab

Means followed by a common letter are not significantly different according to DMRT.

The response to different types and rates of legume residues in the pot experiment and the second field experiment suggests that management of residue breakdown, by choice of species, method of incorporation and application of fertilizer, can have significant effects on the short, medium, and perhaps even long-term availability of nutrients. Therefore, management of residues can affect the input of carbon and other nutrients into the system and the rate at which soil organic matter turns over. This in turn will affect the amount of soil organic matter in the various soil organic matter pools and, therefore, the overall supply of nutrients, the availability of nutrients and the general chemical, physical and biological fertility of the soil.

After two crops, the management systems being used in the first field experiment have not resulted in large differences in rice production compared to the responses expected from higher input organic and inorganic systems, although there are trends towards improved soil fertility in the medium term. Comparison of product offtake, net carbon addition and estimated nutrient balances indicates the potential of the more conservative and less exploitative systems for continued sustainable production. Specific management systems are needed for different regions and even for different areas of the small farms in the Northeast of Thailand. Different technologies of conservation farming need to be evaluated in terms of the flows of carbon and the other nutrients into, out of, and within the soil–plant–animal system. As differences develop between the experimental system, the carbon and nutrient flow will be more fully assessed and a number of indicators of soil fertility, and therefore system sustainability, will be evaluated.

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Rice Production Systems in the Cuulong (Mekong) Delta of Vietnam

C. Van Phung and N. Van Luat*

Abstract

The Cuulong Delta plays an important role in rice production in Vietnam, more than 80% of this region is under rice cultivation. In 1993 rice production in this area reached a new record of nearly 12 million t representing more than 50% of the country's total rice production even though this delta covers only 12% of the total country's area. There are two rice production systems in the Cuulong Delta. The rainfed rice cropping system is comprised of floating, indigenous, and tall modern varieties which are tolerant to adverse soil conditions. Rice production under this system was about 2 million t in 1993. The irrigated rice production system is mainly under double rice cropping. Modern high yielding rice varieties from IRRI and CLRRI are widely grown under this system. The area under production in this system is increasing at the expense of the rainfed rice system as a consequence of a large investment in construction of canals and embankments for flood control, drainage, and irrigation.

AGRICULTURAL production in Vietnam has made remarkable progress since 1989. Through the last decade, rice production has exceeded demand. As a result, Vietnam has emerged as the third major rice exporter in the world market. The Cuulong Delta (CD) covers an area of 39 000 km^2 (about 12% of the country's total area) in which rice production accounts for around 2.7 million ha. In 1993 rice production in this region amounted to nearly 12 million t accounting for more than 50% of Vietnam's rice production. Contributing factors for the improvement in rice production are a massive investment in the development and maintainance of canals and embankments for flood control, drainage and irrigation (Duong 1992). This allows farmers to switch from a single crop of low yielding tradional rice to two or three crops of high yielding rice.

In the CD, where only rice is widely adapted to problem soils (acid, saline and saline acid soils) and flooding, there is a high potential for rice production. This paper is mainly focussed on rice production systems in this region.

* Cuulong Delta Rice Research Institute (CLRRI), Omon, Cantho, Vietnam.

Features of the Cuulong Delta

The CD lies in the southern part of Vietnam and comprises 11 provinces namly Long An, Tien Giang, Ben Tre, Dong Thap, Cuulong, Tra Vinh, Cantho, An Giang, Soc Trang, Minh Hai and Kien Giang. The provincial locations and current land use are presented in Figure 1.

Water resources

The Mekong river and tributories are closely connected to the formation of the Delta. The annual flow of the Mekong river is about 475 billion cubic metres with large seasonal variation. Inundation usually takes place in August, reaches its peak in October and recession begins at the end of November. Figure 2 shows the duration and maximum depth of inundation in the CD.

Salt intrusion is a serious problem on the Camau pennisula. The Long Xuyen quadrangle is less than 5 km from the sea. The eastern coastal side of the delta is also affected by salinity. The total salt affected area in the Cuulong Delta is about 1.7 million ha.

An important feature of the Delta are the tides of the surrounding seas. The tide of the South China sea is predominantly semi-diurnal with an amplitude of 2.5–3.0 m whereas that of the Gulf of Thailand is mostly of the diurnal type with an amplitude of only some 0.4–1.2 m. These differences offer an opportunity for tidal irrigation and drainage for about 10% of the CD.

Soil Resources

The major soil groups of the CD are:

- Alluvial soils of high fertility which have no serious constraints to agriculture production. They are mainly in the central part of the CD.
- Acid sulfate soils characterised by high acidity, potentially toxic levels of aluminium and iron. These are located mainly in the Plain of Reeds and Long Xuyen quadrangle.
- Saline soils composed of permanent saline soil scattered along the coastal sides and the temporary saline soils which are affected by saline water intrusion into the mainland during the dry season.
- Saline acid sulfate soils are mainly found in the Camau peninsula under mangrove forest.
- Other soils are peats in the Uminh forest, grey soils at the extreme north of the delta and mountainous soils which are found in the northwest and southwest of this region. The areas covered by each soil group are presented in the Table 1. together with the classification of these soils under the FAO/UNESCO and USDA systems.

Climate

The CD is classified as a 'moist monsoon, hot tropical' climate by Papadakis (1966) with mean annual rainfall ranging from 1500–2000 mm and temperatures ranging from 20–34°C. Maximum temperature occurs in April–May then falls to a favourable level with the arrival of the monsoon.

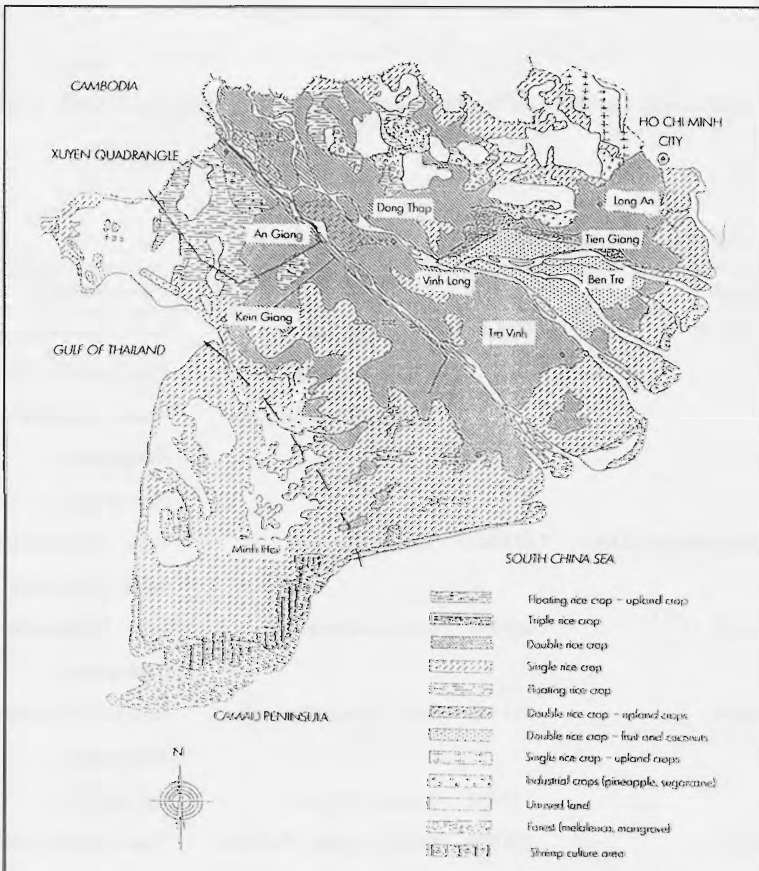

Figure 1. Present land use in the Cuulong Delta.

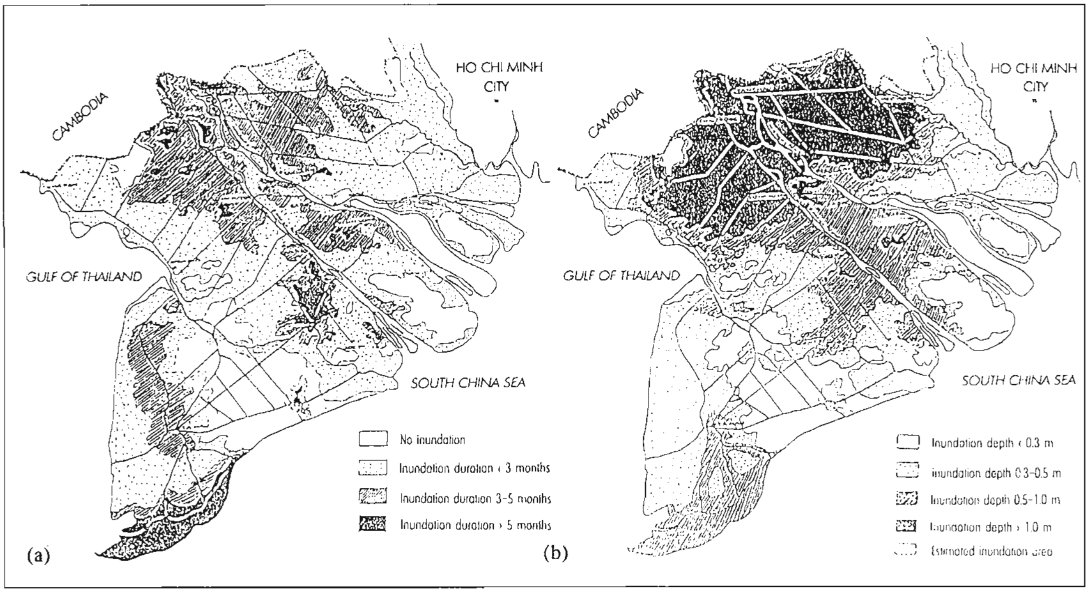

Figure 2. Flood maps of the Cuulong Delta: (a) continuous duration of inundation over 0.3 m depth; (b) maximum depth of inundation.

Table 1. Classification of the Cuulong Delta soil.

Order No.	Soil groups	Area (ha)	FAO/UNESCO taxonomy	USDA taxonomy
1	Alluvial soils	1094248	Eutric Fluvisol	Aeric, Typic Fluvaquents
			Mollic Fluvisols	Typic-Aeric Ustifuvents
			Mollic, Humic Gleysols	Aquic - Tropaquents
				Humaquepts
				Haplaquepts
2	Acid sulphate soils (ASS)	1054342	Thionic Fluvisols	Typic - Histic Sulfaquents
				Sulfic Tropaquents
3	Saline soils	809034	Mollic Solonchaks	Salic - Hydraquents
				Haplaquents
4	Saline ASS	631443	Salic Thionic Fluvisols	Salic sulfic Tropaquents
				Tropaquepts
5	Peats	34052	Thionic Histosols	Humaquepts
6	Grey soils	108989	Gleyic, Plinthic Fluvisols	Typic - plinthic, histic Tropaquents
7	Mountainous soils	34678	Gleyic Acrisols	

Source: Tran, N.N. 1990. The Cuulong Delta: Resource, Ecology and Development..

This delta has an abundance of solar radiation, about 370–490 kcal/cm^2/year. Despite cloud in rainy season, solar radiation is adequate for good rice yields.

Population and labour

According to statistical data from 1990, the CD has a population of 14.6 million and a growth rate of 2.4%. From 1981 to 1990, the population increased by 3.5 million people. Agricultural production in the delta is based on private smallholdings with an average size of about 1 ha. The labour force in 1990 was estimated at 40% of the population in which 56% of the workers are in the agricultural sector. The labour force is still over-supplied and waiting to be absorbed into other sectors of the economy or any farming systems which have a high demand for labour.

Rice Production Systems of the Cuulong Delta

Water availability for irrigation is a major determinant of the rice production systems used in the Cuulong Delta. At present there are rainfed and irrigated rice production systems in this region.

Rainfed rice production system

This is the traditional rice cultivation method of the CD where inundation depths are more than 0.5 m. The total estimated area under this system is about 762000 ha (Nedeco 1993). The typical characteristics of most cultivars used are tall, weak to strong photosensitivity and low response to fertilizer application unless more modern varieties are used. Floating rice, and single and double transplanted rice are mainly used under this system. Nowadays, some modern varieties which are tall, medium duration and tolerant to adverse soil conditions are also cultivated.

Floating rice is practised where inundation depths are more than 1 metre. The estimated floating rice area was about 500 000 ha in 1975, but it is now reduced to less than 100 000 ha due to construction of embankments and drainage systems which lower the inundation depth. This is the reason why most of the floating rice areas are now shifting to a double rice cropping system.

Land preparation for floating rice cultivation commences in March and continues up to May depending on the rainfall. On acid sulfate soils, early ploughing is required to prevent upward movement of toxic salts into the upper layer. Dryseeding, at the rate of 80–100 kg/ha, is commonly practised at the onset of the monsoon season. Though fertilizers are rarely applied there are still some farmers using nitrogen at the rate of 30 kg/ha at 30–40 days after seedling emergence. Harvesting is done from December to February depending on variety. Average yields are about 1.5 t/ha.

Single and double-transplanted rice are cultivated on lowlands where maximum water depth is less than 1.0 metre. The current area under this form of cultivation is about 600 000 ha. Normally indigenous varieties which are tall and toleraant to adverse soil conditions are used. Ploughing may be done in early April or May but seedlings can only be raised when there is standing water on the rice fields. Under normal conditions, transplanting time begins in June or July, the 40–50-day-old seedlings are transplanted at a spacing of 30 × 2 or 40 × 2 cm with 10–15 seedlings/hill. For double-transplanted rice, the second transplanting starts in early August. Fertilisation for these crops is usually practised before flooding at low nitrogen rates (30–40 kg N/ha) because almost all traditional varieties have a low response to nitrogen. Phosphorus is sometimes used at the rate of 30 kg/ha. Depending upon level of photosensitivity of cultivars, harvesting time may be early in November or late in January or February. Average rice yield is about 2.7 t/ha. At present, the area under double-transplanted rice is smaller than that of single-transplanted rice. The area and yield of rainfed rice are shown in Figures 3 and 4.

Modern rice varieties such as IR42 are also used under this rainfed system because they are a tall plant type, have tolerance to salinity and acidity and are

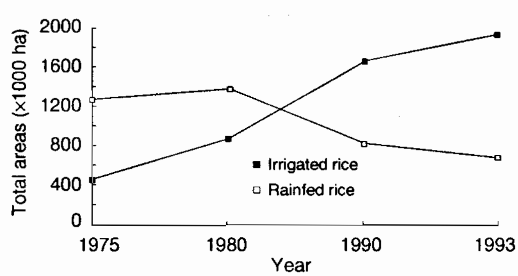

Figure 3. Total areas under rainfed and irrigated rice.

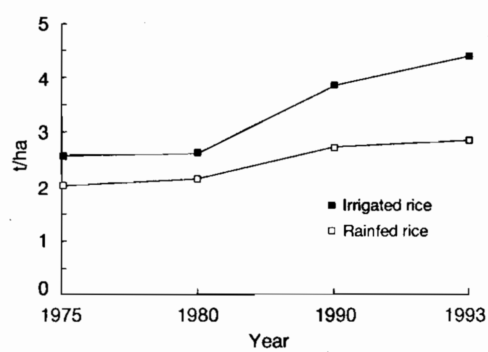

Figure 4. Average yields of irrigated and rainfed rice.

high yielding. They are mainly grown in Soc Trang and Minh Hai provinces.

Normally this traditional crop is followed by one or two leguminous crops such as soybean, mungbean or other short duration food crops as maize, sweet potato etc.

Irrigated rice system

Over the last decade there has been expansion of intensive rice cropping of two to three rice crops per year at the expense of one traditional rice crop through the introduction of short duration, high yielding, rice varieties and irrigation systems.

Double rice cropping covers the largest area in the CD. The total cultivated area of dry and wet season rice is 1 013 000 and 975 000 ha respectively. Land preparation is mainly by tractor, power tiller or buffalo. Ploughing, tillering followed by puddling soils is required before sowing wet season rice but only puddling is required for dry season rice. The wet season crop begins in April and the dry season starts in early November. Farmers in the CD now prefer broadcasting over transplanting to save labour. A seeding rate of 180 to 22 kg/ha is common. Dry seeding is practiced in provinces where soil acidity is a major constraint for rice production otherwise wet seeding is extensively used. Since most of soils in the CD are acid, especially at the beginning of the wet season, phosphate application is required to maximise returns (Tan et al. 1994). P is usually applied at the rate of 16–25 kg P/ha meanwhile nitrogen at 80–120 kgN/ha is quite common. Up until the present K has not shown any increment in rice yield but it is also recommended for rice fertilisation to sustain rice production in this region. Response of rice to N in the dry season is much higher than in the wet season and this is why farmers apply as much as 180 kgN/ha in the dry season to obtain maximum yield. In this cropping system, some leguminous crops, sesame and maize are also cultivated after harvesting of dry-season rice to increase farmer incomes.

Since rice is the staple food and demand for this product in local or international markets is increasing continously, 3 crops/year and even 7 rice crops/2 years are now sown and harvested on the alluvial soils in the CD where water for irrigation is available all year round. To save time in the cropping cycle, minimum or zero tillage is widely adopted for this cropping pattern where rice straw is spread over the moist rice field and burned, then wet seeding follows. Cultivation methods are the same, as described above, for cropped rice. The average rice yield is about 4–5 t/ha. There are some reports of declining yield in this intensive cropping pattern but it is not publicly recognised.

Conclusion

The Cuulong Delta still has potential for expansion of production the area if resources are invested in irrigation and drainage. However, postharvest technologies and food processing in this region need to keep pace with food production. In addition, information is required on market prices of agricultural products so that farmers can make better decisions to increase as a consequence their income.

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Role of Organic Matter in Controlling Chemical Properties and Fertility of Sandy Soils Used for Lowland Rice in Northeast Thailand

I.R. Willett*

Abstract

Rice yields in the Northeast of Thailand are generally low and this is related to the inherently infertile nature of the sandy soils of the region and unreliable rainfall. This paper briefly reviews laboratory work on the role of organic matter in improving the fertility of these sandy soils.

Poor rice growth and erratic responses of rice to fertilizers in sandy paddy soils under rainfed conditions are linked to very low levels of cation exchange capacity and buffering capacities for pH and nutrient ions. Strong positive interactions between organic amendments and mineral fertilizers on rice yield have been obtained in glasshouse and field experiments. In unflooded (oxidised) conditions the soils have very low cation exchange capacities because of their highly weathered nature and low contents of clay and organic matter. Data from a group of soils from throughout the region show that organic carbon dominates cation exchange capacities. It is clear that manipulation of soil organic matter, and to a lesser extent pH, offers the only practical means of increasing cation exchange capacities.

Laboratory experiments have examined compost, buffalo manure and green manures as organic amendments for these soils during flooding. Reduction resulting from flooding caused rapid increases in pH and elimination of aluminium toxicity. It also increased the buffering capacity of the soils, for example against marked decreases in pH on addition of salt. Addition of organic matter contributes to pH and nutrient ion buffering. As rice is produced under rainfed conditions the soils are subjected to periods of oxidation on drying. Under these conditions, the addition of organic matter is essential to increase buffering capacities for pH and nutrient ions, and hence improve soil fertility. Other benefits of organic amendments such as provision of slowly available nutrients and improvement to soil structure would also apply. More effective use of fertilizers will be made after the soils have been enriched in organic matter, particularly under rainfed conditions.

THE sandy texture and inherent infertility of soils of Northeast Thailand have been recognised for at least forty years (Pendleton 1962). In comparison with soils used for rice in other parts of Thailand those of the Northeast were identified as the least fertile (Kawaguchi and Kyuma 1969). Correspondingly, yields of rice in the Northeast region are amongst the lowest in the country, although climatic factors may be partly responsible (Vityakon and Keerati-Kasikorn 1987). The soils of the lowland regions have been derived from alluvial deposits, and apart from the recent alluvium of the major rivers, the soil parent materials were highly weathered and coarse textured. During their formation the soils have been further weathered and may have been subjected to ferrolysis during alternating periods of saturation and drying (Brinkman 1977). The soils are therefore generally highly leached and weathered Ultisols and Alfisols with coarse textured surface horizons. Under native forest vegetation the organic matter content of the surface horizons may have been as high as 10% but this rapidly declined after clearing and cultivation (Vangnai et al. 1987).

The sandy soils of the regions are inherently infertile with low contents of total and available forms of

* Australian Centre for International Agricultural Research, GPO Box 1571, Canberra, ACT 2601, Australia.

nitrogen, phosphorus, and potassium for rice production. Sulfur and boron have also been shown to be deficient for dry season crops (Vityakon and Keerati-Kasikorn 1987). In addition, the soils are strongly acidic. Table 1 shows data obtained from lowland soils located in the command areas of small scale irrigation schemes in ten provinces of Northeast Thailand. Most of the surface soils are strongly acidic and exchangeable aluminium occupies significant fractions of the total cation exchange capacity (CEC). The sandy surface horizons are generally low in organic carbon and CEC. The consequences of the

Table 1. Chemical properties of some lowland soils of Northeast Thailand.

Location Province/village	Soil	Depth cm	pH in H_2O	E.C. mS/cm	Organic %	Exch. Al cmol/kg	CEC[a] cmol/kg	Clay %
Khon Kaen, Non, Sawan	Quartzipsamment	0–10	5.3	0.02	0.19	0.41	2.1	6
	Plinthustult	0–10	4.8	0.02	0.39	0.74	3.9	12
Ubon, Don Ngua	Plinthustult	0–10	5.1	0.01	0.17	0.18	2.3	8
	Plinthustult	66–90	5.0	0.01	0.17	3.20	4.2	27
Buriram, Si Lium Ya	Paleaquult	0–10	5.5	0.05	0.41	0.00	3.3	6
	Paleaquult	38–58	5.7	0.04	0.20	3.70	12.1	44
Chaiyaphum, Non Mao	Paleaqualf	0–10	5.4	0.04	1.25	0.01	11.1	27
	Paleaqualf	40–52	5.4	0.02	0.40	1.50	11.5	40
Surin, Piaram	Paleaquult	0–10	4.6	0.07	0.31	0.14	1.4	5
	Paleaquult, improved	0–10	5.0	0.02	0.70	0.02	4.4	11
	Paleaquult	45–55	5.1	0.02	0.13	0.30	6.1	26
Khorat, Chan Dum	Quartzipsamment	0–10	5.1	0.03	0.21	0.11	1.8	5
	Paleaquult	0–10	4.5	0.19	0.57	0.19	3.8	15
	Paleaquult (salinised)	0–10	5.4	1.55	0.21	0.00	1.4	3
	Paleaquult	55–70	6.4	0.08	0.07	0.00	9.1	23
Nakhon Phanom, Kuruku	na[b]	0–10	5.2	0.01	1.06	0.55	5.9	16
	Paleaquult	0–10	4.1	0.10	0.72	1.60	3.9	16
	Paleaquult	60–68	4.6	0.11	0.21	3.50	10.9	43
Udon, Dong Sawan	na	0–10	5.4	0.13	1.27	0.01	10.6	24
	na	60–70	5.8	0.02	0.13	0.01	7.9	38
	na	0–10	6.4	0.05	0.75	0.00	12.0	36
Sisaket, Pho	na	0–6	4.5	0.06	0.53	0.57	2.4	18
	na	30–60	4.2	0.02	0.17	2.20	4.3	39
Sakon Nakhon, Thasongkhon	Paleaquult	0–10	4.7	0.01	0.33	0.13	1.4	2
	Paleaquult	35–52	5.5	0.02	0.10	0.41	8.9	26

[a] Compulsive exchange method of Gillman and Sumpter (1986).
[b] na – soil classification not available.

low CEC are that the soils have very little capacity to retain nutrient cations, the soils are very poorly buffered against changes in pH (Ragland and Boonpuckdee 1988) and they undergo marked seasonal fluctuations in pH (Topark-Ngarm et al. 1990).

The sandy texture and low buffering capacity is at least partly responsible for the low and variable responses of crops to applications of conventional fertilizers (Ragland and Boonpuckdee 1987).

In these sandy soils normal approaches in raising yields by inorganic fertilizer additions have failed without additions of organic amendments (Ragland and Boonpuckdee 1988). The addition of organic matter in combination with inorganic NPK fertilizer results in strong positive interactions between the organic and inorganic amendments (TATKRP 1986; Willett and Intrawech 1988). One trial with bunded rice grown on a sandy Typic Paleaquult (TATKRP 1986) produced the yield results shown in Table 2.

Table 2. Rice yields from different treatments on sandy Typic Paleaquult.

Treatment	Rice yield (kg/ha)
(a) Control	1775
(b) 156 kg/ha 16-16-8 + 95 kg/ha ammonium sulfate	1888
(c) 18.8 t/ha compost	1650
(b) + (c)	2519

Role of organic matter in controlling cation exchange properties

The importance of organic matter in contributing to the CEC of sandy soils is shown in Figure 1 for the group of soils shown in Table 1. The CEC was determined at soil pH and low ionic strength by the method of Gillman and Sumpter (1986). Clay content, organic carbon (OC, Walkley-Black) and soil pH all strongly influenced CEC. The data can be summarised by the following multiple regression which accounted for 95.5% of the variance:

$$CEC = -10.5 + 0.18\ clay + 4.1\ OC + 2.0\ pH$$

The effects of clay on CEC were considerably smaller than those of organic carbon (both expressed as %), and in practical agriculture it is clear that manipulation of soil organic matter, and to a lesser extent pH, offers much greater opportunities to raise CEC than attempts to raise clay contents by applying and mixing large quantities of finer textured soil.

In sandy soils it appears that organic matter has an essential role in providing adequate cation exchange and buffering capacity, as well as the more commonly stated roles of providing a source of slowly available nutrients or its contribution to soil structure.

Effects of adding organic matter on chemical properties of sandy paddy soils during saturation

Flooding soils for rice production brings about chemical changes because of reduction, which strongly influences the fertility of soils for lowland rice production. The effects of adding organic matter

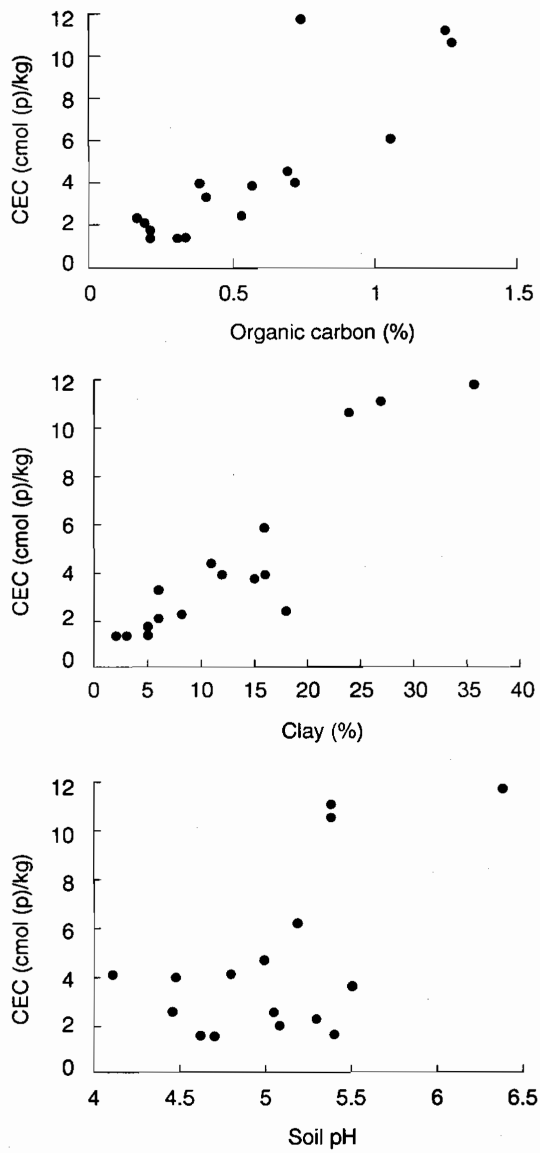

Figure 1. Effects of soil properties on cation exchange capacity of 16 surface soils from NE Thailand.

(compost and *Sesbania rostrata* as a green manure) on the reduction processes in sandy paddy soils have been determined in laboratory experiments to assess their effects on soil chemical properties and their contribution to buffering capacity. The effects of flooding, with and without compost (15.4 g/kg of soil), on the reduction of two sandy paddy soils (Willett and Intrawech 1988) are shown by the analyses of soil solutions with time after initial flooding (Fig. 2). Flooding caused rapid decreases in redox potential (Eh). Such rapid decreases in Eh in soils of low organic C content show that the soils are weakly buffered against changes in Eh and these are probably related to low levels of free oxides of iron and manganese (Takai et al. 1957). There was no effect of compost on Eh suggesting that the material did not contain readily oxidisable materials.

The soil solution pH values were relatively stable between the range of 6.0 to 6.5. This contrasts with the pH values of the air-dried soil which were 4.7 and 5.3 for soils Tt and Ki. Only two days of flooding were required to raise pH well above values associated with aluminium toxicity. Such marked and rapid changes in pH on flooding indicate very low pH buffering. Ragland et al. (1987) also reported rapid rises in pH on saturation, and observed a corresponding rapid decline in the levels of extractable aluminium. There was little effect of compost on soil solution pH (Fig. 2), but soil pH was slightly increased (Willett and Intrawech 1988). Ragland et al. (1987) observed that air-dried buffalo manure increased the pH of similar sandy soils. The effectiveness of the manure in raising soil pH was about 2.5% of the effect of calcium hydroxide.

Concentrations of Fe^{2+} rose rapidly during saturation and accumulated to relatively high values. This may be related to the lack of exchange sites for Fe^{2+} liberated into solution by the reductive dissolution of iron (III) hydroxyoxides. However, there has been no evidence of iron toxicity in these soils. Compost did not affect Fe^{2+} concentrations which also suggests that it did not contribute readily oxidisable material.

Soil solution P concentrations increased after 16 days of flooding of soil Ki and after 30 days of flooding Tt. The release of P by reductive dissolution in flooded soils is often delayed until significant dissolution of iron(III) hydroxyoxides (Willett 1991). There was no effect of compost on soil solution P but extractable forms of P were increased by similar compost and *Sesbania rostrata* green manure. The P concentrations recorded are much higher than normally found in flooded soils and are high in relation to the external P requirement of rice of 0.12 mg/L (Roy and De Datta 1985). The P concentrations decreased on prolonged flooding, possibly by re-adsorption. High soil solution P concentrations in soils known to be deficient in P for crop growth reflect that the soils have little capacity to buffer the P concentration. Once P in the solution has been absorbed by roots there is very little capacity for the solid phase to replenish the solution.

After 43 days of flooding NaCl (100 g / kg of soil) was added to the surface of the flooded soils. The

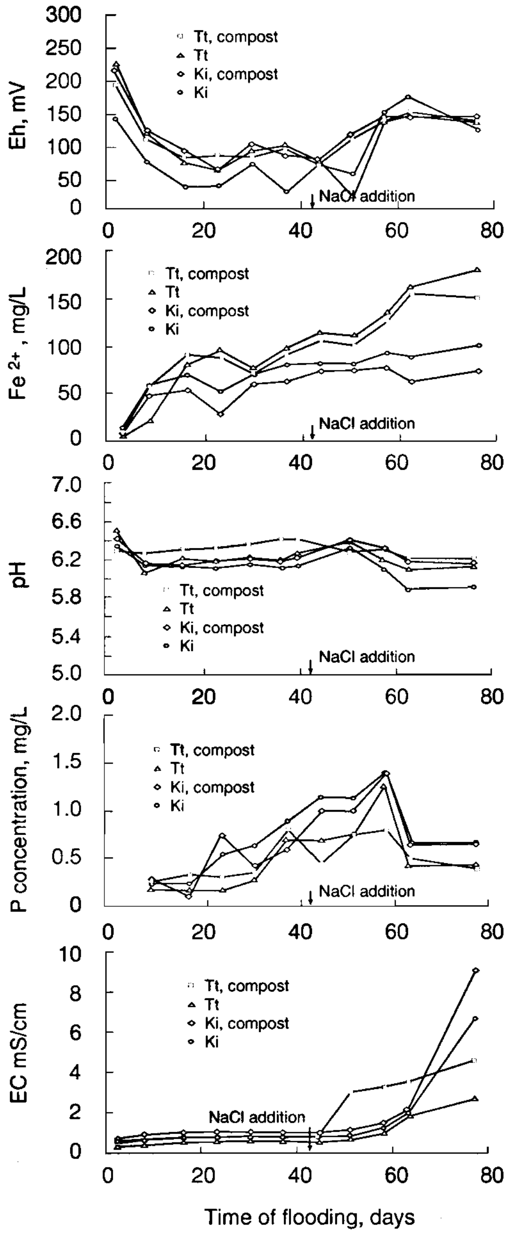

Figure 2. Effects of compost addition on chemical changes of two sandy paddy soils during flooding.

movement of the salt to the depth of the soil solution sampler can be observed from the EC values. It may be seen that there was very little effect of salt on soil solution pH. This contrasts sharply with the effects of adding salt to moist (oxidised) soils. Figure 3 shows a comparison of the effect of salt on soil pH (soil Tt) under flooded and moist conditions (the data are for soil pH rather than solution pH, and EC values were converted to saturation extract values to allow comparisons). It may be seen that salt had relatively little effect on pH under flooded conditions compared to oxidised conditions. Under flooded conditions compost reduced the effect of salt on pH. Both reduction by flooding and compost addition appear to reduce the effects of salt on pH, reflecting their contributions to buffering capacity.

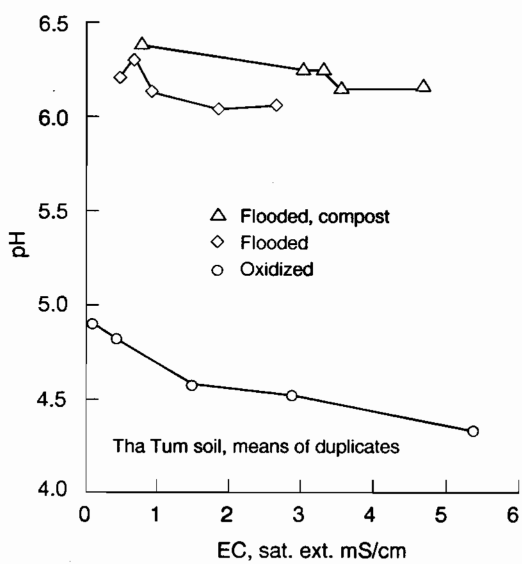

Figure 3. Relationship between soil pH and electrical conductivity of saturation extract under flooded and oxidised conditions.

Analogous decreases in pH, and associated increased aluminium toxicity, may result from the addition of inorganic salts in the form of conventional fertilizers to these soils, and this may be a factor in the poor responses of some crops to fertilizers. Conversely, the addition of fertilizer to soils that have been kept saturated for a few days, or have been amended by compost, or other organic matter, may be better protected from the displacement of aluminium in to the soil solution. Saturation or organic matter amendment may also protect against severe acidification of the rice rhizosphere during uptake of ammonium from nitrogen fertilizers (Ragland and Boonpuckdee 1988).

Concluding Comments

The experience with sandy paddy soils briefly described here, is that organic matter is essential to maintain adequate cation exchange capacity. This in turn is related to providing the soils with buffering capacity against changes in pH caused by changes in oxidation–reduction, accumulation of salts (from saline subsoil or application of mineral fertilizers), and the release of protons during uptake of ammonium ions by roots. The importance of organic matter in this role is greater for sandy soils under oxidised conditions than when they are reduced, and this is significant under rainfed conditions in which bunded rice crops are often subjected to drying during periods of low rainfall. Other benefits of organic matter associated with management of nutrients or soil structure may of course accrue, but the single most important factor is the provision of soil organic matter as a source of buffering capacity. The results also indicate that more efficient use of fertilizers can be obtained by applying them to continuously flooded soils. In rainfed conditions where continuous flooding cannot be maintained additions of organic materials are essential for effective utilisation of nutrients.

Acknowledgments

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The Fate of Organic Matter and Nutrients in Lowland Rice Systems

L.J. Wade and J.K. Ladha*

Abstract

For each of the principal lowland rice ecosystems, prospects for addition of organic residues were examined, and the likely impact on soil organic matter, nutrient availability and nutrient cycling are considered. Addition of organic residues is important for long-term system sustainability in all ecosystems, in order to maintain soil organic matter, soil structure, and soil fertility. Under rainfed conditions, where reduced and oxidised conditions occur with alternate flooding and drying, addition of organic matter would be especially important, to provide adequate cation exchange capacity, improved buffering capacity for nutrient retention, and better soil structure. In Northeast Thailand, where rainfed rice is grown on coarse-textured soils of low CEC, addition of organic residues would be essential to protect nutrient cations from leaching loss. Nevertheless, there is little evidence that addition of organic residues has been able to impact positively on soil organic matter, organic carbon and total nitrogen in these extreme conditions. Manipulation of residue quality and the input of C and N to the system may allow the rate of turnover and nutrient release from different organic matter fractions to be altered, offering the prospect of significantly improving the chemical, physical and biological fertility of soil in the medium to long-term. Alternatively, application of slow release fertilizer to the rice crop and incorporation of rice straw may result in similar increases in water and nutrient use efficiency. Carefully-planned, well-conducted and integrative long-term experiments would be necessary to examine such prospects, in conjunction with simulation modelling. Nevertheless, farmer adoption of green manures remains low.

RAINFED lowland rice encounters an environment more complex than for any other rainfed crop. Because rainfed lowland rice is grown in bunded fields without water control, hydrologic conditions may fluctuate from submergence to drought, with major consequences for root growth, nutrient availability and weed competition (Garrity et al. 1986). Various systems of crop establishment are employed, from direct dry-seeding to transplanting, and seedling vigour, weed competitiveness and capacity to withstand stress are influenced by the choice. Most surveys of constraints to rainfed lowland rice production indicate that drought, weeds, submergence, soil fertility, crop establishment, soil physical characteristics and socioeconomics are the major problems. The ultimate challenge is the combination of seasonal variability, spatial heterogeneity, agrohydrologic complexity, and their interactions with genotype and management.

In contrast, irrigated lowland rice encounters a more stable environment, where control of water minimises the prospect of flood or drought, and where the consistent soil saturation reduces weed problems and minimises changes in pH and nutrient availability associated with flooding and drying. Access to irrigation also increases the flexibility of the cropping system, permitting the ready adoption of legumes in the rotation. Under rainfed systems, growth of a legume or green manure must utilise resources not able to be captured by the rice crop, or alternatively, whose loss to the rice crop has minimal adverse consequences for its performance and stability. Thus, the crop rotation adopted, and the amount of organic residue which may be added to the soil, are ultimately dependent on the agrohydrology of each location.

* IRRI, P.O. Box 933, 1099 Manila, Philippines.

This paper considers prospects for cycling of nitrogen and addition of organic residues in the principal lowland rice ecosystems, before examining the impact of residue addition on soil organic matter, nutrient availability and nutrient cycling. The paper concludes by identifying limitations to adoption of the techniques and topics for further research.

Nitrogen Dynamics and Budgets in Lowland Rice Systems

Lowland rice systems may be grouped into three categories, according to the duration of the non-flood period: continuous-rice with permanent flooding, double-rice with a short non-flood period, and single-rice with a long non-flood period. This grouping recognises the predominant response of nitrogen dynamics to wetting and drying cycles. Essentially, there is a net gain in soil nitrogen under anaerobic conditions (Ladha et al. 1993), but there may be major losses during transition periods, when nitrification under aerobic conditions may lead to losses due to denitrification and leaching (George et al. 1992; Ladha et al. 1995). Linn and Doran (1984) demonstrated that the changeover from nitrification to denitrification occurred at about sixty percent water-filled pore space in rice cropping systems.

For continuous-rice with permanent flooding, Ladha and Ventura (unpublished) have demonstrated a net gain in nitrogen balance over 16 consecutive crops, regardless of whether a legume or inorganic nitrogen were included in the rotation. In contrast, for rice systems with a non-flood period, George et al. (1992) showed that while nitrogen was accumulated during the dry season, much was lost due to leaching of nitrate with the early rains. These authors proposed the use of a catch crop to mop up mineral nitrogen early in the season, and if a legume was used, perhaps to contribute biologically fixed nitrogen as well (George et al. 1984). A leguminous catch crop resulted in a positive nitrogen balance, while weedy or weed-free fallow resulted in a negative balance (Ladha et al. 1995). When a long non-flood period occurs, especially with frequent wet/dry transitions, losses of nitrogen may be substantial. Consequently, permanently flooded systems should be sustainable for nitrogen, whilst rainfed systems require careful management to ensure capture of readily-leached mineral nitrogen and maintenance of soil organic matter levels.

Irrigated and Favourable Rainfed Lowland Rice Ecosystems

Chaudhary et al. (1994) reviewed prospects for addition of organic matter to various rice ecosystems. In the irrigated rice wheat areas of northwest India, Pakistan and Nepal, a legume may be grown for grain and green manure, following harvest of the wheat. In regions where the onset of the rainy season is gradual and the duration is relatively prolonged (West Bengal, Bangladesh, Philippines), the initial seasonal rains may be sufficient to support a green manure, prior to direct-seeded rice. In areas suited to two sequential rice crops, a pre-rice green manure may be grown where the monsoon pattern is appropriate, and a grain legume or oilseed may be relay-sown pre-harvest into the first rice crop for incorporation during land preparation for the second (Garrity and Flinn 1988).

In the Cuulong Delta of Vietnam, investment in flood control, drainage and irrigation is leading to an intensification of the cropping system (Phung and Laut, these Proceedings). Planting of a single rainfed crop of a low-yielding traditional variety is being replaced by two to three crops per year of a high-yielding irrigated variety. The switch is accompanied by an increase in use of N:P fertilizer, from 30:30 in the rainfed system to 120:30 and 180:30 for irrigated wet and dry season crops, respectively. Some decline in yield trend may be occurring in this intensive system, but the decline is difficult to quantify in the absence of longer-term experiments.

In India, a number of longer-term experiments are examining the role of organic matter in rice–wheat systems. Bijay Singh (these Proceedings) reported a declining trend in soil organic matter, and implicated nutrient removal in grain and burning of crop stubbles as two major contributors to the decline. An integrated approach, comprising the incorporation of stubble together with green manure and chemical fertilizer, led to a buildup of soil organic matter and sustainable high yields. This was in accord with other recent evidence (Becker et al. 1994 a,b).

Likewise in Bangladesh, an integrated approach of using cowdung and ash with inorganic nutrients sustained soil fertility and increased soil organic matter and yield of rice (Bhuiyan et al. these Proceedings). Incorporation of a leguminous green manure could provide about 70 kg N/ha, providing a substantial yearly saving on the cost of N fertilizer for this Boro-fallow–T. Aman rice double cropping system. These authors, however, drew attention to conflict in demands for inputs. For example, rice straw is normally used to feed cattle or for roofing, rather than incorporated.

Whilst growth of a legume or green manure is possible in these irrigated and favourable rainfed lowland rice ecosystems, nutrients removed in grain must be replenished. Further nutrient losses occur if crop residue is burnt or removed, rather than incorporated. Thus, chemical fertilizers must generally be applied together with organic amendments in order to sustain productivity in these intensive systems.

Unfavourable Rainfed Lowland Rice Ecosystems

Under rainfed systems, growth of a legume or green manure must utilise resources not able to be captured by the rice crop, or alternatively, whose loss to the rice crop has minimal adverse consequences for rice performance and stability. Reduced growing season duration or a period of flooding during the season may also restrict opportunities for crops other than rice. In the submergence-prone rainfed lowlands of eastern India (Madhya Pradesh, Orissa and Bihar), Chaudhary et al. (1994) considered intercropped green manure offered the greatest prospect for the beusani system. Because of the likelihood of loss of mineralised N to leaching at the commencement of the wet season, George et al. (1992) suggested that a crop needed to be established with the early rains. Use of a green manure legume was preferred, so some biological N fixation could follow any initial capture of mineral N. Where conditions permitted, both pre- and post-rice green manure crops have been examined, the former grown on the early rains prior to rice establishment, and the latter grown on residual moisture following harvest of the rice crop.

Soils of Northeast Thailand and Laos are coarse-textured, strongly acidic, permeable, and low in fertility, organic matter and CEC. Exchangeable aluminium forms a significant proportion of the CEC, soils are poorly buffered against changes in pH and there is little capacity to retain nutrient cations (Willett these Proceedings). In the drought-prone rainfed lowlands of Laos, P deficiency must often be corrected first, before worthwhile responses to other nutrients are obtained (Lathvilayvong et al. these Proceedings). Unfortunately, farmyard manure is applied only to seedbeds, and little fertilizer is used by farmers. *Sesbania rostrata* has performed consistently as a pre-rice green manure when P was applied, contributing 5–12 t/ha of biomass in 50–55 days, providing for 60–90 kg/ha uptake of N by the following rice crop. Absence of extension services, problems of seed and fertilizer supply, lack of infrastructure, unavailability of credit, and low income are cited as impediments to adoption of improved methods.

Fertilization strategies for *Sesbania rostrata*/ rainfed lowland rice cropping systems have been examined at six sites in Northeast Thailand from 1987 to 1991 (Herrera et al. 1994). The importance of seasonal variability, spatial heterogeneity and agrohydrologic complexity in these rainfed environments was demonstrated by 48% of the total variance for rice yield being attributable to the interaction between site and year (Garrity and Wade, unpublished). Other predominant sources were Sesbania treatment × site (12%), rice treatment × site × year (13%) and error (23%). Seasonal conditions affected agrohydrology of each site in each year, with major consequences for planting, emergence, survival, and growth of Sesbania. Application of FYM or P substantially increased the growth of the green manure in each of the five years. In turn, the incorporation of Sesbania strongly affected subsequent growth and yield of the rice crop, subject to seasonal favourability later in the season. The rotations had little residual impact on soil organic matter, but the rice nevertheless derived some benefit within the season. In contrast, Bray-P was markedly influenced by P application.

Recent research has indicated that significant increases in yield may be possible on these soils using slow release fertilizer, relative to the use of normal fertilizer (Hampichitvitaya et al. 1995). Presumably, the slow release characteristic mimics the effect of applying normal fertilizer and organic residues together. Whether these responses are due to rate of nutrient release, capacity to retain nutrient cations, or enhanced soil water retention and extraction is not known. Current research is examining changes in root growth in response to slow release fertilizer and subsoil compaction (Hampichitvitaya et al. 1995). Since these soils are so deficient in nutrients and organic matter, the prospect may arise that greater responses may be possible in the long term if the fertility status could be substantially raised. This leads to a question of the relative importance of drought, nutrients and other factors in such environments.

When organic residues were applied to rainfed lowland rice in Northeast Thailand, Wonprasaid et al. (these Proceedings) considered that the increase in rice yield may be due in part to better soil water relations. Yield of rice increased with the application of inorganic nutrients only when applied together with legume residues. Whilst incorporation of green manure has increased yield of rainfed lowland rice in Northeast Thailand, there has been no evidence of any long-term improvement in soil fertility or in the level of soil organic matter. These authors obtained pot and field evidence that management of residue breakdown by choice of species, method of incorporation and application of fertilizer may have significant effects on short-, medium- and perhaps long-term nutrient availability. Specifically, a high C:N ratio may be necessary to slow the rates of residue breakdown and nutrient release. This delay may reduce nutrient loss, and better synchronise nutrient availability and crop demand (Becker et al. 1994 a,b). Wonprasaid et al. (these Proceedings) hypothesised that, by altering residue quality and C and N inputs to the system, it should be possible to change the rates of residue breakdown, release of nutrients, the amounts of soil organic matter in different fractions, and the general chemical, physical and biological fertility of the soil in the longer term.

Willett (these Proceedings) examined the role of organic matter in controlling chemical properties and fertility of sandy soils in Northeast Thailand. Manipulation of organic matter, and to a lesser extent pH, offered the greatest prospect for raising the CEC of these strongly acidic, low CEC, infertile soils. Addition of organic matter was considered essential for providing adequate cation exchange, improved buffering capacity to retain nutrients, and better soil structure. In rainfed conditions, where reduced and oxidised conditions occur with alternate flooding and drying, addition of organic matter would be especially important to protect nutrient cations from leaching loss.

Becker et al. (1995) examined situations in which green manure was more likely to effectively contribute to the cropping system. On light soils, legumes accumulated more N and had greater fertilizer equivalence. Similarly, green manures provided a more stable supply of N on light soils, by reducing rates of nutrient release and leaching loss, relative to inorganic fertilizers. As a result, nitrogen use efficiency was similar for irrigated and rainfed situations for organic residues, but declined sharply for inorganic fertilizers under rainfed conditions. Consequently, organic residues are preferred for unfavourable environments, as long as seasonal conditions permit sufficient growth of the green manure prior to incorporation, the rice may be properly established prior to any seasonal submergence, and adequate water is available for growth of the rice crop. Problems in using green manures, however, include availability of seed, labour requirement and cost of residue incorporation, capacity to produce adequate biomass in unpredictable rainfed environments, and shift in fertility if material is brought in from adjacent fields. For green manures to be adopted, Fujisaka (1993) concluded that labour costs must be low, inorganic fertilizer costs must be high, nitrogen must be limiting, opportunity costs for land must be low, seed must be available, and productivity must be stable. These constraints may be reduced if naturally regenerating annual legumes could be identified and encouraged to grow at the commencement of the wet season (P.F. White, IRRI Cambodia, pers comm.).

Because prospects for increasing soil organic matter are poor on the coarse-textured soils and resources for growing a green manure crop are limited, an alternative approach would be to concentrate on the rice crop itself. Effort would focus on maximising rice growth by applying fertilizer directly to the rice and incorporating the rice stubble (H.J. Nesbitt, IRRI Cambodia, pers comm.). This approach, with less reliance on increasing soil organic matter, should involve slow release fertilizer (Harnpichitvitaya et al. 1995), perhaps in conjunction with rice lines selected for an enhanced capacity to extract nutrients and water from the soil profile (Wade et al. 1994). Systematic studies are required to examine all of these approaches.

Conclusions

Clearly, there is a need for addition of organic residues to sandy soils in the rainfed lowlands, to increase buffering capacity, nutrient utilisation, soil structure, soil water holding capacity and system sustainability. Phosphorus is needed to facilitate the growth of legumes, and often yield response of rice is only obtained when chemical fertilizer and organic residue are applied together. Whilst the need for green manures and organic residues is more critical on sandy soils of the rainfed lowlands, prospects for success are also greater there. Nevertheless, there is little evidence that addition of organic residues has been able to impact positively on soil organic matter, organic carbon and total nitrogen. Manipulation of residue quality and the input of C and N to the system may allow the rate of turnover and nutrient release from different organic matter fractions to be altered, offering the prospect of significantly improving the chemical, physical and biological fertility of soil in the medium- to long-term. Alternatively, application of slow release fertilizer to the rice crop and incorporation of rice straw may result in similar increases in water and nutrient use efficency. Carefully planned, well conducted and integrative long-term experiments would be necessary to examine such prospect, in conjunction with simulation modelling. Nevertheless, farmer adoption of green manures remains low.

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Development of an In-vitro Perfusion Method to Estimate Residue Breakdown Rates

Y. Konboon and R.D.B. Lefroy*

Abstract

A procedure is required to screen leaf litter and crop residues to estimate breakdown rates and to examine the effects of chemical treatment or soil biota on decomposition rates. An apparatus has been developed at the University of New England (UNE), Australia, which utilises a hospital drip bag and administration set and this is compared with a more elaborate glass device.

The C release rate and total C release from barrel medic (*Medicago truncatula*) hay was found to be the same over 42 days. The low cost and ease of operation of the UNE in-vitro perfusion apparatus allows sufficient sets to be used to allow statistically valid comparisons to be made between residues or between treatments.

ORGANIC matter is a major determinant of both physical and chemical fertility of soil, and it is important for the maintenance of an active soil biota. Through the breakdown of organic matter by micro-organisms, plant nutrients are supplied directly to plants and to other micro-organisms, and substances are produced which help bind soil particles together to give a stable structure. This is in addition to the direct effects of the many organisms such as fungi, which assist aeration and aggregation.

The processes of organic matter decay are largely controlled by soil micro-organisms and are therefore influenced by temperature, moisture, pH and soil aeration. The type of organic matter also affects the breakdown rate. Plant material low in lignin and other polyphenols, and high in nitrogen and soluble carbohydrates, decomposes relatively quickly. Thus the rate of initial breakdown varies between immature and mature tissue as well as between species.

Considering the above, it is not surprising that the organic-matter content of soils declines rapidly after tropical forests are cleared for agricultural production, and that there is increasing interest in using plant residues and other organic materials for improving soil productivity in agricultural systems in the tropics. To develop the effective use and management of residues, a detailed understanding of decomposition rate and nutrient release is needed, and this requires techniques that can be used to monitor changes in decomposition and nutrient release of residues. A technique is reported here which studies the breakdown rate and nutrient release from plant residues.

The perfusion technique has been used after modification from the apparatus of Nyamai (1992). By using this apparatus, the decomposition rates of plant residues can be evaluated by CO_2 evolution. To verify the results from the perfusion study, a pot trial was conducted. The objective of the study was to compare results of organic matter breakdown from the in-vitro apparatus of Nyamai (1992) with a low cost alternative developed at University of New England (UNE) Armidale, Australia.

Materials and Methods

The UNE perfusion apparatus and its components

The perfusion apparatus used in this experiment is shown in Figure 1a. The main components of the apparatus are sample compartment, solution sampling tap, reservoir for collecting and mixing the perfusion solution before recirculation, perfusion solution bag, and CO_2 free air to carry CO_2 evolved from decomposition to the CO_2 trap. Each part of the apparatus is shown in Figure 1b and described below;

* Department of Agronomy and Soil Science, University of New England, Armidale, NSW 2351, Australia.

a) $CaCl_2$ solution bag (part A) : 500 mL viaflex container with female luer adaptor, manufactured by Baxter Healthcare Pty Ltd was used as the bag.
b) Solution administration set (part B) : solution administration set with luer slip adaptor, manufactured by Baxter Healthcare Pty Ltd was used to connect the $CaCl_2$ bag and the sample compartment. This allows $CaCl_2$ from the bag to flow through the plant material in the sample compartment. The rate of flow is adjusted by the attached luer slip adaptor. Plastic tube (0.4 cm diameter) cut to the required length is used as an air inlet tube (part J), air outlet tube (part I), and $CaCl_2$ recirculation tube (part H).
c) Sample compartment section : this consists of two lids (part C1 and C2), spring (C3), nylon mesh (part C4 and C5), sample compartment (C6) and outer part of sample compartment (C7). Three holes (0.4 cm diameter) were drilled in lid C1 and 2 holes in lid C2, and the two lids glued together (ensuring that two holes from each lid were aligned). Air inlet tube (J) and solution administration set (B) were glued into the aligned holes of lids C1 and C2. The air outlet tube (I) was glued into the third hole of lid C1.

The sample compartment (C6) is made from a 100 mL screw cap polycarbonate sample jar (70 × 45 mm size). Several holes, 0.25 cm diameter, were drilled in the bottom of this compartment to allow $CaCl_2$ solution to pass through. The plant material to be studied was placed between two layers of 0.4mm nylon mesh in the sample compartment with a spring (C3) between the upper nylon mesh and the lid. The compartment was screwed firmly into lid C2.

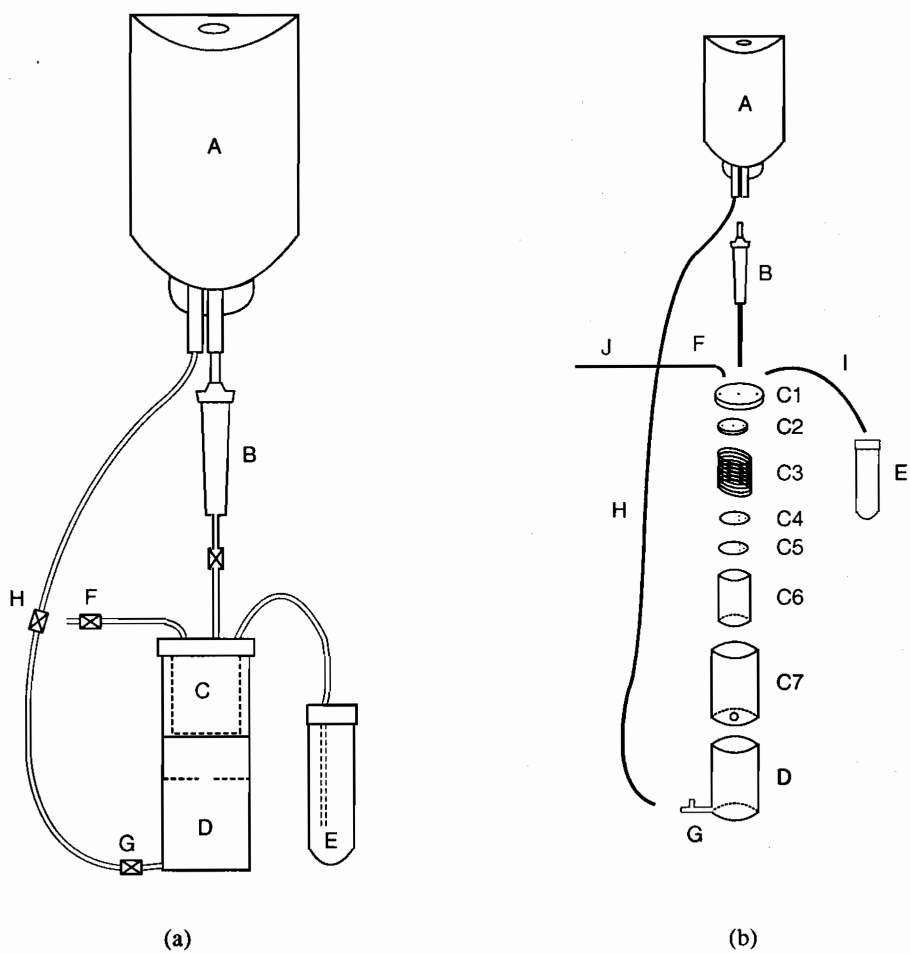

Figure 1. (a) The UNE perfusion apparatus, and (b) further details of components. See text for further explanation.

The outer part of sample compartment (C7) was made from a 250 mL screw cap polycarbonate sample jar (100 × 65 mm size). A 1 cm diameter hole was drilled at the bottom of the jar to allow $CaCl_2$ solution to pass through to the lower reservoir. This outer part was then screwed firmly into lid C and fitted tightly into the lower reservoir (D).

d) Reservoir (part D) : a reservoir was made from the same container as the outer part of sample compartment (C7). A hole was drilled at the bottom of the container and connected with the $CaCl_2$ sampling tap—part G (a 3 way stop-cock luer fitting manufactured by Indoplas Pty Ltd was used). The other end of the tap was connected to the solution recirculation tube (H) and this tube connected with the plastic tube from the solution bag. This connected tube allows $CaCl_2$ to recirculate from the reservoir back to the solution bag.

e) CO_2 trap vial (E) : 50 mL centrifuge tube with lid was used. Two holes were drilled in the lid, The air outlet tube (I) was inserted in one hole and the other hole used for ventilation.

f) Scrubbing agent (F) : fish tank air pump was used as an air supply. CO_2-free air was produced by pumping air through sodalime to trap CO_2 before it flowed through the system. The CO_2-free air flowed through the main air line and then passed through the air inlet tube of each apparatus. A tap was fitted to each air inlet tube to enable control of air flow into each compartment.

All joints of the assembled apparatus (Fig. 1a) were sealed with silicone to ensure there were no leaks.

Nyamai perfusion apparatus and its components

The main components of Nyamai perfusion apparatus are a sample compartment, solution sampling device, reservoir for collecting and mixing perfusion solution before circulation and an adequate air-flow rate to provide enough suction pressure for recirculation of the $CaCl_2$ solution (Fig. 2).

Experimental design and treatments

The UNE and Nyamai perfusion apparatus were compared in a study of the breakdown rate of barrel medic (*M. truncatula*) hay. Treatments were arranged as a Randomised Complete Block Design (RCBD). The UNE apparatus was replicated 3 times while the Nyamai apparatus was not replicated due to a shortage of apparatus. A control treatment, where no residue was present in the sample compartment was also included to measure CO_2 in the air introduced into the system.

The residues were cut into small pieces and oven-dried at 80 C for approximately 24 hours. A 2.1 g sample of medic hay was put into the sample compartment of each apparatus between nylon mesh discs to prevent the loss of residue from the compartment.

In the UNE apparatus, pressure was maintained on the sample in the sample compartment by a stainless steel spring to maintain even movement of $CaCl_2$ through the sample (Fig. 2).

Management of the UNE perfusion apparatus

The perfusion solution bag was filled with 200 mL of 0.005 M $CaCl_2$ solution, a concentration aimed to simulate a soil solution. Each day, the 200 mL of $CaCl_2$ solution flowed through the sample, by gravity, at a rate of approximately 1 drop/10 seconds. The

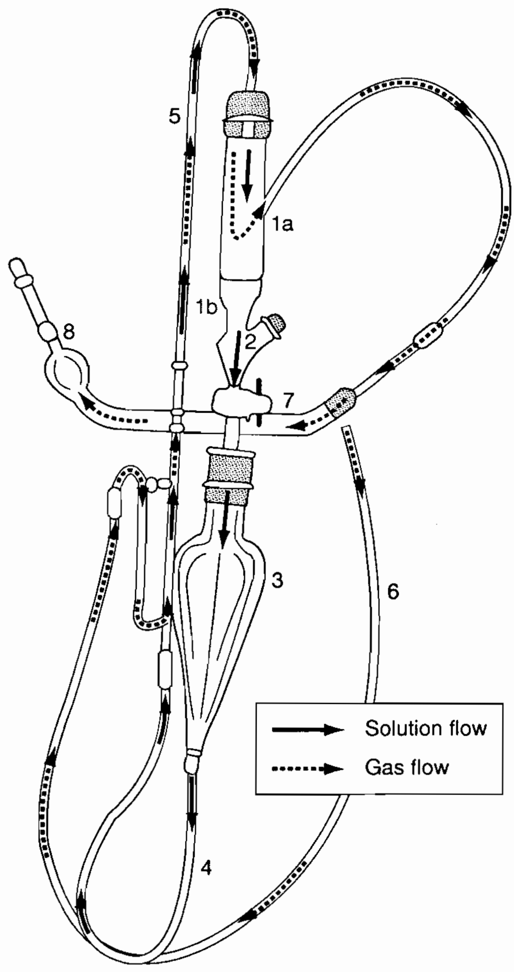

Figure 2. Nyamai in-vitro perfusion system (Nyamai 1992). 1a, sample column; 1b, suction device; 2, solution sampling unit; 3, reservoir; 4, PVC tube for solution recirculation; 5, glass tube for solution recirculation; 6, scrubbed air tube (CO_2-free air); 7, CO_2 absorption solution; 8, glass tube containing sodalime.

solution was collected in the reservoir before being recirculated manually back to the perfusion solution bag to begin the next cycle. This was achieved by lowering the $CaCl_2$ bag to below the level of the reservoir. CO_2-free air was pumped through each apparatus to enable measurement of the amounts of CO_2 produced by microbial respiration. The rate of flow was standardised in each apparatus by counting the air bubbles in the CO_2 traps and checked daily for leaks, reduction of pressure or blockage.

The management of the Nyamai perfusion apparatus

The reservoir was filled with 200 mL of $CaCl_2$. The $CaCl_2$ solution in the reservoir was carried by air pressure to flow through the plant material in the sample compartment continuously with a flow rate of 5 mL/hour. The $CaCl_2$ was then collected and mixed in the reservoir (Fig. 2).

CO_2 measurement and data analysis

CO_2 evolution during the first 14 days, vials containing about 35 mL of 0.5 M. KOH were used to trap evolved CO_2 and these vials were replaced daily. After this period, the rate of CO_2 evolution decreased and the amount and concentration of KOH were reduced to 30 mL of 0.25 M and replaced every 2–3 days. The trapped CO_2 was measured by adding 15 mL of 10% w/v $BaCl_2$ to the KOH to precipitate $BaCO_3$. The remaining KOH was then back titrated against 0.5 M. HCl to the phenolphthalein end-point to neutralise KOH. Finally, more HCl was added to the methyl orange end-point to dissolve $BaCO_3$. The amount of CO_2 was calculated by using the formula;

$$\text{mg evolved } CO_2 \text{ / day} = \frac{(T2 - T1) \times M \times 22}{t}$$

where: $T1$ = amount of HCl used to neutralise KOH
$T2 = T1$ + amount of HCl used to dissolve precipitated $BaCO_3$
M = Molarity of HCl
22 = 22 mg CO_2/1mL 1M HCl
t = time in days

The CO_2 in the control treatment was subtracted from the calculated value for CO_2 release.

The experiment was run for 6 weeks in a 25°C controlled temperature laboratory at the Department of Agronomy and Soil Science, University of New England. Statistical analysis was undertaken by calculating the standard deviation of the mean of the 3 replicates of the UNE system and comparing the Nyamai data with this value.

Results and Discussion

There was no significant difference in the rate or total amount of C released from the residues between the UNE and Nyamai perfusion methods. After 42 days, an average of 49.8% of C had been released from the medic hay (Table 1 and Fig. 3). In the study of Nyamai (1992) the half time for breakdown of Leucaena was found to be 19 days and this compared to field a observation of 25 days.

Table 1. Carbon released from medic hay (*M. truncatula*) as determined by the UNE and Nyamai perfusion apparatus.

Perfusion system	C released (mg)	C released(%)
UNE	450.3 ± 37.2	49.7 ± 3.9
Nyamai	459.7	49.8

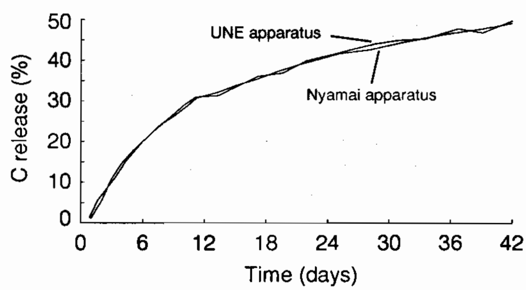

Figure 3. C release from medic hay (*M. truncatula*) as determined by the UNE and Nyamai apparatus.

The close agreement between the two methods means that either can be used to study breakdown rates. The advantages of the UNE system are that it is easy and cheap to construct which means that sufficient units can be assembled to conduct statistically valid comparisons between residues or between treatments where modifications have been made to residues such as chemical treatment or inoculation with soil suspensions.

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Soil Organic Matter: Its Fractionation and Role in Soil Structure

A.M. Whitbread*

Abstract

An understanding of the form and function of SOM in soil is essential to sustainable crop production. Various methods of SOM fractionation are used to study SOM forms and to gain an understanding of interaction between SOM and aggregate formation. Physical SOM fractionation techniques are based on the concept that SOM associated with particles of various sizes, differs in structure and function. This distribution of SOM has been studied by disrupting soil structure, commonly by sonication and shaking, followed by the separation of physical fractions on the basis of size or density. Problems associated with the use of these techniques include the redistribution of SOM into size separates in which it is not normally located, incomplete dispersion, fragmentation of macro-OM, and arbitrary size and density limits.

Physical SOM fractionation techniques have been useful in studying SOM structure and function, but their use for identifying organic binding agents, responsible for maintenance of soil structure, is limited.

Most soils rely on aggregation of particles to maintain favourable conditions for soil microbial and faunal activity and plant growth. Certain components of SOM such as polysaccharides, soil humic substances, root material and fungal hyphae have an important role in soil structural stabilisation. The measurement of labile carbon by oxidation with potassium permanganate and total carbon has shown a concentration of carbon in water stable aggregates. The stability of macroaggregates increased at higher levels of carbon, presumably due to organic bonding mechanisms. The effect of management upon SOM, specifically upon these labile components, and changes in soil structure are essential for the development of sustainable agricultural systems.

It is generally accepted that soil organic matter (SOM) has beneficial effects on soil biological, chemical and physical properties, which in turn influences the productive capacity of soils. It is also accepted that SOM is a major contributor of N, P and S as well as other nutrients to plants. Soil microbial activity is also dependent on SOM as a carbon source for metabolic activity which in turn influences nutrient fluxes and soil structure.

The SOM content of soil is generally found to decrease rapidly following the clearing of native vegetation for subsequent cultivation and cropping. Although total organic carbon of the soil declines due to cultivation, of particular concern is the decline in the more labile carbon fractions which are associated with soil nutrient dynamics, (Parton et. al. 1987) as well as having a role in the stabilisation of soil structure (Allison 1973).

The rate of organic carbon decline varies with management practices, soil type and climatic conditions. Bowman et al. (1990) investigated nutrient losses in soil cultivated for 0, 3, 20 and 60 years. Total C, N and P declined by 55–63% over 60 years, but more than half this decline occurred in the first three years of cropping. Chan et al. (1992) found a 31% difference in organic carbon levels between direct drill/stubble returned (2.42%) and conventional tillage/stubble burnt (1.68%). Janzen et. al. (1992) investigated the changes in the light fraction material (incompletely decomposed organic residues–labile organic matter) over three long-term rotation systems. The light fraction content was generally highest with continuous cropping or perennial forages and lowest in soils subject to summer fallows. Respiration rate, microbial N, and N mineralisation were found to be highly correlated with the light fraction content.

* Department of Agronomy and Soil Science, University of New England, Armidale, NSW 2351, Australia.

Numerous studies have linked organic carbon levels with aggregate stability, infiltration and soil strength, so a decrease in organic carbon is often associated with degrading soil physical conditions. Soil aggregation and aggregate stability are the main factors affecting the susceptibility of soil to raindrop impact and consequently surface sealing and soil erosion.

To develop more sustainable cropping systems, management systems which maintain and even improve soil organic matter levels need to be developed. An understanding of organic matter decomposition and its effects on nutrient and carbon balances and soil structure is essential in order to develop sustainable systems.

Soil organic matter fractionation

SOM is composed of a number of fractions ranging from very active (labile) to stable (non-labile). According to the ^{14}C dating techniques, the stable organic carbon fraction may have a turnover time as long as several thousand years (Campbell et al. 1967) while the active pool has a turnover time of less than a few decades (Hsieh 1992). The distribution of organic carbon and organic nitrogen among these pools is influenced by soil management factors such as crop rotation (Janzen 1987), tillage (Dalal and Mayer 1987; Santruckova et al. 1993) and fertilizer application (Christensen 1988).

Physical fractionation into various components based on size or density has long been used to study the dynamics of SOM. Methods which allow a quantitative isolation of size and density separates of SOM have been developed and will be discussed.

Common fractionation techniques

The term SOM encompasses organic residues in various stages of decay which are derived from plant, microbial and animal origin. SOM transformations depend on a complex interaction of the physical, chemical and biological processes within soils. A knowledge of these transformations is essential for an understanding of the structure, fertility and chemical reactivity of the soil and the impact of various management factors such as fertilizer, manure and residue additions. The chemical aspects of SOM and microbially mediated processes appear to be well understood (Christensen 1992) while physical soil fractionation and organo-mineral complexes have been studied less.

The interactions between SOM and soil minerals have been investigated predominantly by various dispersion and separation procedures. The realisation that simply shaking soil in water would not ensure complete disintegration of microaggregates, led to soil dispersion techniques which utilised various dispersion energies.

Methods of Disruption

Sonication

Sonication, either in or not in combination with chemical treatments, is the most common form of disruption. Sonication produces a vibrational energy to the soil suspension causing cavitation. The collapse of these bubbles produces shock waves which disrupt bonding agents (Gregorich et. al. 1988). The degree of dispersion relies not only on instrument specifications, but on actual experimental procedures and soil characteristics. A review of various experimental methods used showed sample weights ranging from 10–100 g, vibrational periods from 3–30 minutes and energy dissipation per mL of solution, ranging from 90–5350 J/mL (Christensen 1992). Therefore the degree of dispersion varies enormously between experiments making comparisons difficult. Procedures for its use are reviewed in Elliott and Cambardella (1991) and Christensen (1992).

Ultrasonic dispersion has been reported to have several possible undesirable effects on soil:

- breakdown of primary particles
- abrasion of clay minerals due to cavitational hotspots
- SOM detachment from organo-mineral complexes and redistribution
- release of microbial SOM components and redistribution
- slight increases in pH
- increases in SOM and element solubility.

Each of these problems have been discussed by Christensen (1992) who considered most of them to be relatively insignificant to the final result. The greatest problem with the use of sonication appears to be the redistribution of OM among size/density fractions. This depends on the energy output and duration of sonication both of which should be standardised.

Shaking

Shaking, end-over-end, rotary, high-speed mixers, wrist and reciprocal methods are gentler than sonication and a wide range of energies may be obtained (Elliott and Cambardella 1991). High-speed mixers may cause abrasion of primary particles (Thornburn and Shaw 1992) and simple shaking, even for long periods does not ensure adequate dispersion (Young and Spycher 1987). Shaking with resins may completely disperse soils, but reactions with SOM reduces their application (Watson 1970). Gregorich et. al. (1988) found that the C content of clay, silt and sand sized separates varied with the degree of soil dispersion and as a consequence, shaking is not recommended for isolation of primary organo-mineral complexes.

Chemical pretreatments

Sonication and shaking are sometimes used in combination with various chemical pretreatments to increase the dispersion of the soil. By using chemicals which selectively solubilise or oxidise OM, information may be obtained regarding the functional groups of the organic matter in soil. Other chemical agents such as acetylacetone (Churchman and Tate 1987), remove polyvalent metal cations which assist in the bonding of clays and OM. Sodium saturated exchange resins have also been used as dispersing agents (Elliott and Cambardella 1991). Chemically assisted dispersion procedures may introduce unintended, in-process changes in SOM and distribution and the use of chemicals in dispersion procedures should be avoided unless the effects of the chemical are specific and well documented (Christensen 1992).

Methods of Separation

Density fractionation

Density fractionation assumes that SOM can be separated into pools differing in structure and function. It has been used to separate the light fraction (LF) SOM isolated from whole soils by mild dispersion procedures as well as LF from size separates after thorough dispersion. The LF is considered to be decomposing plant and animal residues with a relatively high C:N ratio, a rapid turnover and a low specific density. The heavy fraction (HF) includes the organo-mineral complexed SOM which is more processed with a narrower C:N ratio and a slower turnover rate (Greenland and Ford 1964; Greenland 1965, 1971). Densities of ~ 2.0 and ~1.6 g/cm^3 are commonly used to separate light organo-mineral complexes and undecomposed plant debris, respectively (Elliott and Cambardella 1991). Liquids used for separation may be inorganic (NaI, ZnBr, CsCl, Na polytungstate) or organic (tetrabromomethane, tetrabromoethane) (Christensen 1992). There can be no critical density set to separate various fractions, but if each individual soil is examined, fractionating a range of organo-mineral complexes is possible (Oades 1988).

There have been many different procedures used to isolate LF material and Table 1 illustrates a small number of these procedures.

Sedimentation under gravity is based on Stoke's law and sedimentation dynamics are discussed in detail by Elonen (1971). Exceptions to the assumptions of Stoke's law, such as deviations from spherical shape and particle density, result in incorrect sedimentation times and collections. Various microscopic, microbiological and chemical analyses may be performed on these fractions. For each sedimentation size class, there may be primary, organo-mineral and undecomposed plant residues. As Balesdent et al. (1988) and Tiessen and Stewart (1983) reported, the so called 'clay or silt associated' OM can be a heterogenous pool of OM.

Soil fractionation techniques have allowed much information to be gained on the location and dynamics of SOM and the effects of landuse. In order to study the mechanisms involved in soil structure, the arrangement and functions of various bonding agents and the effects of management need to be known. Fractionation techniques which investigate these issues need to be developed. The fractionation techniques so far discussed do not appear appropriate for investigating soil structure dynamics.

The Role of SOM in Soil Structure

In order to investigate the role of som in soil structure, the processes by which soils maintain aggregation need to be identified. The work of Tisdall and Oades (1982) and Oades (1984) on soil binding agents has become the generally accepted theory of the bonding of many agricultural soils. They present a

Table 1. Procedures used for separating light fraction organic matter.

Reference	Dispersion methods and time (minutes)	Density (g/cm^3)	Solution
Greenland and Ford (1964)	US 3	2.0	Bromoform
Ladd et al. (1977)	US 2 & 3	1.6 & 2.1	Tetrachloromethane/Nemagon
Spycher (1989)	Stir 0.5	1.5	NaI/Water
Dalal and Mayer (1986)	Shake 60	2.0–2.4	Bromoform/Ethanol
Skjemstad et al. (1990)	Ground	1.6	ZnBr2/water
Dick et al. (1994)	LUDOX method		Silica

conceptual model for soil structure that describes the association of OM with the three types of physical units that exist in mineral grassland soil: free primary particles (sand, silt and clay), microaggregates and macroaggregates (>250µm). A summary of aggregrate hierachy and the associated bonding agent is presented in Table 2.

In their model, SOM is intimately associated with the binding of particles into aggregates, the stability of which rely on the binding agents involved. Tisdall and Oades (1980) classified the binding agents into: (i) transient, comprised of microbial and plant derived polysaccharides which may be rapidly decomposed by microbes; (ii) temporary, including roots and fungal hyphae, especially mycorrhizal, and (iii) persistent, aromatic humic material in association with amorphous Fe and Al compounds and polyvalent metal cations.

Soil structure is not simply a random arrangement of the various particles responsible for soil texture. Tisdall and Oades (1980) proposed four stages of aggregation in the organisation of a red brown earth which was further substantiated by Waters and Oades (1991) (Table 2). Aggregates >2000 µm with greater than 2% OC, are mainly held together by temporary binding agents. If the OC content of these soils falls below 1.0%, transient binding agents become mainly responsible for structure. Inorganic binding agents, including highly disordered aluminosilicates and crystalline iron oxides, are also involved in binding these aggregates, but to a lesser extent.

Aggregates 20–250µm in diameter consist of particles of 2–20µm diameter bonded together by persistent organic materials, crystalline oxides and highly disordered aluminosilicates. These aggregates resist breakdown to rapid wetting due to being characteristically small as well as the additive effects of the binding agents.

Aggregates 2–20µm in diameter are formed from particles of <2µm diameter bonded by persistent organic bonds. Electron microscopy shows bacteria surrounded by a capsule of carbohydrate to which particles of the clay are attached. When the bacterial cell or colony has died, its contents decay leaving fibrous components attached to clay particles. Aggregates of < 2µm in diameter, are made from individual clay plates held together through a combination of Van der Waal's forces, H-bonding and coulombic attraction. Greenland (1965, 1971) showed that the ionic charge on the clay surface was influenced by organic and inorganic materials. Aggregates <2µm in diameter have also been shown to be made up of fine particles held together by OM and iron oxides.

Formation of Bonding Agents and Factors Affecting Their Supply

Transient binding agents

Transient binding agents include polysaccharides produced by microbial activity and root exudates. Polysaccharides may be produced rapidly but are also decomposed rapidly (Swift 1991). Many microorganisms produce extracellular mucilages or gums which are predominantly polysaccharide (Tisdall and Oades 1982). Aggregate stability has been shown to change substantially with little overall change in SOM level. It becomes apparent that particular components such as polysaccharides are largely responsible for aggregation (Swift 1991). Additions of plant and animal residues, as well as encouraging root growth, are likely to stimulate polysaccharide production. As polysaccharide persistence is short term; systems with more consistent turnover rates (e.g. green manuring and additions of

Table 2. Aggregate hierarchy and bonding mechanisms

Aggregate/particle size	Bonding agents	Landuse implications for stability
Macroaggregates >250µm	Temporary and transient (transient agents play a greater role when OC low)	High impact of vegetation and cultivation
Microaggregates 90–250µm	Persistent bonding agents (organic nucleus encrusted with inorganic components)	Low impact
Microaggregates 20–90µm	Persistent bonding agents. Few organic entities. Voids in aggregates due to biological oxidation of organic compounds	Low impact
Clay microstructure <20µm	H-bonding. Van der Waals coulombic attraction. Some evidence of bacteria and mucilages	Low impact

Adapted from Waters and Oades (1991) and Tisdall and Oades (1982) residues with slower decomposition rates) will encourage continued polysaccharide production and concomitant increases in aggregate stability.

Temporary binding agents

Temporary binding agents include root material, vesicular–arbuscular mycorrhizal (VAM) hyphae as well as ectomycorrhizal fungi and several species of saprophytic fungi (Tisdall 1994). They have been shown to bind macroaggregates and particles together by acting as a 'sticky string bag' (Oades 1993) as well as probably becoming organic cores in stable microaggregates (20–250μm). The stability of macroaggregates is thus related to management practices which directly influence root and hyphae growth.

Persistent binding agents

The persistent binding agents probably include complexes of clay-polyvalent metal-OM derived from resistant fragments of roots, hyphae and bacterial cells developed in the rhizosphere (Tisdall and Oades 1982). Wierzchos et al. (1992) showed the importance of organically bonded iron and aluminium and OM influencing the fabric of microstructure after extraction with acetylacetone. Strongly sorbed polymers such as some polysaccharides and organic materials stabilised by association with metals are included (Tisdall and Oades 1982). Microaggregation is therefore less sensitive to soil management effects.

Composition of Aggregates

Secondary organo-mineral complexes are usually separated by some form of sieving into various size classes up to 6–8 mm in diameter. Further separation of these aggregates into particle sizes or density fractions and subsequent chemical and biological analysis of these fractions have been preformed to investigate the structural and dynamic properties of OM.

Several studies have reported macroaggregates to be enriched or depleted in clay and silt (Christensen 1986) and this phenomena occurs depending on the sand size and content of the soil. If the sand fractions are mainly smaller than the macroaggregate classes, the particles may become detached from the aggregates and accumulate in the <250μm size fraction. The macroaggregates then appear enriched in the silt and clay fractions. If the sand accumulates in similar size classes to the macroaggregates, aggregates may appear to be depleted in silt and clay. The use of corrections for loose primary particles by calculating the content of true aggregates in a given size class (Christensen 1986; Black and Chanasyk 1989) is recommended by Christensen (1994).

Several studies have reported carbon content to be higher in the macroaggregates. Dormaar (1983) and Carter (1992) found carbon content highest in macroaggregates (1–2 mm) compared with the whole soil. Similarly, Elliott (1986) found microaggregates to contain less organic C, N and P than the macroaggregates, even when expressed on a sand-free basis. Christensen (1986) found the carbon content of a loamy sand and a sandy clay loam subjected to long-term straw incorporation to peak in the 2–20 mm and 0.25–0.5 mm stable aggregates. He reported that the carbon content was closely correlated with the clay-silt content of the aggregates. Christensen (1994) concludes that for soils low in inter- and intra-aggregate macro-OM, the carbon content of true macroaggregates is highly correlated with their clay and silt content. Cambardella and Elliott (1993) found carbon contents of slaked samples to be higher than capillary wetted samples. This suggests that slaking has left behind only the most stable aggregates which are enriched in OC.

SOM from microaggregates has been shown to be more stable than the SOM responsible for binding microaggregates into macroaggregates. Waters and Oades (1991) showed OM associated with macroaggregates to be more labile, less highly processed and more readily mineralised than that associated with microaggregates. Elliott (1986) also showed C:N, C:P and N:P ratios to be much narrower from microaggregates than macroaggregate size classes. Skjemstad et al. (1990) using the ^{13}C natural isotope abundance technique, examined aggregates for soils originally under rain forest (C3) but which had been under pasture (C4) for up to 83 years. Continuous pasture for 35 and 83 years had left microaggregates with 39 and 33% rainforest C, while macroaggregates held 51 and 25%, respectively. As macroaggregates are composed of microaggregates containing older C, the SOM stabilising macroaggregates was taken to be younger and more transient (Christensen 1994).

Whitbread et al. (1994) measured total organic carbon and labile organic carbon (Lefroy et al. 1993) on soil fractions after wet sieving. Both labile organic carbon and total organic carbon was concentrated in the macroaggregates (500–4000 μm) and there was a large decrease in carbon associated with cropping (Fig. 1). Aggregates from cultivated soils were also found to be less stable to wetting than the uncultivated soils.

The lability of carbon may also be indicated by C evolution during the incubation of soil samples. Elliott (1986) found the amount of C and N mineralised to be greater for macroaggregates than microaggregates, and this mineralisation rate was enhanced when macroaggregates were crushed to a similar size as the microaggregates. Gupta and Germida (1988) also found macroaggregates from native and cultivated soils to evolve more CO_2 than microaggregates over a two week period. The use of a $KMnO_4$ to oxidise labile fractions of organic carbon report similar results (Fig. 1).

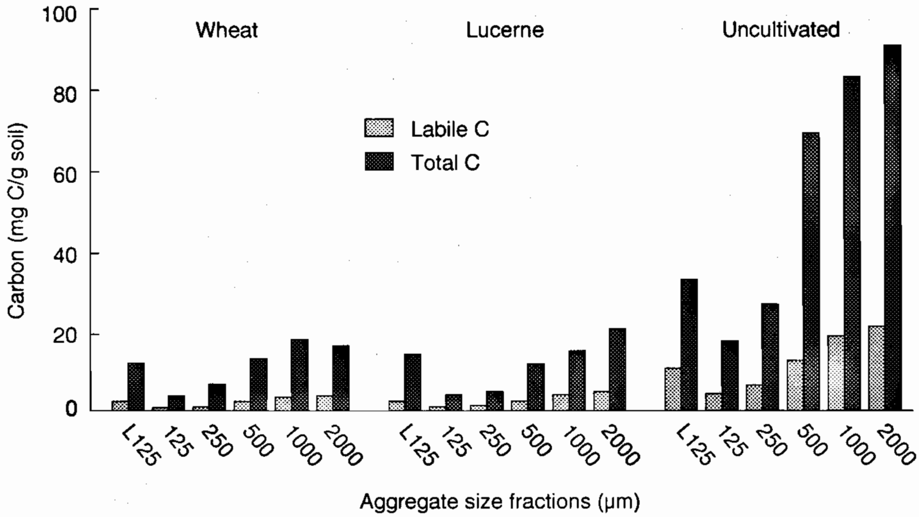

Figure 1. TOC and LOC in aggregate size fractions of the wetted sieved samples for an Alfisol with different management histories.

Conclusions

Physical fractionation techniques have often relied on the breakdown of soil structure into its textural classes or density fractions in order to study SOM dynamics. This appears to be inappropriate for investigating how soil structure is maintained. The bonding agents responsible for structure have been well defined, although the effects of farming systems on them are not fully understood. Techniques which can rapidly assess the impacts of management on bonding agents and structure are required in order to develop sustainable farming systems.

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Characterisation of Two Chemically Extracted Humic Acid Fractions in Relation to Nutrient Availability

D.C. Olk and K.G. Cassman*

Abstract

Differentiation of less chemically protected soil organic matter (SOM) from more protected SOM may allow better characterisation of the SOM molecules active in nutrient cycling. Using a sandy loam from California, USA, a Philippine irrigated lowland clay, and a Philippine clay planted to upland crops, NaOH-extractable SOM was separated into the calcium (Ca) - bound humates (CaHA) and the non Ca-bound mobile humic acid (MHA) fraction. In all soils, the MHA was less humified than the CaHA in terms of total nitrogen (N) and hydrolyzable amino acid content, E_4:E_6 ratio, and degree of aromaticity. In previous research, MHA addition to the vermiculitic California soil reproduced the positive effect of manure addition on potassium availability. Current research at IRRI is studying the effects of recent crop intensification in the irrigated lowland rice system on properties of the MHA and CaHA and resulting changes in N cycling.

DESPITE decades of research, chemically extracted humic acid (HA) fractions of SOM have not been clearly related to SOM dynamic or other soil processes in cultivated systems (Cambardella and Elliot 1992; Feller 1993). To isolate HA fractions meaningful to nutrient cycling, SOM could be extracted based on the degree of chemical protection: more protected SOM should be less active in nutrient cycling. The longevity of chemically protected SOM is well known (Jenkinson and Rayner 1977) and has been attributed to binding with exchangeable or structural cations (Martin and Haider 1986). Binding to calcium (Ca) could be one definition of chemical protection because Ca is generally the dominant exchangeable cation and the stabilising effect of Ca on SOM is well known (Kononova 1975; Muneer and Oades 1989).

Humic acids extracted by NaOH have been separated into Ca-bound and non Ca-bound fractions in earlier characterisations of SOM properties (Posner 1966; Campbell et al. 1967; Mathur and Paul 1967; Shinkarev et al. 1987). The non Ca-bound fraction was named the mobile humic acids (MHA) in pioneering work by Tyurin (Kononova 1966). To our knowledge, however, no published studies have related the properties of the MHA to nutrient availability.

The objective of this paper is to compare the properties of the MHA and the Ca-bound humates (CaHA) in three cropping systems: a temperate climate, cotton-based rotation, tropical irrigated rice, and tropical dryland rice. Some implications for nutrient availability are also discussed.

Materials and Methods

The MHA and CaHA were extracted from a sandy loam of the San Joaquin Valley, California, USA, classified as a Haploxeroll, and from two IRRI clay soils, (Tropudalf and Tropauept, Table 1). The California soil was formed in granitic alluvium and is highly calcareous. The IRRI soils developed in recent volcanic tuff and their most common exchangeable cation was also Ca, but precipitated Ca is not present. Selected physical and chemical properties of the soils are presented in Table 1. The California soil has been in a cotton-based rotation since 1945 (Cassman et al. 1989). The Tropaquept at IRRI has been triple-cropped to irrigated lowland rice since 1968 and the Tropudalf has been planted to dryland rice for a similar period.

* International Rice Research Institute, APPA Division, P.O. Box 933, 1099 Manila, Philippines.

The California soil was extracted following the procedure described by Olk et al. (1995). Briefly, air-dried soil was incubated under N_2 for 20 hours in 0.25 M NaOH at a solution:soil ratio of 2.5:1. The solutions were centrifuged, the solubilised MHA decanted and acidified to pH 2. The soil was washed twice more in water to maximize HA recovery; these precipitates were combined with the precipitate of the NaOH wash and considered MHA. The soil was decalcified by 0.1 M HCl washed until the pH of the supernatant remained below 1.5, then incubated under N_2 for 20 hours in 0.25 M NaOH. As with the MHA extraction, the solutions were centrifuged, the solubilised CaHA decanted and acidified to pH 2. Both HA fractions were then stirred in 200 ml of a 0.5% HF and 0.5% HCl solution for three days with daily solution replacement. The HA were H+-saturated by dialyzing for 24 hours against 0.01 M HCl, 0.001 M HCl, and water. The HA were frozen and lyophilized. Both HA fractions typically had ash contents of 1–2% or less.

The extraction procedure was modified for the IRRI soils in consideration of their high clay content. The initial solution: soil ratio was 10:1. After decantation of the first NaOH wash, both soils were washed twice with 0.0025 M $CaCl_2$ and the lowland rice soil four additional times with water to continue MHA solubilisation while inducing flocculation and settling of fine clays. The precipitates from the $CaCl_2$ and water washes had high ash contents and were not combined with that of the NaOH wash. The soils were then decalcified and extracted for the CaHA as above. The IRRI soils were stored at 4°C from sampling until extraction, and their moisture contents were maintained at field levels during storage.

The ratio of light absorbances at 465:665 nm (E_4:E_6) was determined on solutions of 12 mg HA solubilised in 50 ml 0.05 M $NaHCO_3$ (Chen et al. 1977). Total carbon (C) and nitrogen (N) concentrations of the HA extracted from the California soil were measured by a modified Walkley-Black method (Nelson and Sommers 1982) and colorimetric analysis (Dorich and Nelson 1983) of an acid digest, respectively. Total C and N of the HA extracted from the IRRI soils were determined on a CHN automated elemental analyzer. Hydrolyzable amino acids were determined by the ninhydrin method following 24-hour hydrolysis in 6 M HCl at 110°C. Radiocarbon ages were measured at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory, CA, USA.

Results

In each of the three soils, the C concentration was similar for both HA fractions, while the MHA was enriched in N and had lower C:N ratios than the CaHA (Table 2). The MHA had a higher hydrolyzable amino acid content than the CaHA in all soils, but this difference was smaller in the IRRI soils because of lower amino acid concentration in the MHA. The amino acids in all HA fractions were dominated by glutamine plus glutamic acid, asparagine plus aspartic acid, glycine, alanine, and lysine (data not shown), which are often the most common amino acids in microbial cell walls (Stevenson 1982). The relative proportions of individual amino acids were similar for MHA extracted from the California and IRRI irrigated lowland soils (Fig. 1) and the IRRI dryland rice soil (data not shown).

The lower E_4:E_6 ratios of the CaHA suggest that this fraction has a greater molecular weight and may be more condensed and aromatic than the MHA (Stevenson 1982). ^{13}C nuclear magnetic resonance scans confirmed the greater aromaticity of the CaHA in all soils as reported elsewhere (Olk et al. 1994, 1995).

Together the MHA and CaHA accounted for about 20% of the total soils organic C in all soils despite different soil organic C contents (Table 1). However, proportions of total soil organic C extracted as MHA and CaHA varied with soil. The amount of C extracted as

Table 1. Selected physical and chemical characteristics of soil extracted for humic acid fractions[a].

Site	Cropping system	Great group	Percentage clay	Soil organic C[b]	pH[b]	Exchangable cations		
						Ca	Mg	K
				g/kg soil		cmol$_c$/kg soil		
California	cotton	Haploxeroll	21	11.3	8.0	20	2.8	0.27
IRRI	dryland rice	Tropudalf	40	13.0	5.8	15	9.0	1.34
IRRI	irrigated rice	Tropaquept	66	28.8	6.2	22	16.3	0.75

[a] Soil was from the 0–10 cm layer of the California soil, 0–14 cm layer in the IRRI dryland rice soil and 0–15 cm layer in the IRRI irrigated rice soil.
[b] Total soil organic C was measured by a modified Walkley-Black method (Nelson and Sommers 1982), and pH in a 1:2 suspension of soil: 0.01 M $CaCl_2$.

Table 2. Elemental composition and some chemical properties of the mobile humic acid (MHA) and calcium humate (CaHA) fractions.

Fraction	Site	C concentration	N concentration	C:N	Hydrolyzable amino acids	E_4:E_6	Total C	Total N
		g/kg HA			mol/kg HA		g/kg soil	
MHA	California	514	55	9.3	1.50	6.0	0.32	0.03
	IRRI, dryland	500	47	10.6	1.06	6.4	1.41	0.13
	IRRI, irrigated	530	43	11.8	1.03	6.0	3.80	0.31
CaHA	California	540	40	13.4	0.69	4.4	2.18	0.16
	IRRI, dryland	521	36	14.5	0.63	5.0	1.13	0.08
	IRRI, irrigated	510	35	14.5	0.65	4.3	2.82	0.19

MHA from the IRRI soils was 4 to 12 times greater than from the California soil. The amount of C extracted as CaHA was lowest in the IRRI dryland soil. Total N extracted as MHA and CaHA followed similar patterns.

The MHA was dated as modern for all soils (data not shown). The radiocarbon age of the CaHA was 290 years in the California soil and modern in both IRRI soils.

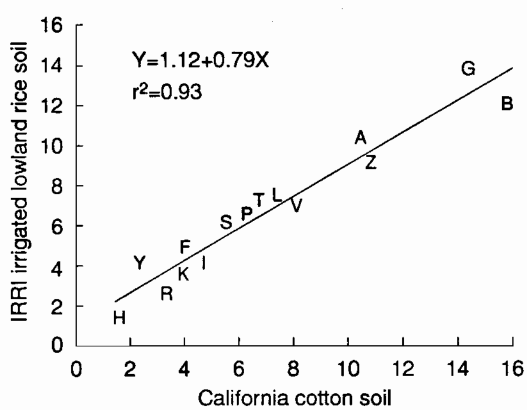

Figure 1. Molar fractions of hydrolyzable amino acids in the mobile humic acids (MHA) extracted from the IRRI irrigated lowland soil vs molar fractions of the MHA extracted from the California cotton soil. Molar fractions are expressed as percent of total hydrolyzable amino acids. Amino acids are represented by the following abbreviations: A (alanine); B (asparagine + aspartic acid); F (phenylalanine); G (glycine); H (histidine); I (isoleucine); K (lysine); L (leucine); P (proline); R (arginine); S (serine); T (threonine); V (valine); Y (tyrosine); and Z (glutamine + glutamic acid). Amino acids were hydrolyzed by 6 M HCl at 110°C and measured by the ninhydrin method.

Discussion

In each of these three soils and cropping systems, the MHA represent an early stage and the CaHA a more advanced stage of humification, based on the higher total N and hydrolyzable amino acid content, the higher E_4:E_6 ratio, and lower aromaticity of the MHA. This interpretation is consistent with chemical changes in SOM due to humification as described by Tsutsuki and Kuwatsuka (1978), Anderson (1979), and Stevenson (1982). Differences in the degree of humification of MHA vs CaHA are attenuated, however, in the IRRI soils. The modern ^{14}C dates of the CaHA in the IRRI soils suggest that the CaHA turns over faster in these soils than in the California soil. Differences in climate, soil mineralogy, clay content, and amount of precipitated Ca in the California soil may influence the rate of turnover of the CaHA. These differences may also influence the proportions of MHA and CaHA.

Nevertheless, each extracted fraction was relatively similar for all three soils in such chemical characteristics as C:N ratio, E_4:E_6 ratio, and molar fractions of individual amino acids. Such similarities across this spectrum of soil environments support the usefulness of this extraction method for studying SOM properties in diverse cropping systems and soils. The reproducible chemical properties also underline the apparent ubiquity of basic soil processes controlling SOM formation in different soil environments.

Characterisation of the MHA and CaHA may help elucidate the role of SOM in nutrient cycling. Addition of MHA to the highly vermiculitic California soil reduced K fixation, increased 1 M NH_4Cl-extractable K by 30% in K adsorption isotherm incubations, and increased plant K uptake by 42% in a pot experiment (Olk and Cassman 1993; Olk and Cassman, submitted). These laboratory results reproduced the positive effect of steer manure addition on the availability of previously applied K fertilizer in a field experiment (Cassman et al. 1992). Addition of CaHA had no significant effect on K availability.

We are currently studying the effects of intensified irrigated rice cultivation on MHA and CaHA properties in tropical lowland soils. In preliminary results the intensity of irrigated rice cropping in submerged soil markedly affected certain HA properties while having little effect on others. Changes in HA properties with flooding intensity were greater for the MHA than for the CaHA. Subsequent research will address the effects of these altered SOM properties on N mineralisation and availability in the irrigated lowland system.

This experimental approach can be useful for other systems. Characterisation of young, labile SOM may become more necessary for understanding nutrient availability in Asian agriculture given the recent trend toward crop intensification: the SOM fractions most active in nutrient cycling in these new systems may also be the same fractions most affected by intensification. Moreover soil extraction for MHA and CaHA may be appropriate even when the soil exchangeable cations are not dominated by Ca, as the CaHA may also contain SOM bound by Ca and Fe (Posner 1966; Olk et al. 1995).

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Organic Matter: Chemical and Physical Fractions

J.M. Oades*

Abstract

A short historical review highlights the dominance of chemistry in studies of soil organic matter until the mid 1970s when recognition of soil organic matter as a biological system led to studies of soil microbial biomass, modelling of C and N cycles in soils and to fractionations of soil organic matter using physical procedures and no reactive chemicals.

Physical fractionations of soil organic matter have allowed separations of particulate organic matter from 'humus' which is the result of interactions of microbial biomass and metabolites with the clay matrix.

Modern spectroscopic techniques involving nuclear magnetic resonance, infra-red and mass spectometry are discussed together with their applications to whole soils and soil fractions.

APPROACHES to studies of organic matter in soil have changed significantly during the last 20 years. During the 1960s studies of organic materials were dominated by chemists and fractions such as humic acids, fulvic acids and polysaccharides were being isolated, fractionated on the basis of a range of physical and chemical properties and then characterised by various state-of-the-art techniques available at the time. Little attempt was made to understand the relevance of the various fractions to the dynamics of organic materials in soils although various chemically-based concepts were advanced to describe the processes of humification.

The beginning of other approaches to the study of soil organic matter (SOM) arose largely from the use of ^{14}C as a tracer in both laboratory and field studies. Incubations with uniformly-labelled ^{14}C-glucose and plant materials established unequivocally that the procedurally-derived fractions — humic, fulvic and humin — did not represent a sequence of humification and were of little use in studies of the dynamics of C and N in soil. It was clear that these chemically extracted and derived fractions cut across the range of biological entities and processes in soils.

Oades and Ladd (1977) made a plea for a change towards a more biologically meaningful approach to studies of organic matter in soil and since the 1970s we have seen the development of three approaches to studies of SOM. These can be listed as (1) modelling of C and N cycles, (2) the assessment of microbial biomass, and (3) the fractionation of SOM by physical procedures.

Microbial biomass

Various methods were used in attempts to recognise and quantify the microbial biomass in soils. For example adenosine triphosphate (ATP) was determined as a compound present in all living organisms (Jenkinson and Oades 1979; Oades and Jenkinson 1979). Other chemicals considered to be present only in bacteria such as diaminopimelic acid or in fungi e.g. ergosterol are currently being used in studies of soil microbial biomass.

Of more significance was the development of the fumigation procedure for quantifying the soil microbial biomass as an entity. The technique pioneered by Jenkinson and Powlson (1976) is based on the premise that if the soil microbial population is killed by fumigation with a volatile chemical such as chloroform then the microbial residues become a substrate for an introduced population of microorganisms. The new population releases CO_2 from the dead microbial population. This CO_2 can be measured and used to calculate the size of the original soil microbial biomass. Numerous results have shown that the soil microbial biomass represents usu-

* Department of Soil Science, Waite Campus, The University of Adelaide, Glen Osmond, South Australia 5064.

ally from 3 to 5 percent of the total organic carbon in soil. The values obtained for C present as soil microbial biomass depend on the treatment of soil prior to fumigation and incubation and on the time of year. There are moves to use measurements of soil microbial biomass as an indicator of soil quality or soil health. However the microbial population is reactive to supplies of energy, water and oxygen and thus has somewhat limited utility in this respect.

The fumigation procedure has been followed by chemical extraction procedures rather than incubation. This has allowed the use of ninhydrin to determine amino compounds instead of release of CO_2 or carbon compounds. Of more significance, perhaps has been the extraction of isotopes of C, N, P and S added to the soil as tracers. These techniques have allowed study of the cycling of these organogenic chemicals through the soil microbial mass (Jenkinson and Ladd 1981).

The microbial biomass was described as a pool of organic matter which turned over very rapidly. It thus became the 'active' pool in early versions of the Rothamsted model of C turnover in soils (Jenkinson and Rayner 1977).

Simulation models of C turnover in soils

The pioneering work of Jenkinson led to the Rothamsted model. This model is based on data obtained from long-term trials at Rothamsted (and elsewhere) in which decomposition of uniformly labelled plant materials was studied to obtain measurements of soil microbial biomass. The model was designed to deal mainly with agricultural systems (Jenkinson et al. 1991).

A somewhat more sophisticated model was developed by Parton et al. (1987) which was originally designed to simulate C cycling in natural ecosystems, but in recent years has been modified to suit agroecosystems. Both the Rothamsted and CENTURY models are research models which require substantial data inputs for application to natural or agricultural systems. Both contain three conceptual pools with short, medium and long turnover times. These pools cannot be measured in soils and thus while the models can be developed and tested against long-term trials, determination of mean residence times using ^{14}C and other data they cannot be truly validated.

Within the Cooperative Research Centre for Soil and Land Management at the Waite Campus of the University of Adelaide a simple two pool model has been developed as a decision support system to help to assess whether particular rotations and management systems are exploitive or beneficial with respect to the reserves of C in the soil. The acronym for this model is SOCRATES which in full is Soil Organic Carbon Resources And Turnover in agro-Ecosystems (Peter Grace, unpublished). The model contains the same decay rates and constants utilised in the Rothamsted and CENTURY models but the inputs to run the model are climatic data and annual inputs for the various rotations involved. The model does not aim at high precision but is capable of predicting trends in C contents of soils over decades for defined crop rotations and management.

Physical fractionations of soil

Fractionation of soils by physical methods only to study organic materials is not new but received a boost in the 1970s with recognition that 'pools' of soil organic matter should have some meaning with respect to biological processes in the soil and not be based on chemical procedures (Oades and Ladd 1977). Pioneering work was published by Turchenek and Oades (1979) who demonstrated trends in the chemistry of organic materials from plant-like coarse particles to microbial-like fine particles, or clay fractions in soils. The initial approaches were to separate 'light fractions' from soil by flotation on various heavy liquids or to obtain 'macro organic matter' by combinations of sedimentation and sieving techniques. Work over the last two decades has been reviewed in some detail by Oades (1989) and Christensen (1992, 1995).

A major decision necessary before soils are subjected to physical fractionation is the degree of disaggregation required. Thus one must ask the question 'Why am I fractionating soils using only physical techniques?' It was established by Waters and Oades (1991) that if soil aggregates are obtained from soils by wetting and minimal physical input, e.g. gentle wet sieving, then the aggregates of various sizes tend to have the same chemistry. To obtain fractions with different chemistry requires substantial disaggregation such that most of the clay fraction is dispersed. When this occurs it is clear from the application of solid state ^{13}C nuclear magnetic resonance (NMR) that there are systematic changes in chemistry from coarse to fine particles (Fig. 1). The trends illustrated by the fractionation of a Mollisol show clearly the dominance of carbohydrates in plant materials in coarse particles which is present in decreased quantities in finer particles. Aromatic materials represented by signals around 130 ppm are concentrated in particles of diameter 1 to 20 μm while aliphatic components reach highest concentrations in clay fractions which usually have C:N ratios of 6 to 8, which is the C:N ratio of bacteria.

One generalisation which has been proposed from studies of physical fractions of soil organic matter is that the particulate material in soils may represent a pool with a turnover time of several decades. This has been confirmed to some extent in long-term field trials, the use of ^{14}C-labelled plant materials and application of $\partial^{13}C$ values.

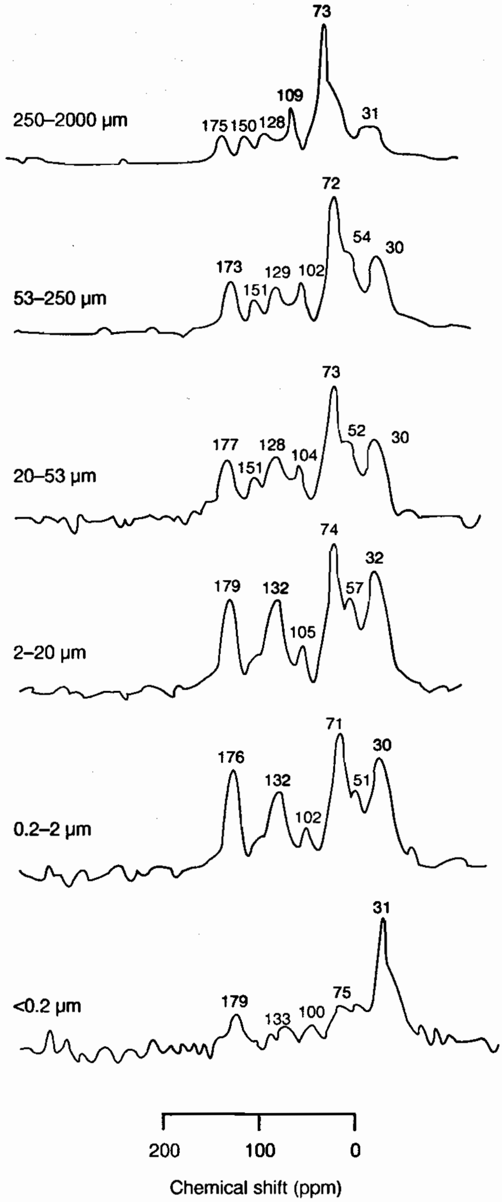

Figure 1. Solid state CP/MAS ^{13}C NMR spectra for a mollisol.

However, the system is more complex in aggregated soils; both 'free' and 'occluded' particulate organic matter needs to be recognised. Recent work by Golchin et al. (1994) has linked soil structure and C cycling in a proposed model which illustrates C cycling during aggregate stabilisation and degradation (Fig. 2). The model is based on data obtained by separating a range of fractions based on density using sodium polytungstate. The model is also based on the premise that most organic material in soil is particulate and that decomposition depends on attack on this solid substrate by shells or skins of micro flora and fauna which slowly decompose materials from the outside in a manner very similar to the weathering of particles of rocks.

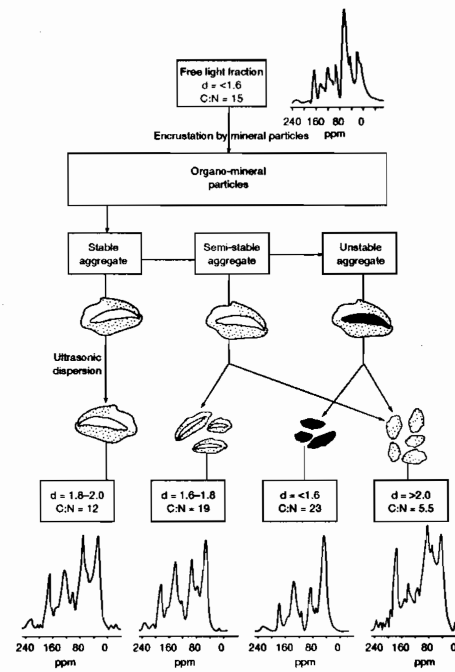

Figure 2. C cycling during aggregate stabilisation and degradation.

Free particulate organic matter is plant-like in character, although C:N ratios less than 20 indicate a several-fold concentration of N from fresh plant materials. It is separable from the soil with no aggregate disruption at densities <1.6 Mg m^3. As a substrate it sustains a skin of 'decomposers' which produce extracellular polysaccharides and metabolites which interact with the clay matrix. The particle of organic matter thus becomes the centre of an aggregate and is occluded and surrounded by clay matrix held together by polysaccharide glues. Some of this occluded particulate material is released during disaggregation using ultrasonic energy. The model illustrates a sequence with time as the aggregate become more unstable as the occluded particulate material becomes a less available source of energy for micro-organisms, and the mucilaginous polysaccharide glues are also slowly metabolised leading to the instability of aggregates. The particulate material in the unstable aggregate is released as a highly aromatic component relatively free from inorganic materials. Measurement of $\partial^{13}C$ values have shown this material survives for than 50 years in the soil. Thus particulate material cannot all be regarded as readily available substrate which turns over in 1 or 2 decades. It is clear that from the point of view of turnover this fraction is heterogeneous.

There is now convincing evidence that organic matter is protected from rapid decomposition by being inside aggregates. This has been illustrated by Waters and Oades (1991) in systematic studies of aggregates by transmission electron microscopy. The scale involved was 100 µm upwards. Similarly for particles < 20 µm Skjemstad et al. (1994) have demonstrated that organic matter on the outside of these aggregates was significantly younger than that inside the aggregates. This was done by oxidising the organic matter on the outside of aggregates using a high energy UV source. The mean residue time of the total organic matter associated with the aggregates and that remaining after UV oxidation of the material on the outside of the aggregates indicated that the organic matter associated with the surfaces of aggregates was modern. The organic matter protected inside the aggregates had a mean residence time of 1300 years.

These studies show that the position of organic materials within the soil matrix across various scales impacts on the rate of decomposition and that the 'matrix' effect is very important in C turnover. The work also illustrates the importance of maintaining soil aggregation to preserve organic matter in soils and vice versa.

Modern Spectroscopic Techniques

Studies of the chemistry of soil organic matter have been revolutionised with developments of a range of spectroscopic techniques. The most important of these are:

1. CPMAS ^{13}C nuclear magnetic resonance or solid state ^{13}C NMR
2. Pyrolysis gas chromatography mass spectrometry or pyrolysis GCMS or pyrolysis MS
3. Various forms of infra red (IR) spectroscopy including Fourier Transform IR and Acoustic IR.

The most significant of these techniques at the moment is solid state ^{13}C NMR but by the year 2000 this battery of spectroscopic techniques will replace wet chemistry and we shall be able to obtain the chemical signatures of natural solid bio polymers rapidly.

The Waite Campus of the University of Adelaide houses a Varian 200 MHz spectrometer dedicated to the studies of natural bio polymers. It is possible to obtain the chemical signatures of whole soil or any soil fraction. The data obtainable are illustrated for particle size and density fractions in Figures 1 and 2. Comparisons of whole soils can now be made for the first time and Figure 3 shows a comparison of the chemical compositions of Chinese and Australian Oxisols and Mollisols. For current soil management practices this information is of academic interest only but illustrates the future possibilities for studies of one of our very important natural resources.

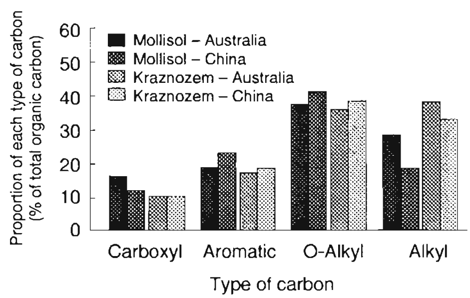

Figure 3. Comparison of the chemical compositions of Chinese and Australian Oxisols and Mollisols.

Conclusions

What does this mean with respect to the management of organic materials in various rotations and management systems in modern attempts to ensure that we have sustainable but productive soil resources?

The following conclusions may be drawn:

1. Like the range of chemical fractions of soil organic matter the various fractions obtained by using only physical procedures are heterogeneous with respect to turnover times.
2. Because the pools used in models are conceptual the models cannot be truly validated.
3. Therefore for the management of soil organic matter in agroecosystems we should use a simple decision support system which fits the data currently available, i.e. we need predictions now and cannot wait to obtain inputs from sophisticated research models. SOCRATES is suggested as a decision support system.
4. If predictions are that a particular management system is maintaining or improving the C resources then we assume from the point of view of the natural resource base that the system is sustainable?
5. The dynamics of soil C will be pursued at the fundamental level using modern spectroscopic techniques and utilising both natural and added isotopes.

Research Priority

The biggest gap in studies of soil organic matter in agroecosytems is knowledge of the annual C inputs to the soil from various management systems.

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Modelling of Soil Organic Matter Dynamics

R.J.K. Myers*

Abstract

Simulation modelling has the potential to be a useful research tool in evaluating the long-term consequences of management on soil organic matter levels. It can provide an early indication of trends prior to confirmation with field data. Several simulation models exist that can be used for this purpose. The CENTURY model is designed for long-term simulation of soil organic matter changes. The model is described and its strong and weak points noted. It simulates soil processes well but plant growth processes are simulated less well. It has been evaluated using a data set from a long-term experiment in central Thailand. In general the model predicted the nature of the changes of crop production and soil organic matter with time in response to inputs of different plant residues and N fertilizer. Other models are known to simulate crop growth well but simulate soil organic matter changes less well. With further refinement CENTURY and these other models will greatly aid research into developing sustainable agriculture.

In the search for sustainable systems of farming, it is important to evaluate whether an input contributes to sustainability or not. Most evaluations of sustainability assume that organic matter is a good thing, and that enhancement of organic matter levels, or arresting the decline, is a good thing. Therefore, an important component of the evaluation of the impact of a particular practice is to monitor the change in organic matter in the soil in comparison with the change when that practice is not implemented. Monitoring of changes in organic matter is constrained by the difficulty of detecting changes against a large and variable background of the existing soil organic matter. Vallis (1973) showed that to detect a change in total N of 50 kg/ha in a Queensland pasture, 150–1000 soil samples would need to be collected and analysed. If soil organic matter using a particular sampling technique has a CV of 10%, and if the practice being tested is only increasing organic matter at a rate of 3% per year, no change could be detected within three years. The fact that most research projects last only 2–3 years means that benefits to organic matter cannot reasonably be expected to be detected within the lifetime of a project. Not only that, but experience has shown that organic matter does not normally accumulate along a smooth upward curve. Vallis (1972) observed annual changes in soil total N that were not smooth. As a result of weather and other conditions, in some years N decreased, in other years it increased. An initial trend could be misleading and the correct identification of long-term trends requires monitoring over longer periods of time. In some cases a practice might be very exciting in the short term, but unstable in the long term.

For these three reasons, there is a need for some means of determining soil organic matter changes in the long term. In the past this was done by the use of long-term experiments. Unfortunately, long-term experiments are tedious and costly, and often the treatments become obsolete during the course of the experiment. In the current research environment, very few long-term experiments can be conducted.

Simulation modelling has long been hailed by some as the answer to this problem. The idea has been that simulation models could be developed, validated and/or verified against the results from past experiments, then used to evaluate long-term effects in the future using computer-generated weather data. Everyone appreciates that the simulation modellers of the past were very strong on expectations but usually

* International Board for Soil Research and Management (IBSRAM), P.O. Box 9–109, Bangkhen, Bangkok 10900, Thailand.

slow to deliver the goods. Eventually some of the long-awaited models have been developed. These models which simulate organic matter dynamics in farming systems now provide a useful research tool for adding value to our research on organic matter. It is not my intention to review the various models in existence. Many of them are variations on the one theme. Rather it is my intention to concentrate on one model, the CENTURY model (Parton et al. 1987; Parton et al. 1988), to describe it, its strengths and weaknesses, and to evaluate it against a data set from central Thailand. Other types of models will only be discussed in order to compare and contrast them with CENTURY.

Simulating Organic Matter Dynamics

Whereas numerous models exist that simulate organic matter dynamics in soils, the approaches used by the modellers do not vary substantially. All assume that soil organic matter can be subdivided into various discrete pools each with its own susceptibility to decomposition. The number of these pools varies between models. No model as yet considers soil organic matter as a continuum of resistance to decomposition. Between models, similar approaches are taken to the kinetics by which decomposition occurs. The functions describing the modifying effects of temperature and soil water are essentially the same.

A non-exhaustive list of the models that are not described in this paper is as follows:

- NCSOIL (Molina et al. 1983)
- Un-named model of organic matter decomposition in tropical soils (Bouwman 1989)
- The Rothamsted model of organic matter turnover (Jenkinson and Rayner 1977, Jenkinson 1990)
- Un-named model of carbon turnover (Van Veen and Paul 1981)
- Phoenix model (McGill et al. 1981)
- The CERES models (IBSNAT, University of Hawaii)
- The pasture CNSP model of McCaskill and Blair (1990).

The CENTURY Model

Outline of model

The CENTURY model (Parton et al. 1987; Parton et al. 1988) is a general model of the soil–plant ecosystem that has been used to represent C and nutrient (N, P and S) dynamics for grasslands, crops, forests and savannas. It consists of different plant production submodels linked to a common soil organic matter submodel. The soil organic matter submodel simulates the flow of C, N, P and S through plant litter and the different inorganic and organic pools in the soil. The model is a simulation model that operates on a monthly time step. It has been designed specifically for long-term simulations, that is for simulating changes in soil occurring during 50–100 years, or more. The major input variables for the model include:

- monthly average maximum and minimum air temperature
- monthly precipitation
- lignin content of plant material
- plant N, P and S content
- soil pH and texture
- atmosphere and soil N inputs, and
- initial soil C, N, P and S levels.

Input variables can be measured or estimated from the literature. In some cases, the model is self-correcting, in which case the precise estimation of these variables is not critical.

The flow diagram for the soil organic matter submodel (Fig. 1) shows that soil organic C is divided up into three major components which include active, slow and passive soil C. Active SOM includes live soil microbes plus microbial products (generally it is 2–3 times live microbial biomass). The slow pool includes resistant plant material (lignin-derived) and soil-stabilised plant and microbial material. The passive pool contains physically and chemically stabilised SOM. Flows between the pools are driven by decomposition rate and microbial respiration loss parameters, as modified by moisture and temperature, and also affected by soil texture. Typical turnover times for a grassland site are 2 years for the active pool, 40 years for the slow pool and 2000 years for the passive pool.

The inputs of C are from plant residue (shoot and root) partitioned into structural and metabolic plant components as a function of lignin: N ratio. High lignin: N results in more structural material. Metabolic material decomposes faster. Structural material decomposes at a rate determined by the lignin content. Metabolic and non-lignin structural decomposition products go to the active pool. The lignin material goes to the slow pool. Passive SOM forms from stabilisation of active SOM into stable clay-associated microaggregates, but there is some transfer from the slow pool.

The N, P and S submodels have the same general structure as the C submodel. Critical components are the C:N, C:P and C:S ratios of the different inputs and pools.

With respect to the crop growth submodel, it is set up as a wheat or maize model, but alternative crops can be simulated by changing some of the constants. Rotations can be simulated with some difficulty, that is, by stopping the model and changing the relevant constants. Production depends on supply of moisture as stored water at sowing and precipitation during crop growth. Management factors such as cultivation, fertilisation and organic inputs modify crop production through effects on soil processes.

The model is available from Dr W.J. Parton of Colorado State University, but because of its use of the VIEW module of the commercial software, TIME-ZERO™, for output management from the simulations, there is a price.

Use of model

A model such as this can be put to the test in two ways. Firstly it can be initialised using data from a particular site and the results can be examined to see whether the behaviour of the model is consistent with the generally observed behaviour of the system. Secondly the model can be initialised and tested against known experimental data. I have tried to follow the second option. Data have been obtained from a long-term experiment at Phraputthabat Field Crop Experiment Station near Lopburi in Central Thailand (Uehara et al. 1985; Phetchawee et al. 1986; Watanabe et al. 1989; Inoue 1991 and Samnao Phetchawee, pers comm.). The experiment was initiated in 1976. In this experiment, maize is grown in rotation with mungbean and crop residues are retained. Apart from the control treatment which receives no additional organic inputs, there are five treatments, three of which are green manure crops (Crotalaria, ricebean and Mimosa) and two of which annually receive external inputs (rice straw at 4 t/ha, and compost at 20 t/ha). Each organic input treatment is run with or without annual N and P fertilizer inputs. The model was initialised using actual data where possible, with missing data being estimated in some cases. The data used are summarised in Table 1.

The model has been run for each of the 12 treatments for a period of 15 years for which actual data are available. Weather inputs are actual monthly rainfall data, and temperature data are actual data for the

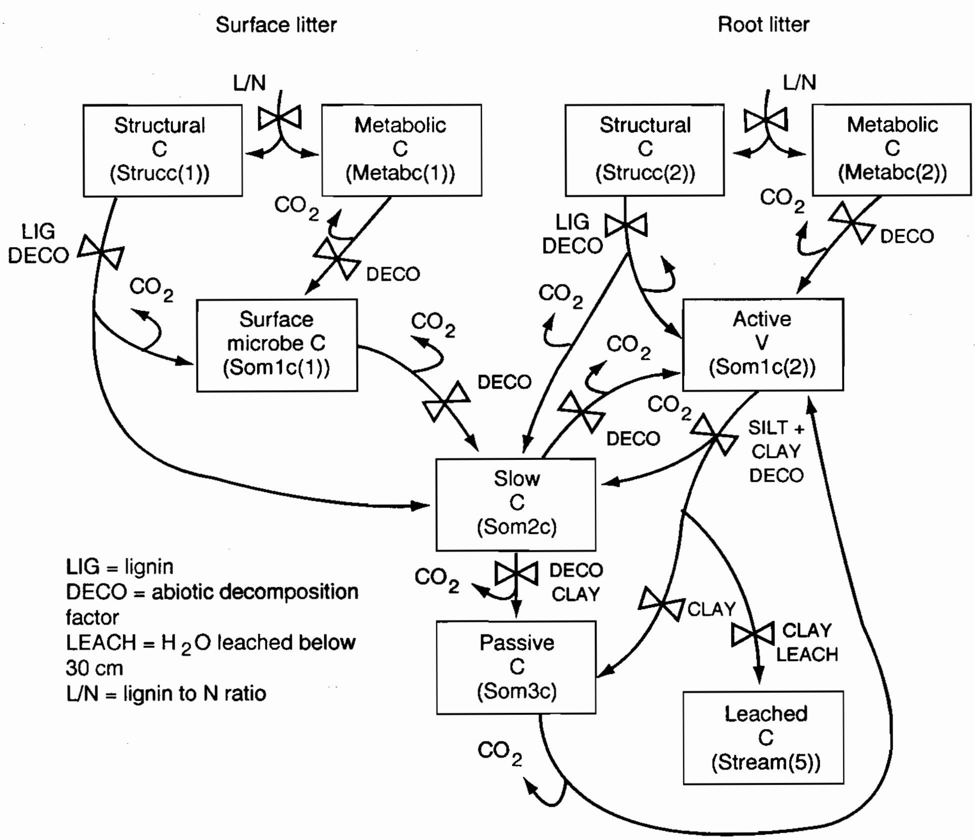

Figure 1. Flow diagram for the soil organic C submodel. The diagram shows the major factors which control the flows and the model output variable names are shown in parentheses for each of the state variables.

final three years and the means of those years for the earlier 12 years. Mean weather data are given in Table 2.

The results of the simulations are reported in Figures 2-13. Because not all the required information was available, some assumptions had to be made. These generally consisted of reasonable estimates of variables such as residue lignin levels, and the C:N ratios of different organic matter fractions. Since the model does not yet simulate crop rotations, it was assumed that the inputs of organic matter from mungbean and green manure crops were made from external sources, and this assumption was made in the knowledge that the direct effect of growing these crops on soil water or nutrient levels was being ignored. Further these inputs had to be assumed to be constant from year to year, and therefore a reasonable estimate of an average input was made from the available data.

The simulation of the control treatment without fertilizer (Fig. 2) and with fertilizer applied annually at 63:24:0 (Fig. 8) suggest that the system was close to an equilibrium at the start, since organic matter declines very slowly without fertilizer and increases very slowly with fertilizer, with above ground crop production simulated at about 2.5 t C/ha (or 6.25 t/ha of dry matter) without fertilizer and about 5 t C/ha (12.5 t/ha dry matter). Measured values for 1988 were 6.42 and 5.22, respectively. Observed soil organic matter showed a great deal of 'noise' but it seemed that organic matter without fertilizer was steady, and with fertilizer it showed a gradual increase. The simulations of rice straw and crotalaria inputs without fertilizer (Figs 3 and 4) both indicated a very slight increase in soil organic matter and a small increase in above-ground crop production. Observed increases in soil organic matter for the same treatments were 29% for rice straw and 14% for crotalaria, and for above-ground crop production were 58% for rice straw and 20% for crotalaria. By contrast, the same inputs plus fertilizer resulted in simulations that suggested 25–30% increase in soil organic matter during 15 years and a doubling of above-ground crop production (Figs 9 and 10). Actual measured increase in soil organic matter with fertilizer was 49% for rice straw and 31% for crotalaria. Above-ground crop production was increased 227% for rice straw and 83% for crotalaria. The simulations of the ricebean and mimosa inputs without fertilizer (Figs 5 and 6) suggested 20% increases in soil organic matter and a doubling of crop production during 15 years. However, observed soil organic matter increases were 68% for ricebean and 85% for mimosa, and crop production increased by 149% for ricebean and 111% for mimosa. For the same materials with added fertilizer, the simulations indicated that there was 40% increase in soil organic matter and crop production more than doubled (Figs 11 and 12). In this case the observed values were of an increase in soil organic matter of 76% with ricebean and 131% with mimosa, and of crop production approximately tripled.

Table 1. Details of organic inputs to the different treatments.

Treatment	Component	C added(g C/m^2/yr)	Lignin (g/g)	C:N
Control	Mungbean	12	0.12	29
Rice straw	Mungbean	22	0.12	58
	Rice straw	160	0.24	40
	Total	182	0.22	42
Crotalaria	Mungbean	11	0.12	40
	Crotalaria	120	0.18	34
	Total	131	0.17	35
Ricebean	Ricebean	183	0.12	19
Mimosa	Mimosa	222	0.18	27
Compost	Mungbean	23	0.18	39
	Compost	346	0.18	19
	Total	369	0.18	19

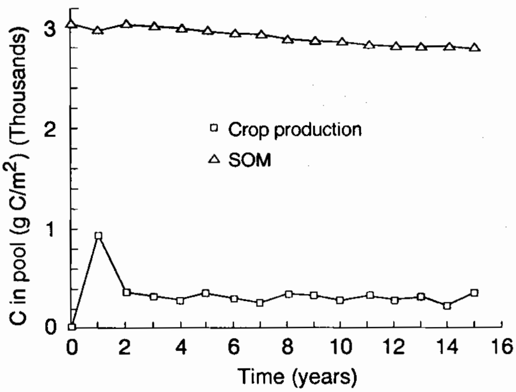

Figure 2. Control, no fertilizer.

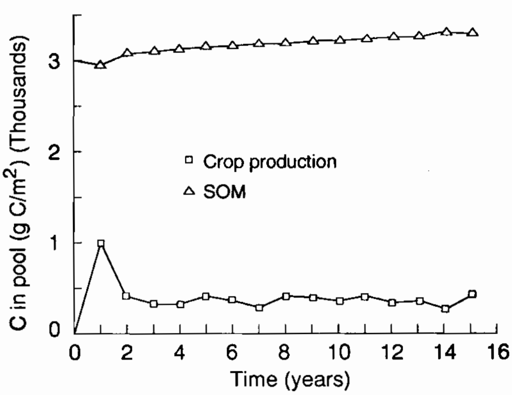

Figure 3. Rice straw, no fertilizer.

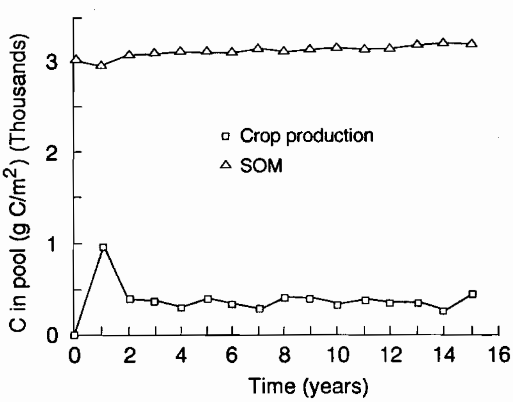

Figure 4. Crotalaria, no fertilizer.

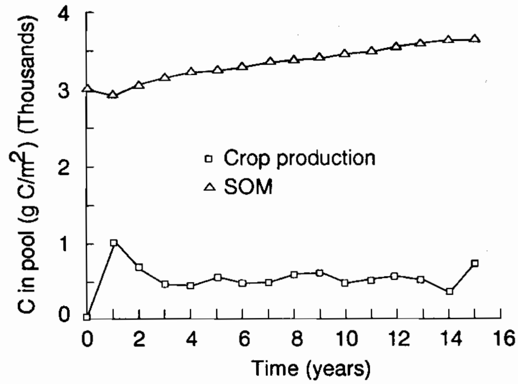

Figure 5. Ricebean, no fertilizer.

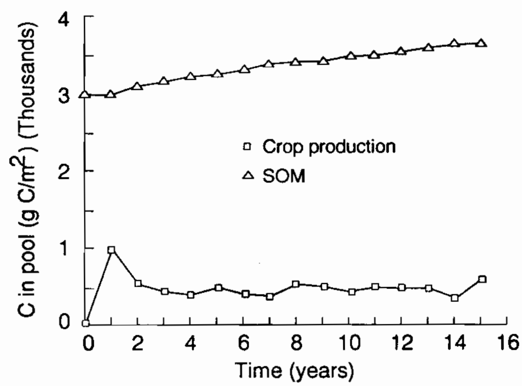

Figure 6. Mimosa, no fertilizer.

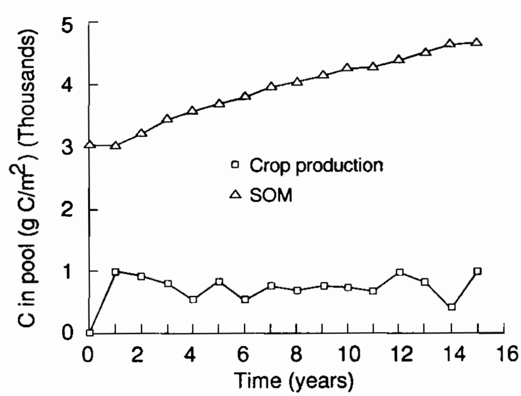

Figure 7. Compost, no fertilizer.

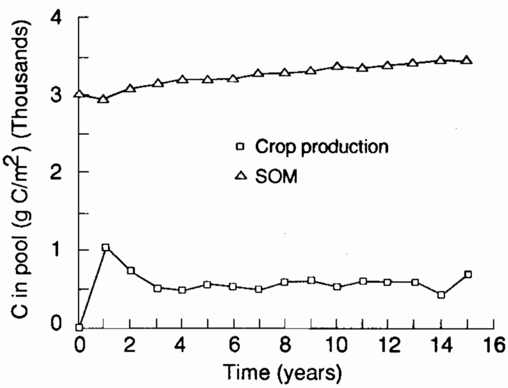

Figure 8. Control, plus fertilizer.

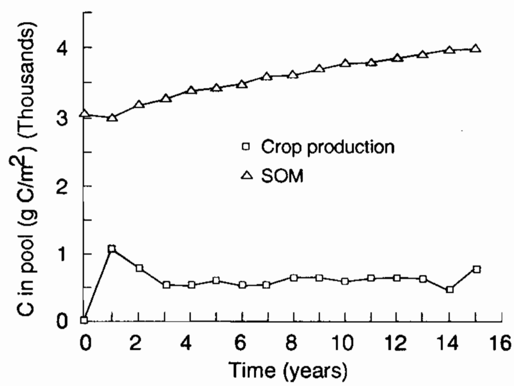

Figure 9. Rice straw, plus fertilizer.

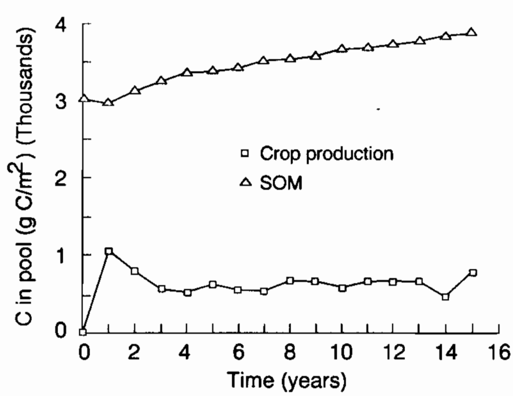

Figure 10. Crotalaria, plus fertilizer.

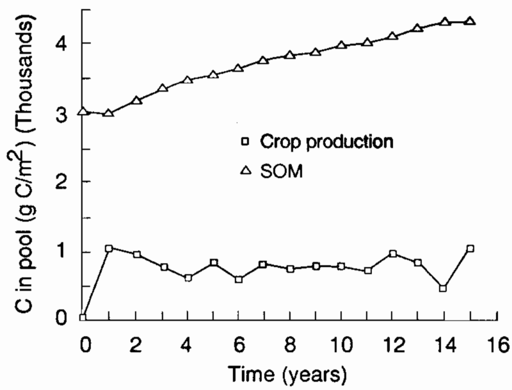

Figure 11. Ricebean, plus fertilizer.

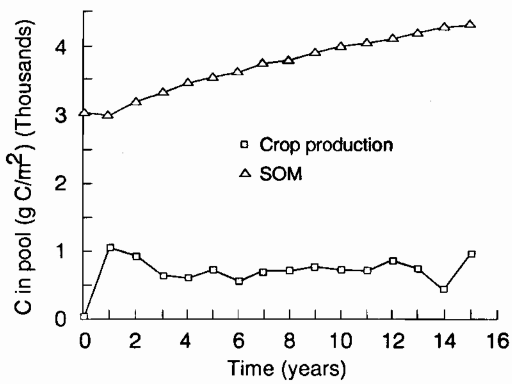

Figure 12. Mimosa, plus fertilizer.

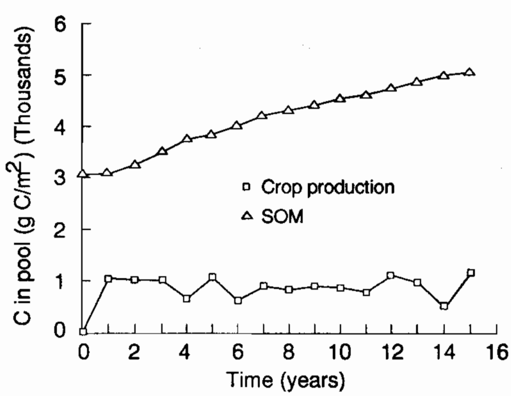

Figure 13. Compost, plus fertilizer.

Finally with input of compost without fertilizer (Fig. 7) the simulation indicated 50% increase in soil organic matter and crop production more than tripled, whereas with fertilizer (Fig. 13), the simulation indicated that soil organic matter had almost doubled and crop production had more than tripled, whereas the observation was that soil organic matter had tripled and that crop production had more than tripled. A summary of these simulations and actual measurements is made in Table 3.

The comparison can be made more easily in Figures 14 and 15 where it is seen that the model generally underestimated organic matter accumulation in this soil, particularly in the plots receiving fertilizer and in the plots receiving the highest organic inputs. Above-ground crop production was reasonably well estimated in about half the cases. In most cases where organic matter was well-simulated, crop production was also well simulated.

Why did the model not do better? One possibility is that some of the organic materials used may not have followed the model's rules regarding incorporation into the various organic matter pools. For example, the compost would have already undergone humification and therefore its C may have preferentially flowed to the passive C pool. Also the mimosa and crotalaria may have contained constituents that may have favoured the C passing to more stable pools. I tried to test this idea by rerunning the model using a much higher estimate for lignin content of these materials, but it made very little difference. A second source of error may have been in the choice of bulk density value for converting % organic C to g C/m^2. I used a value of 1.3 throughout but there were suggestions that some treatments had changed bulk density. However, the maximum error this could have caused was 15%, not enough to account for the overall discrepancies. A puzzling feature of the data is that the apparent increase in soil organic C in the compost treatments seems to be of the same order as the amounts of organic C added as compost. Such an observation is unlikely since considerable decomposition would occur during a 15-year period — normally one would expect any increase in soil organic C to be much less than the amount added. This raises the question of analytical method, and in particular whether the reported values for organic C were obtained by the Walkley-Black procedure which is an

Table 2. Mean weather for the experimental site.

	Rain (mm)	Maximum temperature °C	Minimum temperature °C
January	11	32.6	19.8
February	28	34.1	23.5
March	18	35.3	25.7
April	99	36.2	25.4
May	223	35.0	25.4
June	128	34.8	25.3
July	169	33.5	24.5
August	190	33.6	24.6
September	268	33.6	24.4
October	149	32.9	23.9
November	44	32.8	25.0
December	9	31.0	18.8
Total	1336		

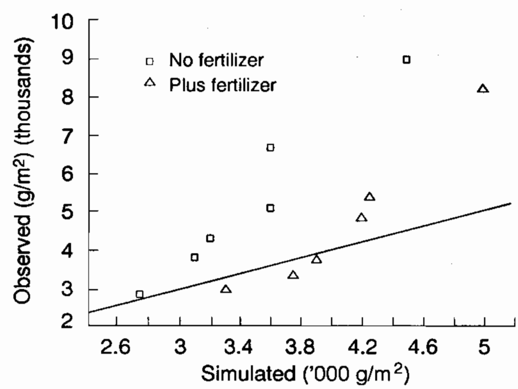

Figure 14. Simulated versus observed SOM.

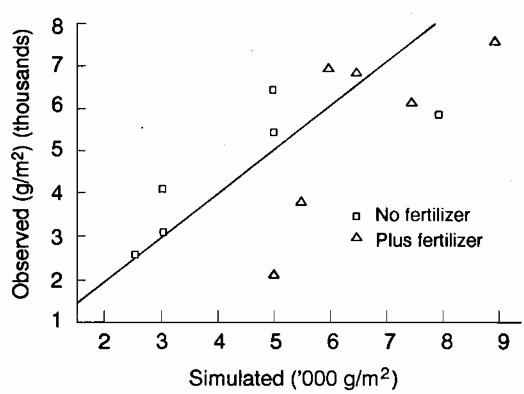

Figure 15. Simulated versus observed crop production.

Table 3. Summary of simulated and observed organic matter (g C/m^2) and crop production (t C/ha) using data from a long-term field experiment at Phraphuttabat Field Crop Research Station (130 km N of Bangkok). The data were collected over 15 years.

Input	Without fertilizer				With fertilizer			
	Soil organic matter		Crop production		Soil organic matter		Crop production	
	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.
Control	2750	2886	2.5	2.6	3300	2964	5.0	2.1
Rice straw	3200	4290	3.0	4.1	3900	3718	6.5	6.8
Crotalaria	3100	3796	3.0	3.1	3750	3302	5.5	3.8
Ricebean	3600	5070	5.0	6.4	4200	4836	7.5	6.1
Mimosa	3600	6656	5.0	5.4	4250	5330	6.0	6.9
Compost	4500	8918	8.0	5.8	5000	8113	9.0	7.5

incomplete digestion with a conversion factor. Such a method would likely overestimate organic C in soils with recent additions of relatively easily decomposable material because more complete decomposition would occur from this fraction. Of course, this is one of the common faults of modellers — if the model doesn't work too well, the data must be wrong!

Conclusions

The main conclusion is that the CENTURY model has been demonstrated to provide a qualitative description of the changes that occur in soil organic matter for one situation in central Thailand. The reasons for it not giving more quantitatively correct output were not identified but some suggestions were made.

It can also be concluded that this and other models can be used to simulate the changes in organic matter that occur in soils with different inputs of organic materials and that we should persist with their development and adaptation to our needs.

Finally we must recognise that there are few data sets available from the Southeast Asian tropics that can be used to validate such models. This situation is in contrast to temperate regions where long-term experiments in Europe and North America have provided vital data for modellers. Some long-term experiments, long criticised by research administrators for the low number of research papers per unit of time and effort, have now repaid the persistence of the generations of researchers who have maintained them. In Southeast Asia, for lowland systems, there are a few longish-term experiments still in progress at IRRI in the Philippines, plus one or two of similar duration in Thailand, but data sets are not easy to obtain. For upland systems the situation is even less-promising since the only candidate appears to be an 8-year-old maize experiment in Malaysia. I see no indication that this poverty of long-term experiments will change. Despite some scientists showing a desire to maintain experiments for longer periods, unfortunately the level of funding from governments will remain a problem and the short 'mean residence time' of donor funding will likely continue to inhibit the maintenance of long-term sites.

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Chemical Fractionation of Soil Organic Matter and Measurement of the Breakdown Rate of Residues

R.D.B. Lefroy, G.J. Blair and A. Conteh*

Abstract

The development of sustainable land management systems requires a clear understanding of the dynamics of soil organic matter (SOM). Measurement of SOM is critical for understanding SOM dynamics, but appropriate measurements must be made. Measurement of total SOM is not sensitive enough to monitor short and medium term changes in SOM, so techniques are required which measure meaningful fractions of SOM. Traditional separation on the basis of solubility into humic acids, fluvic acids and humins is of relatively little value since these fractions are only indirectly related to the rate of turnover. There are various spectrometric techniques which allow separation of SOM or other SOM fractions into more meaningful functional chemical groups. Alternatively the turnover of carbon pools can be estimated by the ease with which portions of SOM can be oxidated or by measurement of the incorporation of isotopes into SOM. Isotopes can either be measured after their addition and subsequent incorporation into SOM or, less intrusively, by measurements of natural variations in isotope ratios which arise from biological processes.

If indices of the sustainability of agricultural systems are to be developed from measurements of SOM, it is essential that appropriate SOM pools are measured.

FOR an agricultural system to be sustainable, the yields must be stable and of an adequate level. Sustainable yield is only possible if the supply of a broad set of resources is maintained. On the other hand, the stability of the system is strongly influenced by factors such as changes in fertilizer inputs, pests and extreme climatic events. Sanchez et al. (1989) indicated that soil organic matter (SOM) is a key material resource as it is a reservoir and source of key nutrients and a modifier of soil textural properties. Thus, the fertility of most agricultural soils depends to a large extent on their organic matter content. SOM contributes to the physical fertility of a soil by affecting soil structure through the formation of stable aggregates. In turn, soil aggregates affect the rate of infiltration of water, the water holding capacity, the gaseous exchange in the soil and the soil strength, and thus the resistance to root penetration. In addition, SOM affects the chemical fertility of the soil through the total supply and availability of plant nutrients. SOM is a direct source of plant nutrients, which are released through microbial activity, as well as being a significant component of the ion exchange capacity of soils (Theng et al. 1989).

SOM is a labile resource that can be depleted or renewed by altering cropping practices (Swift et al. 1991). A system can remain sustainable by manipulating the factors that regulate SOM inputs and decomposition (Ingram and Swift 1989; Woomer and Ingram 1990). Swift et al. (1991) argue that sustainable management of SOM is based on two assumptions. Firstly, that organic matter can be separated into a number of fractions, each of which is differentially responsive to management and landuse practices, and secondly, that the decomposition and synthesis of each of the fractions is regulated by definable sets of physicochemical and biological factors, which in turn may be modified by management. In investigating the effect of management on SOM, it is important that appropriate measurements of SOM are made. To this end, changes in SOM can be measured as changes in total SOM, chemical fractions of

* Department of Agronomy and Soil Science, University of New England, Armidale, NSW 2351, Australia.

SOM, based on chemical groups through to specific compounds, physical fractions or combinations of these fractions.

Measurement of total soil carbon

The status of the SOM resource base can be assessed by measurement of the total amount of organic carbon in the soil. The most commonly used techniques for measuring organic carbon (in soil) is based on the dichromate oxidation proposed by Schollenberger (1927) and modified by Walkley and Black (1934). The principle of this method is that all organic carbon is oxidised by the dichromate under acid conditions, and the amount of dichromate reduced gives an indication of the organic carbon content. In spite of its wide usage, the dichromate procedure are subject to certain limitations. Firstly, the method is based on the assumption that carbon in SOM has an average valency of zero. Secondly, several substances interfere with the determination of oxidisable carbon, notably chlorides, iron (II) and higher oxides of Mn (Walkey 1947). In addition, dichromate procedures cannot be used to discriminate between carbon from carbonised materials and carbon from SOM.

Total carbon measurements have been improved by dynamic flash catalytic combustion of carbon to carbon dioxide, with the resulting CO_2 being measured by a thermal conductiivity detector or, more recently, by coupling the combustion instrument to a mass spectrometer in a continuous flow system. Although these methods provide an improvement on measurements of total carbon by oxidation, measurement ot total carbon, or total organic carbon, is not sensitive to short-term changes in the amount, or more particularly the form of SOM which result from changes in soil management.

Nutrient content of SOM

SOM is a complex mixture of plant and animal residues in various stages of decomposition, of substances synthesised microbiologically and/or chemically from the breakdown products, and of the bodies of live and dead soil biota and their decomposition products (Schnitner and Khan 1972). The main constituents of SOM are carbon, hydrogen and oxygen, but there are significant amounts of other elements essential for the nutrition of plants.

Nearly all of the N found in soils is associated with SOM (Schnitzer 1985). The main forms of N in SOM are proteins, peptides, amino acids, amino sugars, purines, pyrimidines and N in heteocyclic compounds (Schnitzer 1991). Although a cultivated soil normally contains much less organic N than the corresponding native soil from which it was derived, there is relatively little change in the distribution of N between the hydrolysis products, so that cultivated and native soils contain much the same proportions of amino acids, amino sugars and ammonium released on hydrolysis (Jenkinson 1988).

Organic P constitutes between 20 and 80% of the total soil P in most surface soils. Organic P occurs predominately as complex organic esters, in which P is bonded to carbon via oxygen, in sugar phosphates, phosphoproteins, phospholipids, glycerophosphates, nucleotides and a substantial portion of unidentified compounds (Schnitzer 1991).

Over 90% of the total S in most non-calcareous soils is present in organic forms. There are two main forms of organic S (Freney 1986). The sulfate esters account for 30 to 70% of the organic S in soils and are considered to include the most labile forms of organic S. Carbon-bonded S includes the S containing amino acids, mercaptans, disulfides, sulfones and sulfoinic acids.

The content of other important plant nutrients in SOM organic are less frequently studied. Clearly the plant and animal residues added to the soil will contain the other macro-and micro-nutrients in the ratios found in most living organisms. As these residues are broken down, many of the nutrients will be incorporated into living biota and significant amounts of most plant nutrients will be part of, or associated with, the residue breakdown products in the SOM.

Chemical fractionation of SOM

Whilst the elemental content of SOM is of consequence to the nutrition of plants and subsequently animals, more understanding of the forms in which these elements occur in SOM is required. Fractionation has been used to separate SOM into groups of chemical compounds. The first major separation is into two broad classes, humic and non-humic substances. These can be synthesised by microorganisms or can arise directly from, or from modifications to, similar compounds in the original debris.

Carbohydrates usually account for 10 to 20% of the carbon in soils and form the most readily available sources of food and energy for microorganisms. They occur mainly as polysaccharides, and their hydrolysis produces small amounts of sugar alcohols. Apart from the trace amounts of sugar which are soluble in water, the carbohydrates in SOM are not readily isolated because of their association with non-carbohydrate components (Theng et al. 1989).

A diverse group of lipids, ranging from fatty acids to sterols, terpenes, chlorophyll, waxes and resins are present in soils (Stevenson 1982). The hydrophobic properties of these compounds impart resistance to biodegradation, resulting in long residence times in soils.

Humic substances are the dark coloured, amorphous macromolecules, ranging in molecular weight from a few hundred to several thousand, which are synthesised by biological, chemical and physical processes. Humic substances constitute from 50 to 80% of SOM and are considered to include the most stable fractions. Their stability is attributed to their chemical structures, their interactions with metal cations and clay minerals and their inclusion in soil aggregates (Theng et al. 1989).

One of the most common fractionations of SOM is based on differences in solubilities of organic constituents in acid andalkali (Hayes and Swift 1978). The three resultant fractions are fulvic acids, which are soluble in acid and alkali, humic acids, which are soluble in alkali but precipitated by acid, and humins, which are insoluble in both acid and alkali. However, the separation between non-humic and humic substances, and between humic acids, fluvic acids and humins, is far from precise (Allison 1973). The acid-soluble material classified as fulvic acid invariably contains organic substances classified as non-humic (Stevenson and Elliott 1989). Likewise, humic acids extracted with dilute alkali nearly always contain a considerable amount of inorganic material (about 25%), removal of which normally leads to a substantial loss of carbon through hydrolysis and oxidation (Stevenson and Elliott 1989).

Therefore, the complexity of these fractions means that they each contain a wide range of chemical forms, with very different turnover rates. These fractions are not conceptual pools, or related to their rate of turnover, but procedurally defined fractions, based largely on their solubility, and thus with limited value in studies of SOM dynamics (Stevenson and Elliott 1989).

There are a large number of spectrometric techniques which provide more detailed information on radio through to gamma rays (Bisdom et al. 1994). Most do not involve processes which are likely to alter the form of the organic matter compounds and, therefore, can provide detailed information on the nature of SOM in situ.

Four techniques which are being used increasingly in SOM studies are Nuclear Magnetic Resonance (NMR), Fourier Transform Infrared (FT-IR) spectroscopy, Electron Spin Resonance (ESR) spectroscopy and Pyrolysis-Field ionisation mass spectrometry.

NMR spectroscopy became a potentially valuable tool for soil scientists when techniques were developed for solid state analyses, as opposed to analysis of solutions, and as data acquisition was improved by Fourier transformation methods. The technique does not separate specific compounds, but allows quantitative analysis of specific functional groups of ^{13}C, ^{15}N and ^{1}H (Hatcher et al 1994). ^{13}C NMR spectroscopy has been used to obtain detailed information of the organic matter of intact soils and soil fractions, particularly since the development of cross-polarisation magic-angle spinning (CPMAS) improved the sensitivity of solid-state ^{13}C NMR spectroscopy such that samples with less than 2% carbon could be analysed (Wilson 1981, 1987).

CPMAS ^{13}C-NMR has been applied to mineral soil and its size and density fractions (Barron et al. 1980; Wilson et al. 1981a, 1981b) and the humin fraction of SOM (Hatcher et al.1980; Preston and Newman 1992). The technique has also been used to follow changes in SOM resulting from cultivation (Skjemstad et al. 1986; Oades et al. 1988) and natural processes of decomposition (Kögel-Knaber et al. 1991).

Infrared spectroscopy was initially used in studies of purified fractions of humic and fulvic acids. The development of Fourier Transform Infrared (FTIR) spectroscopy, and associated techniques such as Diffuse Transformed Reflectance Infrared Fourier Transform (DRIFT) spectroscopy and Attentuated Total Reflectance (ATR) spectroscopy, has considerably increased the potential for use in studies of SOM, particularly the interactions between clay minerals and SOM in whole soil samples or fractions of SOM (Ladd et al. 1993; Piccolo 1994). One problem arising in the use of infrared spectroscopy in studies of SOM in whole soils is the absorption of infrared energy by the soil mineral component. This often produces spectra similar to the organic component making structural identification difficult.

Electron Spin Resonance (ESR) can be used to investigate the presence of O, N and S in free radicals in whole soil samples or extracted fractions of SOM (Cheshire 1994). The presence of free radicals appears to be directly proportional to the degree of humification of SOM.

Pyrolysis, or thermal degradation in an inert atmosphere, as opposed to combustion on O_2 or air, causes breakage of weak bonds in organic compounds and release of products characteristic of the parent compound (Saiz-Jimenez 1994). The ratios of the different products obtained gives an indication of the degree of humification. Analytical pyrolysis methods, in combination with field-ionisation mass spectrometry (FIMS), have been used to investigate humic substances (Schulten 1987) and forest soils with organic matter contents of 7 to 44% (Hempfling et al. 1988), enabling characterisation of molecular sub-units of SOM (Hempfling et al. 1988; Hempfling and Schulten 1990) and evidence of management-induced changes in SOM composition of whole soil samples (Schulten and Hempfling 1992). The complex thermal reactions induced by the presence of mineral components causes some problems in the analysis of whole samples of mineral soil, but little problem with pure macromolecules or substantially ash-free fractions of SOM (Saiz-Jimenez 1994).

Physical fractionation of SOM

Understanding the nature of the chemical compounds in SOM, even at the functional group level, is only one part of understanding the role of SOM in soil fertility. The turnover rates of different pools of SOM are affected by both the chemical and the physical nature of the SOM. As indicated above, the stability of humic substances has been attributed to their chemical structures, interactions with metal cations and clay minerals and inclusion within soil aggregates. It is often suggested that this stability is due more to the physical or physicochemical characteristics of interactions with metal cations and clay minerals, and inclusion in soil aggregates, than their chemical structure (Juste et al. 1975); a finding that has been supported by spectroscope investigations of cultivation effects on humic substances (Skjemstad et al. 1986).

Rather than chemical fractionation, many investigators have used physical fractionation procedures to recover various fractions of SOM and to establish the nature of organic matter in organo-mineral complexes (Christensen 1986; Ladd et al. 1993 and Whitbread these Proceedings). Of particular interest is the so called light fraction, consisting largely of unaltered plant residues and their partial decomposition products. Three basic methods of physical fractionation of soil have been used: sieving, sedimentation and flotation.

Fractionation of soil by sieving is based on the separation of components on the basis of aggregate and/ or particle size. The techniques range from dry sieving to wet sieving after complete dispersion of aggregates by physical and chemical methods (Christensen 1986).

Sedimentation has been used to separate particles on the basis of size, shape and density. The sedimentation rate of small particles with high density and less dense, larger particles can be the same; thus fractions obtained by sedimentation are not necessarily homogeneous with respect to density and, therefore, the type of organic matter they contain (Tiessen and Stewart 1988; Balesdent et al. 1988).

Fractionation by flotation, based on density differences, has been used to separate plant and animal debris into a light fraction (Sollins et al. 1984; Skjemstad and Dalal 1987; Skjemstad et al. 1990). Fractions separated on the basis of particle density have yielded useful information on the extent of association of organic and inorganic materials in soils, as well as some mineralogical characterisation of the fraction components (Turchenek and Oades 1979).

Since organic matter can be protected from breakdown by both physical and chemical characteristics, it is likely that procedures which involve both physical and chemical aspects to the extraction of SOM will reveal more meaningful pools of SOM, which are more closely related to pool turnover rate. To this end, there is interest in procedures which involve physical separation of SOM, using sieving, density separation or flotation, followed by chemical analysis of the fractions, using any of the analytical techniques referred to above, or which involve aspects of the physical and the chemical protection of SOM in the one procedure.

In a procedure that combines chemical and physical separation, Eriksen et al. (1994a, b) extracted organic compounds from soil with aqueous acetylacetone, using different amounts of ultrasonic dispersion. The acetylacetone releases organic matter by complexing with the polyvalent metals in the organo-mineral complexes (Keer et al. 1990). The organic extracts were analysed for total nutrient content and were separated into molecular weight fractions by gel chromatography. The amount of protected organic S in the acetylacetone extracts, which was only extracted when the soils were fully dispersed, ranged from 35% to 70% in different soils. Whilst the proportion of protected organic matter increased with clay content, clay content did not explain all the variation. It was shown that the majority of the physically protected SOM was present as large compounds (>100 000 Da).

SOM breakdown

Rather than assessing the chemical forms of SOM by fractionation techniques or techniques which analyse different functional groups, measurements of the rate of breakdown have been used to assess the quality of SOM. Most attempts to develop models of SOM turnover and relate SOM dynamics to soil fertility have involved the separation of carbon into a number of pools on the basis of their rate of turnover (Parton et al. 1987; McCaskill and Blair 1989; Swift et al. 1991).

The decomposition of SOM normally involves uptake of oxygen and liberation of carbon dioxide. The evolution of carbon dioxide has also been used extensively in incubation studies on organic matter decomposition (Jenkinson 1966; Ross and Malcolm 1988).

UV photo-oxidation is a technique which involves measurement of CO_2. This technique uses a mixture of air and irradiation from a high energy UV source to cause rapid oxidation of organic matter to more simple soluble molecules and ultimately to CO_2. The technique provides information on the nature of organic components and their relationships with inorganic particles (Ladd et al. 1993). Since the oxidation of organic matter situated in micropores or included within aggregates is reduced or prevented, this technique includes aspects of both chemical and physical protection (Skjemstad, pers comm.; Skjemstad, unpublished, as cited by Ladd et al. 1993).

Oxidising agents can be used to assess the relative proportions of different forms of SOM in terms of the ease with which they can be broken down. As with the UV oxidation technique, and depending on the physical preparation of the sample, such techniques can involve aspects of chemical and physical resistance to oxidation. Solutions of potassium permanganate ($KMnO_4$) have been extensively used for the oxidation of organic compounds. The rates and extent of oxidation of different substrates is governed by their chemical composition (Hayes and Swift 1978) and the concentration of permanganate. Oxidation with less than the amount of permanganate required for complete oxidation should reveal the quantity of readily oxidisable components in the SOM.

Recently, Loginow et al. (1987) developed a method of fractionating SOM and fractions or substrates of SOM based on susceptibility to oxidation by permanganate. The degree of oxidation with excess amounts of three different concentrations of $KMnO_4$ was used, in conjunction with the total carbon content of the soil, to obtain four fractions of soil carbon. The method is based on the supposition that the oxidative action of potassium permanganate on soil organic carbon under neutral conditions is comparable to that of the enzymes of soil microorganisms and other enzymes present in the soil. The lower the concentration of $KMnO_4$ required for oxidation of a certain class of compounds, the more labile the organic component.

The degree of oxidation can be analysed by measuring the release of CO_2 or the consumption of oxidising agent. These two methods will give different results; the extent of the difference depending on the average valency of the carbon in the SOM and whether complete oxidation to CO_2 occurs.

Modification of the method at UNE has increased the precision and simplified the technique to use only one concentration of permanganate, thereby dividing soil carbon into labile (C_L) and non-labile (C_{NL}) carbon. These measurements of labile carbon have been used, in combination with similar data from a soil of an uncropped, pristine area, to calculate a Sustainability Index (SI), as a measure of the relative sustainability of different agricultural systems (Lefroy and Blair 1994). This index compares the changes that occur in the total and labile carbon as a result of the agricultural practice, with increased importance attached to changes in the labile, as opposed to the non-labile, component of the SOM.

$$SI = CPI \times LI \times 100$$

$$\text{where: CPI} = \text{Carbon pool index} = \frac{C_T \text{ cropped sample}}{C_T \text{ pristine sample}}$$

$$\text{LI} = \text{Lability index} = \frac{C_{L/NL} \text{ cropped sample}}{C_{L/NL} \text{ pristine sample}}$$

In most agricultural systems, continuous cropping results in a decline in SOM. Measurement of total (C_T) and labile (C_L) carbon from two soils cropped continuously to sugarcane for 60 and 22 years, were compared to an adjacent forest area (Cerri et al. 1985; Cerri et al. 1994). The decline in C_T was accompanied by an even greater decline in C_L (Table 1a). Where there have been very large inputs of organic matter, as in some no burn, trash return sugarcane cropping systems in Australia, measurements show an increase in C_T and near maintenance of the carbon lability, with a consequent increase in the Sustainability Index (Table 1b).

Table 1. The effect of sugarcane cropping on total (C_T) and labile (C_L) carbon and the system Sustainability Index (SI) in a) São Paulo State, Brazil, and b) Mackay, Australia.

Soil History	C_T (%)	C_L (%)	C_{NL} (%)	$C_{L/NL}$	CPI	LI	SI
a) São Paulo State, Brazil							
Forest	4.34	1.10	3.24	0.340			
22 years sugarcane	1.32	0.24	1.08	0.222	0.304	0.655	20
60 years sugarcane	1.61	0.27	1.34	0.201	0.371	0.593	22
b) Mackay, Australia							
Uncropped	1.88	0.36	1.52	0.234			
15 years sugarcane	2.37	0.40	1.97	0.203	1.26	0.87	111

The $KMnO_4$ oxidation technique has been used to monitor small, relatively short-term changes in the amount and quality of SOM in different soils under different management regimes (Lefroy et al. 1993). Currently it is being used in ACIAR PN 9102 to evaluate changes in SOM quality and the SI under different organic and mineral fertilisation regimes.

Use of added isotopes in SOM studies

The dynamics of SOM have also been investigated by measuring the rate or degree of incorporation of applied isotopes into SOM, rather than the chemical or physical form or the rate of breakdown or release. Stable and radioisotopes, when available, have been used in these studies for carbon (^{14}C and ^{13}C), nitrogen (^{15}N), phosphorus (^{32}P and ^{33}P) and sulfur (^{34}S and ^{35}S).

The radioisotope ^{14}C has been used in many aspects of SOM research since first proposed in the 1950s (Bingeman et al. 1953; Hallam and Bartholomew 1953). ^{14}C-labelled substrates have been added to soils to trace the fate of added organic matter in various soil constituents (Gonzalez Prieto et al. 1992; Nowak and Nowak, 1990) and estimate the rate of mineralisation of the substrates (Shields and Paul 1973; Amato et al. 1984; Van Gestal et al. 1993). Although the production of plant material uniformly labelled with ^{14}C is not easy and requires sophisticated equipment (Hetier et al. 1986), it has been used to follow the decomposition of plant residues in the field for many years (Jenkinson 1964; Fuhr and Sauerbeck 1968; Oberlander and Roth 1968). As controls on the widespread use of radioisotopes in the field increases, and the price of stable isotopes and bench scale mass spectrometers decrease, there is likely to be increased interest in using the stable isotope ^{13}C for labelling in field and laboratory studies of SOM dynamics. It must be recognised, however, that interpretation of ^{13}C data is complicated by its presence in the atmosphere (approx. 1.1%) and in the different incorporation of ^{13}C, compared to ^{12}C, in different plant species (see below). ^{13}C-enriched substrates have been used in combination with ^{13}CNMR spectroscopy to follow their breakdown in situ (Baldock et al. 1989).

The short half-lives of ^{32}P (14 days), ^{33}P (25 days) and ^{35}S (87 days) make them less appropriate than ^{14}C ($t_{1/2}$ = 5730 years) for studies of SOM dynamics, particularly long-term studies in the field. Despite these limitations, they have been successfully used in studies of the breakdown of residues labelled with ^{33}P (Friesen and Blair 1988) and ^{35}S(Lefroy et al. 1994) and in the dynamics of ^{35}S in fractions of soil organic matter (Ericksen et al. 1994).

The move from using ^{14}C to ^{13}C is likely to be concomitant with a move from using ^{35}S to ^{34}S, as long as the price of ^{34}S continues to decline and the availability of better and more manageable mass spectrometer systems improves. The interpretation of ^{34}S data is complicated, in much the same way as for ^{13}C, by the presence of different proportions of ^{34}S to ^{32}S in a range of biological and geological forms. There is no stable isotope to replace ^{32}P and ^{33}P.

Addition of the stable isotope of nitrogen (^{15}N) has been used in many experiments in soil fertility, especially in assessment of the efficiency of applied fertilizer N and biologically fixed nitrogen, but ^{15}N labelled residues have also been used in studies of the dynamics of residue N (Catchpoole and Blair 1990).

Natural abundance of isotopes in SOM studies

The ^{13}C:^{12}C ratio in the atmosphere varies with a number of physiographic parameters (temperature, altitude, latitude, etc.), but it is also altered by certain biological processes. The major biological process is photosynthesis, in which discrimination occurs during the carboxylation step against ^{13}C, in favour of the lower atomic mass ^{12}C (Park and Epstein 1960). This discrimination varies with photosynthetic pathway, with greater discrimination against ^{13}C in C3 (Calvin cycle) plants than in C4 (Hatch-Slack cycle) plants, due to greater discrimination in the primary carboxylation step of C3 plants catalysed by the enzyme ribulose bisphosphate carboxylase (RuBP), resulting in lower $^{13}C/^{12}C$ ratios in C3 plants than in C4 plants (Raven and Farquhar 1990). CAM (crassulacian acid metabolism) plants show variable discrimination (Smith and Epstein 1971), but more often similar to C4 plants.

The ^{13}C:^{12}C ratio in SOM is comparable to that of the source plant material (Schwartz et al. 1986), and thus every change in vegetation between C3 and C4 plants leads to a corresponding change in the $^{13}C/^{12}C$ value of SOM. This principle has been used by Schwartz et al. (1986) to study changes in vegetation in the Congo, Skjemstad et al. (1990) in studying the turnover of SOM under pasture, Lefroy et al. (1993) on changes in SOM as a result of cropping, Bonde et al. (1992) on the dynamics of SOM in particle size fractions of forested and cultivated soils, Balesdent and Balabane (1992) in quantifying maize root-derived soil organic carbon, and Mary et al. (1992) in the biodegradation of root mucilage, roots and glucose in soil.

The samples from sugarcane soils in Brazil (Table 1a), provide an opportunity for using this technique in assessing the proportion of carbon derived from the forest (predominantly C3) and the proportion derived from sugarcane (C4). The ^{13}C values, which are calculated as the ^{13}C:^{12}C ratio of the sample compared to the ^{13}C:^{12}C ratio of an international standard, indicate that the reduced amount of carbon in the sugarcane soils is predominately derived from sugarcane, particularly after 60 years of continuous sugarcane cultivation (Table 2).

One advantage of natural abundance measurements, over the addition of stable or radioisotopes, is that the addition of isotope invariably involves some perturbation of the system. If the perturbations are different from the normal perturbations which occur in the system, it can be difficult to separate the effects of the perturbation from true changes in SOM dynamics.

The natural abundance of ^{15}N in soils can also be used in studies of SOM. Since the ^{15}N:^{14}N ratio can be used to separate the biologically fixed N from fertilizer or soil N, the ratio of ^{15}N:^{14}N in SOM can be used to indicate the proportion of the SOM that was derived from leguminous residues.

Another technique which uses variations in the isotope ratios present in soils relies on the elevated amounts of ^{14}C deposited in soils as a result of atmospheric detonation of thermonuclear devices in the 40s, 50s and 60s, Goh (1991). The annual input of carbon, the rate of decomposition and the turnover time of carbon have been determined using this technique (O'Brien and Stout 1978; O'Brien 1984). The main problem in using this method in soil studies is the very low amount of ^{14}C present in the soil and the consequent difficulty and expense of analysis.

Plant residue fingerprints

The ^{13}C of plants provides an in situ label of plant residues, which allows separation of the sources of SOM into being from C3 and C4 residues. It now appears that separation of the sources of SOM may be possible at, or closer to, the species level. The absolute and relative concentrations of longer chain alkanes, which are relatively resistant to breakdown in the digestive system of ruminants, are used to assess the species composition of the diet of animals from alkane measurements in faeces (Dove and Mayes 1991). Similarly, analysis of alkanes in SOM allows separation of the sources of the residue from which the SOM was formed (Rieley et al. 1991). It is likely that as soil scientists have greater access to GC-MS analytical systems, they will make increased use of techniques using alkanes and other resistant chemicals to partition the sources of carbon in SOM.

Table 2. The effect of cultivation on the source of carbon as calculated from the $\delta^{13}C$ values for soils from different cropping systems.

Soil History	$\delta^{13}C$ (%)	% of C from forest
Forest	−22.56	100
22 years sugarcane	−16.51	42
60 years sugarcane	−12.31	3

The breakdown of plant residues

Another aspect of understanding the turnover of SOM is measuring the breakdown rate of different plant residues. The breakdown rate of residues should correlate with the rate of nutrient release from these residues and the rate at which they are converted into various forms of SOM. Whilst the nutrient release from residues can be measured as plant response when the residues are applied in the field, a method whereby the breakdown rate of residues can be measured more rapidly and under controlled conditions would be more useful. A perfusion method to study in vitro decomposition of plant materials has been reported by Konboon and Lefroy (these Proceedings). The rate of breakdown of residues was affected by the nutrient content, including but not exclusively nitrogen, as well as the nature of chemical and physical barriers to decomposition. The breakdown rate of medic hay was 2.4 times greater than the breakdown rate of *Flemingia macrophylla* leaf litter, despite them having similar C:N ratios. Conversely, the breakdown rate of *F. macrophylla* was only 2 times greater than the breakdown rate of wheat, despite the C:N ratio being over 8 times greater in the wheat. The nutrient uptake and growth response of wheat grown with applications of these residues were highly correlated with the in vitro measurements of plant breakdown.

Conclusion

SOM is studied for a large number of reasons. These can range from attempts to understand the detailed interactions between organic compounds and soil mineral surfaces, to attempts to model changes in SOM resulting from different management regimes, but in most studies, an understanding of the dynamics of SOM is the underlying goal. In these various approaches to understanding SOM dynamics, it is essential that appropriate measurements of SOM are made. This can involve measurements of the total amount of soil carbon, although this rarely provides sufficient information, through to detailed analyses of various physical or chemical fractions, or combinations of these. Alternatively, the breakdown or turnover rate of the SOM or its various pools can be estimated.

In conjunction with measurements of yield, nutrient offtake and return and knowledge of the ease with which returned residues breakdown and are incorporated into the different SOM pools, measurement of the SOM status of soils allows agricultural scientists to approach a clearer understanding of SOM dynamics.

The development of indices which allow comparsion of agricultural systems, in terms if their ability to maintain an adequate resource base, is an essential part of the development of sustainable agricultural practices. The soil is the major resource base which is influenced by management. As such, measurements of SOM appear certain to feature in the indices of sustainability which will allow assessment of the exploitative nature of different agricultural systems. It is likely that an appropriate suite of measurements will include some of the measurements outlined above.

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Workshop Summary and Discussion

A questionnaire was distributed to the workshop participants asking them to comment on the current status of soil organic matter and the cycling of nutrients, how farmers currently manage organic matter, which management practices are most appropriate for improving soil organic matter status, the major constraints to adoption of practices to improve organic matter management, and what are the major applied and strategic research areas required. The participants were asked to comment in the context of particular major systems: uplands, agroforestry, lowlands or lowland-upland. The results of the questionnaire were used to guide a discussion period on the final day of the workshop.

It became clear that agroforestry was largely considered as a technology for management of uplands, and in this summary the two systems are considered together. In the lowland-upland systems emphasis was given to the rice crop. The management of the upland phase in these systems seemed to be almost entirely directed to the impacts on rice rather than production of upland crops. The discussion of lowland and lowland-upland systems are considered together.

This report is an interpretive summary of the final discussions at the workshop.

Upland systems

Current situation of soil organic matter and nutrient cycling

It was recognised that soil organic matter levels are generally low (<1% C) and are still declining except in the few instances where appropriate management techniques have been introduced. Some upland areas under native vegetation had naturally high levels of soil organic matter which declined rapidly after introduction of cropping. It was considered that nutrient cycling has been interrupted without adequate return of organic matter and associated nutrients. In some uplands bush fallows were common and this allowed the recovery of SOM but increasing population pressure has resulted in decreased fallow periods and continuing declines in SOM and nutrients. Whilst the consequences of the depletion of nutrients in these systems are clear, the consequences of declining SOM are not. These depend on rainfall and soil properties such as clay content and type, and inherent fertility, and intensity of use. There are no simple threshold values for SOM.

Current farmers' practices for managing SOM

It appeared that farmers do not consciously manage their crops and soils for their effects on SOM. Management practices varied from complete removal of all organic matter from fields (in some parts of northern Vietnam) to areas where legume understoreys are routinely applied in plantation crops (Malaysia) and to well-developed agroforestry systems. Farmers will make management effort for SOM but this is largely restricted to rapid returns from the next crop, rather than concern for the longer term maintenance of levels of SOM.

Farmers use animal manures wherever possible. In Asia it is always in short supply and its application is reserved for high-value crops such as fruit and vegetables. There is never enough to apply to field crops at rates (several tonnes/ha) expected to improved yields. However some farmers apply all available farmyard manure at high rates to each of their fields in turn, following a systematic annual rotation.

Agro-industry residues such as those from the sugar and palm oil industries are being applied with clear benefits to crop production. Their use is restricted to land near processing plants because of the costs and difficulties of transporting the waste materials.

Green manures and cover crop legumes are being used but these practices seem to be restricted to certain organised and larger-scale farming systems such as sugar cane farming in Brazil and rubber and oil palm plantations in Malaysia. The role of green manures and cover crops in reducing runoff and soil erosion in these systems has been recognised and these may be as important as their effects on SOM and nutrient supply.

In countries with mechanised cultivation, trash farming and minimum tillage have been adopted so that residues and stubble can be retained. Applications of these techniques may expand in some Asian countries as their labour costs increase in response to industrialisation. In more temperate areas the production of forages in rotation with crops is practiced. In this case the grazing period allows recovery of SOM and soil physical properties whilst income is maintained from sale of animal products.

Appropriate management techniques

Management techniques are primarily determined by the fact that organic materials are in short supply. Where alternative uses of crop residues as fodder or fuel are not paramount it is recognised that residues should be returned to the soil. Their management should be combined with tillage techniques that retain residues and surface retention is required where wind and water erosion are likely.

In some cropping systems and climates green manure crops are possible in between crops, and wherever possible should be introduced. In some locations with infertile soils it may be necessary to 'prime' the system by importation of organic matter and use of mineral fertilizers.

The production and use of compost may be possible on some systems, particularly those including animal production. However, except where there are government sponsored composting plants, as in some parts of Japan, there seems little likelihood of widescale use of compost.

The introduction of pastures into rotation with crops can also lead to improved soil conditions, including increased SOM. These systems have the advantage of producing income from animal products and animal manure during the non-cropping periods. Their use would appear to depend on the socioeconomic factors affecting livestock farming and their introduction to improve soil conditions for cropping would be a secondary consideration.

Agroforestry is appropriate for upland cropping and offers a means of conserving soil and water and maintaining soil fertility. Systems may range from alley cropping to less intensive systems in which materials from isolated woods are applied to cropped fields. They offer the opportunity of retaining crop residues if the permanent trees or shrubs provide alternative sources of fuel and fodder, fallowing under conditions less prone to erosion, and mulching materials to retain soil water. The introduction of hedgerow species with direct economic returns (such as fruits) is favoured to encourage adoption. Radical changes, for example from subsistence annual cropping to multi-layer systems may be required in acidic uplands which would otherwise need very high inputs for sustainable production.

Constraints to adoption of technologies

Alternative uses of crop residues were considered a major constraint to the retention of these materials on the soil as a source of SOM. Residues are used for animal feeding in Southeast Asia where specific forage crops are not normally grown and in some places the residues are burnt for fuel. Some residues may be burnt in the field to allow traditional cultivation methods in areas where shortages of labour and draught power preclude the incorporation of large amounts of crop residues. Furthermore, there have been cases where retained residues have contributed to increased incidence of soil-borne pests and diseases.

A lack of suitable species was cited as being the major problem with green manuring. Even when a suitable species (such as an adapted legume) was identified, there was usually a shortage of seeds and no arrangements for large-scale seed production, although government agencies provide seed to farmers in some countries. Other technical problems include difficulties in establishing green manure crops outside the main growing season and their impact on the sowing time of the main crops.

Socioeconomic factors also limit the adoption of green manuring. Farmers are reluctant to invest in a crop which does not provide a direct marketable product and are more concerned with immediate returns than with the longer term building up of soil fertility. They appear to be sceptical of the benefits of green manuring unless there are obvious and large responses to the main crop. These problems are exacerbated when the green manure crop requires inputs, for example of P and K fertilizer. Some participants thought that the low educational levels of many farmers also constrained the adoption of green manuring.

The introduction of a pasture phase is limited in areas with no tradition of animal raising. These areas would not normally be fenced so that free grazing is not possible and the labour requirements for cut-and-carry systems is considered too great. In addition, there would be inadequate markets for some products of animal grazing.

Research requirements

Applied and adaptive research is required to show how green manure cropping or grazing cropping systems can be integrated into farm enterprises. A range of systems will be required for various agro-climatic regions. Some participants thought that some systems were sufficiently well established that they should be extended. It may be necessary to run demonstrations of green manuring with emphasis on showing income above mere subsistence.

In agroforestry systems there is still a need for alternatives to *Leuceana* and *Gliricidia*. Ideally the trees or shrubs would be very adaptable to poor soils and drought, and provide organic matter which contributes to long-term accumulation of carbon in the soil as well as the shorter term provision of nutrients.

Suggestions for more strategic research were made for improvement of models of carbon dynamics. The aim would include a rigorous testing of 'synchrony' ideas and the development of a decision support system with minimal data input. At least some of these studies would need to be carried out for long periods of time to demonstrate the long-term benefits of maintaining or improving soil organic matter.

Lowland systems

This section was originally separated into irrigated (continuous) rice and rainfed upland-lowland systems. With the notable exception that irrigated rice crops were generally considered to be less sensitive to soil organic matter levels than rainfed rice, the systems had much in common and are presented together.

Current situation of soil organic matter and nutrient cycling

The view was expressed that levels of SOM were generally low (<1% C) in soils used for rice production. It was noted that some soils were naturally low in organic matter whilst in others it had been high under native vegetation and had declined, and is still declining. Some areas such as Northeast Thailand and Cambodia were noted as areas with particularly low levels of SOM and that this was closely related to low inherent soil fertility. In other areas such as the Mekong Delta in Vietnam the soils were considered to have adequate levels of organic matter. In Bangladesh the levels of SOM are generally low and farmers rely on mineral fertilizers to maintain yields. In irrigated systems with continuous rice it was considered that soil organic matter did not limit yields, although this had been brought in to question because of apparent declines in yields of long-term plots at IRRI.

There may be a loss of fertilizer-use efficiency on some soils subjected to long-term continuous rice but the link between this and SOM has not been proven.

Current farmers' practices for managing SOM

With continuous rice the straw may be grazed before ploughing for the succeeding crop or removed as a source of fodder or fuel. In some areas such as the central plain of Thailand it is frequently burnt. Animal manures are rarely used on soils used for rice as they are reserved for higher value crops such vegetables. In Laos and Cambodia animal manure is applied to rice seed beds but is not applied after transplanting. Kitchen wastes are used to supplement manures in Bangladesh but the amounts of organic matter are always too low for adequate amendment. Green manuring, the application of human wastes ('night soil') and azolla are used in Vietnam and China but their use has declined because of increased availability of cheap sources of nitrogenous fertilizers, and the rising opportunity cost of labour.

Appropriate management techniques

The retention of crop residues and the application of animal manures were considered appropriate means of improving soil organic matter levels in rice systems. As noted above, however, these materials are usually in short supply, or are too labour intensive to apply on a wide scale. Pre-rice green manures are a promising means of supplying organic matter to rice soils and some systems such as those based on *Sesbania rostrata* have proven effective in experiments. In climates where it is too dry to grow green manure crops before rice, post rice forage legumes may be possible and have the advantage of income from animal production. In some areas green manuring is achieved by collecting leaves from trees and applying them to rice paddies. This suggests that there may be some scope for agroforestry systems including wetland rice. Undersowing of direct seeded rice with mungbean as a green manure, or as an alternative insurance crop if rains fail, has shown some promise in experiments.

Constraints to adoption of technologies

Competing uses for crop residues as sources of fodder or fuel mean that farmers value them and there is a real cost in retaining residues for incorporation in the soil. In some places (Northeast Thailand, Vietnam) rice straw is being removed from paddies for use in mushroom production. In cases where there is excess straw it may be burnt in the paddies as the farmers do not have the labour or equipment to incorporate the materials. In addition, short-term immobilisation of nitrogen may occur after straw is incorporated into soils.

Major constraints to using green manuring are the investment required in the green manure crop (additional cultivation, seeds, extra labour for incorporation) and the delayed return from the rice. In rainfed areas farmers may be unwilling to make the investment in the green manure crop as a poor wet season may result in little or no return. Lack of water control, with drought or flooding, also make it difficult to produce reliable green manure crops in rainfed areas. In many cases the effects of green manures on the succeeding crop have not been sufficient to convince farmers to adopt the practice. It is, of course, difficult to convince farmers of the need for long-term maintenance of SOM when the suggested practices are returning losses, at least in the short term. As in the uplands, the risk of economic losses is increased because some promising green manure crops need fertilisation. For example *Sesbania rostrata* has proven effective in Northeast Thailand but it is necessary to add phosphatic fertilizer to obtain high levels of biomass, and in Laos the soils are frequently very deficient in phosphate and it needs to be applied to all green manure crops. Furthermore, farmers are not attracted by the requirement to plant special plots of the green manure that grow through to maturity to provide seed for the following year. Fears that *Sesbania rostrata* also acts as a host of nematodes for rice are also a constraint to its adoption.

There is also a lack of suitable species for green manure crops in rice-based systems, and a lack of seed supplies or easy methods of seed production.

Concern was expressed that application of green manures to rice soils will intensify soil reduction and lead to greater emissions of methane, a potent 'greenhouse' gas. If this is the case, and methane emission cannot be decreased by some other technique, it could lead to the discouragement of green manures.

Research requirements

Applied research is required to screen a wide range of potential green manure crops for rice-based cropping systems and adaptive research is required to integrate promising green manure crops into the cropping systems. Some green manure crops undergo rapid decomposition and provide little residual carbon. They should be selected for their ability to provide nutrients in the short term and yet be able to contribute to the more resistant pools of soil carbon. Further work should also take into account the combination of organic and mineral fertilizers to balance the need to accumulate carbon in the soil with the avoidance of short-term nitrogen immobilisation.

For continuous rice it was proposed that an occasional break with a green manure crop, or food legume, may be beneficial in maintaining rice yields. Food legumes have the advantage that they yield a cash return, although after the seed is harvested, they contribute less nitrogen and organic matter than green manure crops. These approaches need to be tested in long-term experiments.

Some basic soil characterisation work is therefore necessary before results could be transferred from other areas. In Cambodia it was suggested that basic information on soils is lacking.

Suggestions for strategic research needs included the application of simulation modelling in association with some long-term field experiments. These should aim to understand the dynamics of the decomposition of applied organic materials, and how it can be manipulated by other factors such as water regime, temperature and soil pH. Applications of nuclear magnetic resonance in combination with pyrolysis and incubation experiments was considered a promising means of understanding some of the processes of carbon dynamics.

The formation of multidisciplinary teams was emphasised as a way to improve the relevance of the research. The socioeconomic aspects of SOM management are not well understood so there is a great need for the research teams to work closely with farmers. In this way the researchers will gain an improved understanding of the indigenous knowledge systems of the farmers. This in turn will lead to a better definition of the constraints to adoption of current technologies and the development of more relevant technologies attractive to the farmers.

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