

# Modelling Nutrient Management in Tropical Cropping Systems

*Editors: R.J. Delve and M.E. Probert*



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# Preface

In tropical regions, organic materials are often more important than fertilisers in maintaining soil fertility, yet fertiliser recommendations and most crop models are unable to take account of the level and quality of organic inputs that farmers use.

Computer simulation models, such as the Agricultural Production Systems Simulator (APSIM) developed by CSIRO and the Queensland Department of Primary Industries, have proven their value in many cropping environments. These proceedings report the results of an ACIAR-supported project to test and improve the capability of APSIM to predict the decomposition of various organic inputs, the dynamics of nitrogen and phosphorus in soil, and crop yields. They document the achievements of the project and show the benefits of linking laboratory, field and modelling studies.

Another activity of the project was to train and support national collaborators in East and southern Africa in the use of APSIM for integrated, nutrient-management practices.

The project was implemented through the Soil, Water and Nutrient Management Consortium (SWNM) of the Consultative Group on International Agricultural Research (CGIAR). Project partners came from a number of institutions with an interest in simulation modelling and nitrogen and phosphorus dynamics.

As a result of this project, the APSIM computer model has been enhanced in several areas and tested against long-term data sets. The information gained will be widely used by researchers and extension services in the tropics.



Peter Core  
Director  
ACIAR

# 1

## Introduction

**R.J. Delve\* and M.E. Probert†**

These proceedings derive from the end-of-project meeting of the ACIAR-funded project ‘Integrated nutrient management in tropical cropping systems: improved capabilities in modelling and recommendations’ (Project no. LWR2/1999/003). The meeting was held in Nairobi, Kenya in January 2003. The project was managed by the Tropical Soil Biology and Fertility Institute for the Soil, Water, and Nutrient Management consortium of the Consultative Group on International Agricultural Research (CGIAR), in collaboration with CSIRO Sustainable Ecosystems/Agricultural Production Systems Research Unit (APSRU).

Smallholder farmers in the tropics rely to a large extent on organic inputs and biological processes for managing soil fertility. Biologically based farming systems range from annual cropping and fallow rotations involving biologically fixed nitrogen, to intensive continuous cropping with additions of manures and/or composts, that may be augmented with inorganic fertilisers. There has been considerable advance in the past decade in understanding the role of organic materials in soil-nutrient availability and maintenance of soil organic matter. Models that can simulate nutrient release patterns according to the resource quality, soil conditions, and climate would provide a means of making initial recommendations for testing with farmers according to their resource availability and soil management practices. Currently, crop and ecosystem models do not include appropriate routines

for simulating nitrogen dynamics following incorporation of organic inputs of the diverse nature found in tropical cropping systems.

Another major gap in soil fertility recommendations for the tropics is that of phosphorus management. Crop production on many of the soils in the tropics is limited primarily by phosphorus. Our understanding of soil phosphorus dynamics and indicators of phosphorus availability lags far behind that for nitrogen. Part of the problem in modelling phosphorus is in its complex biogeochemical cycle. To date, no crop or ecosystems model has adequately captured phosphorus dynamics for estimating crop (or ecosystem) production. Considerable data have been gathered on phosphorus dynamics and soil phosphorus fractions in relation to plant productivity from a variety of soil types and management conditions in the tropics. As well as being crucial for improving understanding of P in the soil-plant system and P management, the data can be used for developing phosphorus routines of crop and ecosystem production models.

The APSIM modelling framework (Keating et al. 2003; web site <[www.apsim.info](http://www.apsim.info)>) was selected for this project because it is one of the most appropriate models for use in tropical soil and crop management. This model provides not only the short time-step essential for simulating effects of management on nutrient availability and crop growth, but also incorporates longer-term effects of changes in soil organic matter content on N mineralisation and hence on crop growth. Selection of APSIM was also based on efforts by APSRU towards developing modules to describe the release of nutrients (N and P) from added organic inputs (APSIM ‘Manure’), the dynamics of phosphorus in soil (APSIM ‘SoilP’), and routines within the ‘Maize’ crop module to limit

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growth due to inadequate supply of P in addition to nitrogen and water constraints. These modules provided a framework necessary for simulating the effects of diverse organic inputs on cropping systems found in tropical regions. Once a model has been tested and verified for a particular purpose, in this case the combined use of organic and inorganic nutrient sources, it can be a valuable tool in focusing research and ultimately for making recommendations for crop and soil management.

Project partners came from a range of institutions with an interest in simulation modelling and N and P dynamics. These partners were:

#### *Kenya*

- International Centre for Research in Agro-Forestry (ICRAF)
- International Livestock Research Institute (ILRI)
- Kenya Agricultural Research Institute (KARI)
- Tropical Soil Biology and Fertility (TSBF) Institute

#### *Zimbabwe*

- International Maize and Wheat Improvement Center (CIMMYT)
- International Crop Research Institute for the Semi-arid Tropics (ICRISAT)
- TSBF – Southern Africa Soil Fertility Network

#### *Colombia*

- International Center for Tropical Agriculture (CIAT)
- Colombian Corporation of Farming Investigation (CORPOICA)

#### *Southeast Asia*

- International Board for Soil Research and Management (IBSRAM), with national partners

## **Project Planning and Operations**

The purpose of the project was to develop a modelling capability that can be applied to farming systems where both organic and inorganic sources of nutrients are used. In tropical regions, organic materials are often more important for maintenance of soil fertility than fertilisers, yet current fertiliser recommendations and most crop models are unable to take account of the organic inputs and the different qualities of these organic inputs that farmers use. This project tested and, where necessary, improved the APSIM Manure and SoilP modules so that they can

be applied to the management of soil fertility, especially in low-input systems in the tropics.

A project implementation workshop in 1999 brought together 25 participants with experience in the management of organic inputs and phosphorus dynamics in soil. At the workshop, decisions were made on the nature of the data sets needed to test the model and where new data were to be collected so that they are compatible with inputs required by APSIM.

During the project, meetings were held in Nairobi to familiarise collaborators with APSIM, train them in APSIM use, and to compile data sets for testing and evaluating the Manure and SoilP modules. Any code changes required within APSIM were done in Australia by APSRU, and modified versions of the modules were tested in subsequent workshops. Outside of these formal workshops, modelling support was provided in East and southern Africa, as well as in Asia, to continue developing the data sets, modelling work and support to APSIM users.

## **Project Objectives**

The project objectives were:

- to collate and synthesise data from existing trials compatible with the requirements of APSIM for testing and modification of the manure and phosphorus modules
- to strengthen the capability of APSIM to predict nutrient availability and subsequent crop growth following the addition of organic and inorganic nitrogen and phosphorus nutrient sources
- to train and support national collaborators in East and southern Africa in the use of APSIM for integrated nutrient management practices.

## **Project Outcomes**

These proceedings document the achievements of the project and show the benefits from linking laboratory, field and modelling studies. Resource-poor farmers face difficult decisions over the use of scarce nutrient sources in production systems. Efforts are required to expand our knowledge of the biophysical aspects of alternative uses of organic nutrient sources and also the socioeconomic driving forces behind farmers' decision-making (Chapter 2.1). Often the decisions on the use of organic resources are taken without an assessment or appreciation of the impact

of alternative uses on plant production and on soil and water resources. While existing simulation models are able to simulate responses of crops to, for example, inorganic fertiliser additions, there are still gaps in our ability to simulate short and long-term effects of additions of different organic N and organic and inorganic P resources (Chapter 2.2). A deeper understanding from the farmers' perspective of the comparative values and usefulness of manures and other locally available resources is required in order to increase the production and efficiency of their production systems and to be able to target improved management options using participatory approaches (Chapter 2.3).

Consideration of the influence of organic resource quality on nutrient management and nutrient release dynamics, introduced in Chapter 2.1, is expanded in Section 3. These chapters cover different analytical techniques for measuring resource quality, and relate the resource quality factors to the mineralisation of nitrogen. It is the understanding that comes from such studies that needs to be represented in the models, with the indicators that can be measured being used to parameterise the models.

Simulation models were not able to mimic the complex pattern of N release that has been reported for some animal manures, notably materials that exhibit initial immobilisation of N even when the C:N of the material suggests it should mineralise N. The APSIM SoilN module was tested against existing data sets and modified so that the three pools that constitute added organic matter could be specified in terms of both the fraction of carbon in each pool and also their C:N ratios; previously it has been assumed that all pools have the same C:N ratio (Chapter 4.1). The revised Manure module is better able to simulate the general patterns on N mineralised that have been reported for different quality manures (Chapters 4.1 and 4.2). Attempting to simulate P mineralisation from organic sources in a manner analogous to that done for N results in the P concentration required for net mineralisation being much higher than found experimentally. It is suggested that this arises because much of the P is water soluble. It is expected that specifying the C:P ratio of each pool will overcome this anomaly.

The APSIM Maize module was enhanced so that uptake of P was determined by the availability of P in the soil, the P in the plant was partitioned between the plant components, and crop growth was influenced by the P status of the plant (Chapter 4.3). This

'P-aware' maize module was a major breakthrough in our thinking of how to explicitly reflect P dynamics, and especially P limitations in crop simulations. Further fieldwork has been initiated using funds from other donors to produce the data required to parameterise other crop modules, specifically cowpea and millet (in West Africa, funded by IFDC), pigeonpea, groundnut and sorghum (in India, funded by the UK Department for International Development) and canola (in Australia funded by CSIRO and the Grains Research and Development Corporation).

In this project the SoilP, Manure and Maize modules have been tested against three long-term data sets from western Kenya (Chapter 4.4), central Kenya (Chapter 4.5) and India (Chapter 4.6).

## Conclusions

The APSIM model now includes a capability to simulate the N and P dynamics from different quality manures and their effects on crop growth. There is only one other modelling group that is working on soil P routines and limiting simulated plant growth as a consequence of a P constraint (Daroub et al. 2003).

This project has contributed to the improvement and validation of the APSIM Manure and SoilP modules. The organic resource quality parameters and methods for measuring them that have been identified through this project provide more relevant and streamlined data collection protocols for model parameterisation. Ultimately, the project outputs will contribute to improving the capacity to make recommendations to farmers on better management of nitrogen and phosphorus nutrient sources for crop production.

The improved management of soil fertility needs to be evaluated from economic, social, and environmental perspectives. From the economic sense, combinations of organic and inorganic nutrient sources need to be identified that increase and maintain crop production. This evaluation should include differences in both the short and longer-term benefits. From the social and economic sense, organic resources identified can substitute for mineral fertilisers in areas where fertilisers are not available or affordable. From an environmental aspect, management practices could be identified that would result in smaller losses of nutrients and would rebuild or maintain the soil resource base.



The modified model and protocols resulting from this research are applicable to researchers and extension services in the tropics. At the national levels, the teams trained in the use of the model could provide guidelines and recommendations for both researchers and extension services on the types of organic inputs, and their appropriate combinations with mineral fertilisers, that should provide the best short and long-term effects. Such recommendations could be used for designing long-term experiments for verifying model predictions or directly for achieving impact on-farm.

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**2**

## **Invited Papers**

## 2.1

# The Multiple Roles of Organic Resources in Implementing Integrated Soil Fertility Management Strategies

**Bernard Vanlauwe and Nteranya Sanginga\***

### *Abstract*

The Tropical Soil Biology and Fertility (TSBF) Institute, its African Network (AfNet), and various other organisations, have adopted 'integrated soil fertility management' (ISFM) as the paradigm for tropical soil fertility management research and development. The development of ISFM is the result of a series of paradigm shifts generated through experience in the field and changes in the overall socioeconomic and political environment faced by the various stakeholders, including farmers and researchers. The first part of the paper illustrates these shifts and outlines how the science of organic matter management has developed in the framework of the various paradigms. The second part focuses on the technical backbone of ISFM strategies, by illustrating the roles of organic resources, mineral fertiliser and soil organic matter in providing soil-related goods and services. Special attention is given to the potential occurrence of positive interactions between these three factors, leading to added benefits in terms of greater crop yield, improved soil fertility status, and/or reduced losses of C and nutrients to the environment. The third section aims at confronting the principles and mechanisms for soil fertility management, highlighted in the second section, with reality, and focuses on the impact of other realms of capital on soil management opportunities and the potential of decision aids to translate all knowledge and information in a format accessible to the various stakeholders.

During the past four decades, the paradigms underlying soil fertility management research and development efforts have undergone substantial evolution to respond to changes in the overall social, economic, and political environment the various stakeholders are facing and the experiences gained by researchers.

During the 1960s and 1970s, an 'external input' paradigm was driving the research and development agenda. The appropriate use of external inputs, e.g. fertilisers, lime, or irrigation water, was believed to be sufficient to alleviate any constraint to crop production. Following this paradigm together with the use of improved cereal germplasm, the green revolu-

tion boosted agricultural production in Asia and Latin America in ways not seen before. However, for a variety of reasons, application of the green revolution strategy in sub-Saharan Africa (SSA) resulted in only minor achievements (IITA 1992). This, together with environmental degradation resulting from massive applications of fertilisers and pesticides in Asia and Latin-America between the mid-1980s and early-1990s (Theng 1991), and the abolition of the fertiliser subsidies in SSA (Smaling 1993), imposed by structural adjustment programs, led to a renewed interest in organic resources in the early 1980s following an 'organic input' paradigm. The balance shifted from mineral inputs only to low mineral input sustainable agriculture (LEISA) in which organic resources were believed to enable sustainable agricultural production. After a number of years of

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investment in research activities evaluating the potential of LEISA technologies, such as alley cropping or live-mulch systems, several constraints were identified both at the technical (e.g. lack of sufficient organic resources; lack of sufficient short-term yield increases) and the socioeconomic level (e.g. labour-intensive technologies).

In this context, Sanchez (1994) formulated the ‘second paradigm’ for tropical soil fertility research: ‘Rely more on biological processes by adapting germplasm to adverse soil conditions, enhancing soil biological activity and optimising nutrient cycling to minimise external inputs and maximise the efficiency of their use’. This paradigm did recognise the need for both mineral and organic inputs to sustain crop production, and emphasised the need for all inputs to be used efficiently. This advice was driven by (i) the lack of a sufficient amount of either mineral or organic inputs, (ii) the recognition that both inputs fulfil a set of different functions, and (iii) the potential for creating added benefits when applying organic resources in combination with fertilisers. The second paradigm also highlighted the need for improved germplasm; in earlier studies more emphasis was put on the nutrient supply side without worrying too much about the demand for these nutrients. Optimal synchrony or use efficiency requires both supply and demand to function optimally.

From the mid-1980s to the mid-1990s, the shift in paradigm towards the combined use of organic and mineral inputs was accompanied by a shift in approaches towards involvement of the various stakeholders in the research and development process, mainly driven by the ‘participatory’ movement (Swift et al. 1994). One of the important lessons learnt was that the farmers’ decision-making process was not merely driven by the soil and climate but by a whole set of factors cutting across the biophysical, socioeconomic, and political domain. The ‘sustainable livelihoods approach’ (DFID 2000) recognises the existence of five realms of capital (natural, manufactured, financial, human and social) that constitute the livelihoods of farmers. It was also recognised that natural capital, such as soil, water, atmosphere, or biota does not only create services which generate goods with a market value (e.g. crops and livestock) but also services which generate amenities essential for the maintenance of life (e.g. clean air and water). Due to the wide array of services provided by natural capital, different stakeholders may have conflicting interests in natural capital. The ‘integrated natural

resource management’ (INRM) research approach aims at developing interventions that take all the above into account (Izac 2000). The ‘integrated soil fertility management’ (ISFM) paradigm, which forms an integral part of the INRM research approach with a focus on appropriate management of the soil resource, is currently adopted in the soil fertility research and development community. Although technically ISFM follows the second paradigm (Sanchez 1994), it goes further in explicitly recognising the important role of the social, cultural, and economic processes regulating soil fertility management strategies. ISFM is also broader than ‘integrated nutrient management’ (INM) as it recognises the need for an appropriate physical and chemical environment for plants to grow optimally, besides a sufficient and timely supply of available nutrients.

## **The Science of Organic Matter Management Following Shifts in Soil Fertility Management Paradigms**

The conceptualisation of the role of organic resources in tropical soil fertility management has evolved alongside the changes in the guiding paradigms. In the context of the external input paradigm, organic resources were given little attention and were certainly not felt essential for sustainable crop production (Table 1). Confirming this paradigm, Sanchez (1976) stated that, when mechanisation is feasible and fertilisers are available at reasonable cost, there is no reason to consider the maintenance of soil organic matter (SOM) as a major management goal.

Although organic inputs had not been new to tropical agriculture, the first seminal synthesis on organic matter management and decomposition was not written until 1979 (Swift et al. 1979). Between 1984 and 1986, a set of hypotheses was formulated based on two broad themes, ‘synchrony’ and ‘SOM’ (Swift, 1984, 1985, 1986) building on the concepts and principles formulated in 1979. Under the first theme, the O(rganisms)–P(hysical environment)–Q(uality) framework for organic matter (OM) decomposition and nutrient release (Swift et al. 1979), formulated earlier, was elaborated and translated into hypotheses driving management options to improve nutrient acquisition and crop growth. Under the second theme, the role of OM in the formation of functional SOM fractions was stressed. It is also interesting to note that, during this period,

organic resources were seen mainly as sources of nutrients, and more specifically N (Table 1). During the 1990s, the formulation of the research hypotheses relating to residue quality and N-release led to a vast amount of projects aiming at validation of these hypotheses, both within TSBF and other research groups dealing with tropical soil fertility. This information has been instrumental in permitting proper evaluation of the sustainability and efficiency of systems based on the organic input paradigm.

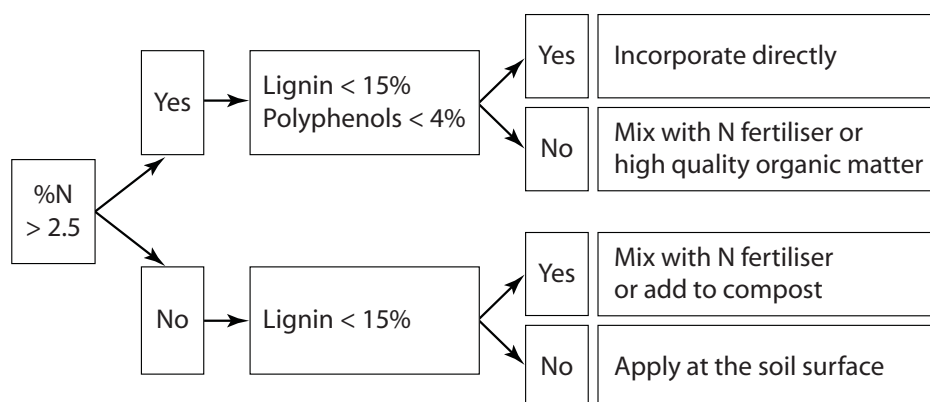
**Table 1.** The changing role of organic resources in tropical soil fertility management.

Period	Soil fertility management paradigm	Role of organic resources
1960s	External input paradigm	Organic matter plays a minor role
1980s	Biological management of soil fertility; LISA	Organic matter is a source of nutrients
1996	Second paradigm – combined application of organic resources and mineral fertiliser	Organic matter fulfils other important roles besides supplying nutrients
Now	Integrated soil fertility management	Organic matter management has social, economic, and political dimensions

A significant part of the work dealing with organic resource management aimed at fine-tuning procedures for organic resource quality determination. Short-term N availability from organic resources was

initially related mainly to their C:N ratio. Efforts to fine-tune organic resource quality assessments were derived from feed-quality assessments, traditionally used in the field of animal science. Examples are the determination of the fibre components of organic resources in terms of hemicellulose, cellulose, and lignin following various modification of the Van Soest fractionation scheme (Van Soest 1963; Van Soest and Wine 1968). Soluble polyphenols (King and Heath 1967) also became standard indicators of organic resource quality, as these appeared to strongly affect the short-term release of mineral N, mainly from leguminous organic resources that commonly have a rather high N content (e.g. Palm and Sanchez 1991). Further work indicated that soluble polyphenols are also very diverse (Harborne 1997) and react differently with proteins in organic resources. The protein-binding capacity, also originating from animal science, was found to be more sensitive in predicting mineral N release than the total soluble polyphenol content (Handayanto et al. 1997). Recently, spectroscopic approaches are being validated for their potential to determine organic resource quality (Shepherd et al. 2004).

Two major events further accentuated the relevance of decomposition processes to tropical soil fertility management. Firstly, a workshop held in 1995, on the theme ‘Plant litter quality and decomposition’, resulted in a book summarising the state of the art in the topic (Cadisch and Giller 1997). Secondly, TSBF, in collaboration with its national partners and Wye College, developed the ‘organic resource database’ (ORD) and related decision-support system (DSS) for OM management (Fig. 1; Palm et al. 2001). ORD contains information on organic resource quality



**Figure 1.** The decision-support system for organic matter management. Source: Palm et al. (2001).

parameters including macronutrient, lignin and polyphenol contents of fresh leaves, litter, stems and/or roots from almost 300 species found in tropical agro-ecosystems. Careful analysis of the information contained in the ORD led to the development of the DSS, which makes practical recommendations for appropriate use of organic materials, based on their N, polyphenol, and lignin contents resulting in four categories of materials (Fig. 1). Recently, a farmer-friendly version of the DSS has been developed by Giller (2000).

The DSS recognises the need for certain organic resources to be applied together with mineral inputs, consistent with the second paradigm. Organic resources are seen as inputs complementary to mineral fertilisers, and their potential role has consequently been broadened from a short-term source of N to a wide array of benefits both in the short and long term (Table 1; Vanlauwe et al. 2002a). The potential for positive interactions is treated in more detail below.

Finally, the ISFM paradigm has also led to increased emphasis on the social, economic, and policy dimensions of organic input management (TSBF 2002).

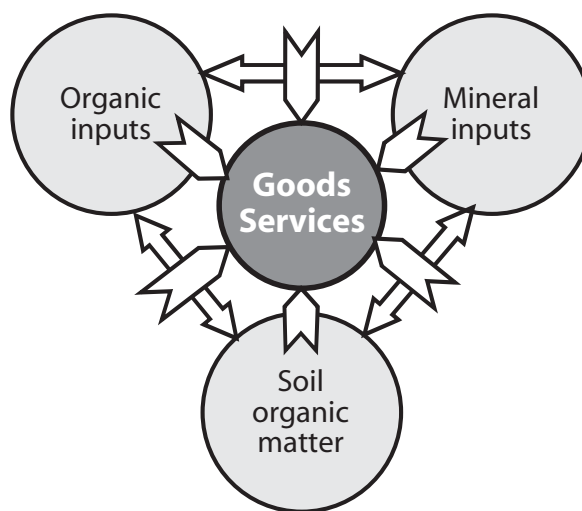
### **The Technical Backbone of ISFM: Optimal Management of Organic Resources, Mineral Inputs, and the Soil Organic Matter Pool**

Optimal management of the soil resource for provision of goods and services requires the optimal management of organic resources, mineral inputs, and the SOM pool (Fig. 2). Each of these resources contributes to the provision of goods and services individually, but, more interestingly, these various resources can be hypothesised to interact and generate added benefits in terms of extra crop yield, an improved soil fertility status, and/or reduced losses of nutrients.

#### **Impact of individual factors on the provision of goods and services**

Numerous studies have looked at crop responses to applied fertiliser in SSA and have reported substantial increases in crop yield. Results from the FAO Fertilizer Program have shown an average increase in maize grain production of 750 kg ha<sup>-1</sup> in response to medium NPK applications (FAO 1989). Value-to-cost

ratios (VCR) varied between 1.1 and 8.9, and were usually above the required minimum ratio of 2. National fertiliser recommendations exist for most countries, but actual application rates are nearly always much lower, and in many cases zero, due to socioeconomic constraints rather than technical ones. For a variety of reasons, fertilisers are expensive in SSA; for example, prices were \$7.5 per 50 kg bag of urea in Germany versus \$13–17 per 50 kg bag in Nigeria in 1999 (S. Schulz, pers. comm., 2000). This is further aggravated by the lack of credit schemes to purchase these inputs, as there is often a large interval between fertiliser purchase and revenue collection from selling harvested products. Mineral inputs have relatively little potential to enhance the SOM status, which is central to the provision of many soil-based ecosystem services (Vanlauwe et al. 2001a). In the case of N fertiliser, they may even contaminate (ground)water resources when not used efficiently. The production of N fertiliser itself requires a substantial amount of energy, usually derived from fossil fuels, and contributes to the CO<sub>2</sub> load of the atmosphere.



**Figure 2.** The goods and environmental services generated by the soil are the result of the management of organic resources, mineral inputs, and the soil organic matter pool, and the interactions between these various factors.

In cropping systems with sole inputs of organic resources, short-term data reveal a wide range of increases in maize grain yield compared with the control systems without inputs (Fig. 3). Although yields on fields with a low soil fertility status (e.g.

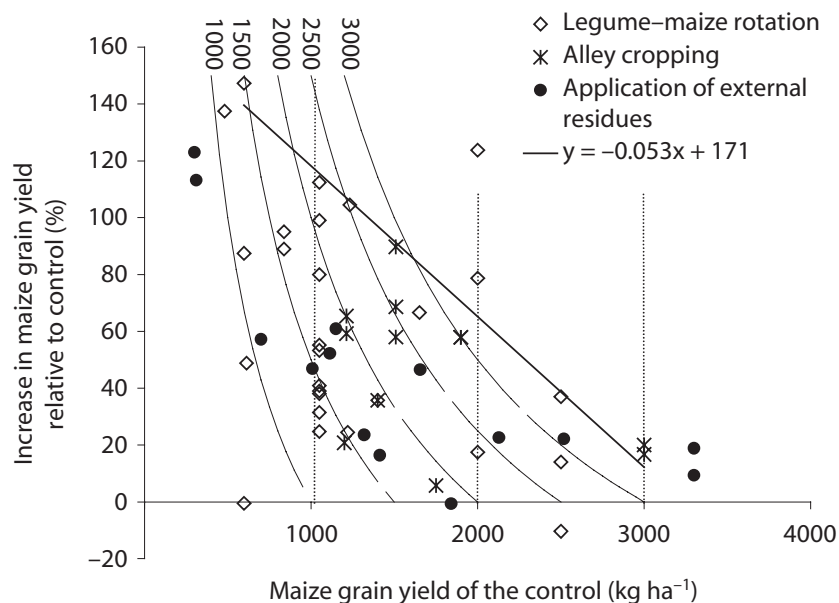
with control yields below 1000 kg ha<sup>-1</sup>), can easily be increased up to 140% after incorporation of a source of OM in the cropping system, this would lead to absolute yields hardly exceeding 1500 kg ha<sup>-1</sup> (Fig. 3). With higher soil fertility status, the maximum increases observed were proportionally lower, falling to virtually nil at control grain yields of about 3000 kg ha<sup>-1</sup>. Thus, in most cropping systems, absolute yield increases in the OM-based treatments are far below 1000 kg ha<sup>-1</sup>, while significant investments in labour and land are needed to produce and manage the OM. This is partly related to the low N use efficiency of OM (Vanlauwe and Sanginga 1995; Cadisch and Giller 1997). Other problems are low and/or imbalanced nutrient content, unfavourable quality, or high labour demand for transporting bulky materials (Palm et al. 1997).

Although most of the organic resources show limited increases in crop growth, they do increase the soil organic C status (Vanlauwe et al. 2001a) and have a potentially positive impact on the environmental service functions of the soil resource. Soil

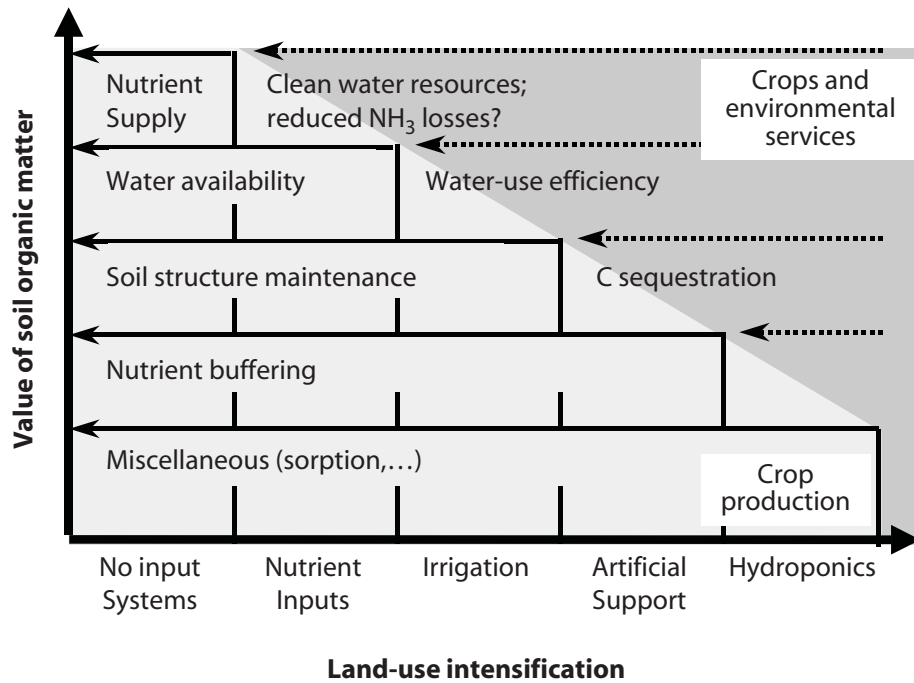
organic matter is not only a major regulator of various processes underlying the supply of nutrients and the creation of a favourable environment for plant growth, but also regulates various processes governing the creation of soil-based environmental services such as buffering the atmospheric CO<sub>2</sub> loads or favouring water infiltration in the soil through a better soil structure (Fig. 4).

### Potential interactions between the various factors on the provision of goods and services

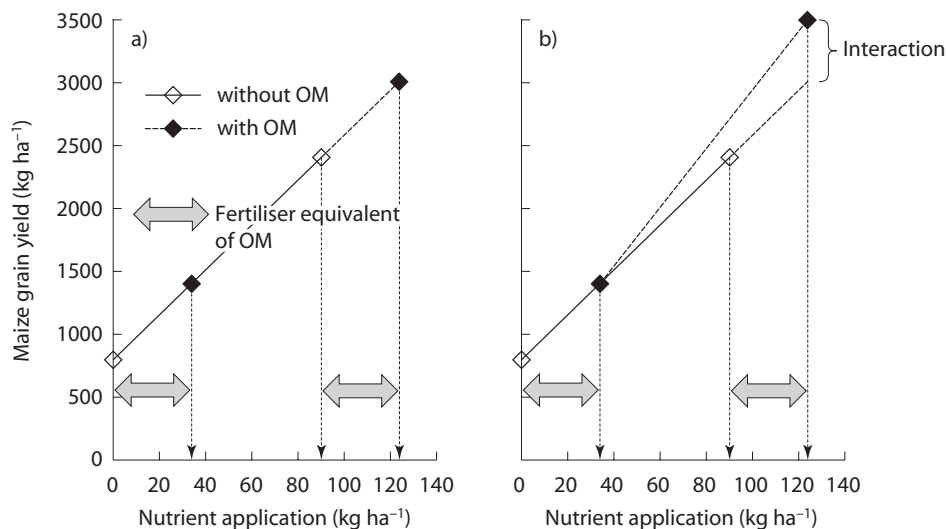
The second paradigm initiated a substantial effort to evaluate the impact of combined applications of organic resources and mineral inputs, as positive interactions between both inputs could potentially result in added benefits (Fig. 5). Two hypotheses that could form the basis for the occurrence of such benefits were formulated by Vanlauwe et al. (2001a): The “direct hypothesis” postulated that: ‘Temporary immobilisation of applied fertiliser N may improve the synchrony between the supply of and demand for



**Figure 3.** Increase in maize grain yield relative to the control in cropping systems based on organic matter management (legume–maize rotation, alley cropping, systems with application of external organic matter) without inputs of fertiliser N as influenced by the initial soil fertility status, expressed as yield in the control plots. The linear regression line shows the estimated maximal increases in grain yield. The curved lines show the absolute yields in the treatments receiving organic matter (in kg ha<sup>-1</sup>). Source: Vanlauwe et al. (2001a).



**Figure 4.** From the crop production point of view, the relevance of soil organic matter (SOM) in regulating soil fertility decreases (plain horizontal arrows) as natural capital is being replaced by manufactured or financial capital with increasing land-use intensification. From an integrated soil fertility management point of view, that also considers environmental service functions besides crop production functions, one could argue that the relevance of SOM does not decrease (dashed horizontal arrows).



**Figure 5.** Theoretical response of maize grain yield to the application of a certain nutrient as fertiliser in the presence or absence of organic matter. The interaction effect is indicated on the graph. It is assumed that the applied nutrient rates belong to the linear range of the response curve. Source: Vanlauwe et al. (2001a).



N and reduce losses to the environment'. The 'indirect hypothesis' was formulated for N supplied as fertiliser and proposed that: 'Any organic matter-related improvement in soil conditions affecting plant growth (except N) may lead to better plant growth and consequently enhanced efficiency of the applied N'. The indirect hypothesis recognises that organic resources can have multiple benefits besides the short-term supply of available N. Such benefits could be an improved soil P status by reducing the soil P sorption capacity, improved soil moisture conditions, less pest and disease pressure in legume-cereal rotations, or other mechanisms. Both hypotheses predict an enhancement in N-use efficiency: processes following the direct hypothesis through improvement of the N supply and processes following the indirect hypothesis through an increase in the demand for N. Obviously, mechanisms supporting both hypotheses may occur simultaneously.

Testing the direct hypothesis with  $^{15}\text{N}$  labelled fertiliser, Vanlauwe et al. (2002b) concluded that direct interactions between OM and fertiliser-N exist not just in the laboratory but also under field conditions. The importance of residue quality and ways in which organic inputs are incorporated into soil to the magnitude of these interactions was also demonstrated. In a multi-locational trial with external inputs of organic matter, Vanlauwe et al. (2001b) observed added benefits from the combined treatments at two of the four sites, which experienced serious moisture stress during the early phases of grain filling. The positive interaction in these two sites was attributed to the reduced moisture stress in the 'mixed' treatments compared to the sole urea treatments because of the presence of organic materials (surface and subsurface placed) and constitutes evidence for the occurrence of mechanisms supporting the indirect hypothesis. Although more examples supporting the indirect hypothesis can be found in literature, it is clear that a wide range of mechanisms could lead to an improved use efficiency of applied external inputs. These mechanisms may also be site-specific, e.g. an improvement in soil moisture conditions is of little relevance in the humid forest zone. Unravelling these, where feasible, as a function of easily quantifiable soil characteristics, is a major challenge and needs to be done in order to optimise the efficiency of external inputs. On the other hand, when applying organic resources and mineral fertiliser simultaneously, one hardly ever observes negative interactions, indicating that even without clearly

understanding the mechanisms underlying positive interactions, applying organic resources in combination with mineral inputs stands as an appropriate fertility management principle.

Because SOM affects a series of factors supporting plant growth, and because of the observed within-farm variability in soil fertility and SOM status, interest has recently developed in relating the use efficiency of mineral N inputs to the SOM status. A set of hypotheses follows the general principles behind the indirect hypothesis outlined above and results in positive relationships between SOM content and fertiliser use efficiency. On the other hand, SOM also releases available N that may be better synchronised with the demand for N by the plant than is fertiliser N, and consequently a larger SOM pool may result in lower fertiliser N use efficiencies. A preliminary investigation, carried out in a long-term alley cropping trial, showed a negative correlation between the proportion of maize N derived from the applied fertiliser and the topsoil organic C content and supports the latter hypothesis (B. Vanlauwe et al., unpublished data). Other reports show higher use efficiency of N fertiliser (H. Breman, pers. comm.) and P fertiliser (A. Bationo, pers. comm.) for homestead fields with a higher SOM content.

Finally, application of organic resources is the easiest way to increase SOM. Although it is only possible in the medium to long term to induce substantial changes in soil organic C content in experimental trials using realistic organic matter application rates, the sometimes large differences in SOM found between fields within one farm prove that farmers are already managing the SOM status. While residue quality has been shown to significantly affect the short-term decomposition/mineralisation dynamics (Palm et al. 2001), it is unclear whether quality is still an important modifier of the long-term decomposition dynamics. Several hypotheses have been formulated, most of them postulating that slowly decomposing, low-quality organic inputs with relatively high lignin and polyphenol content will have a more pronounced effect on the SOM pool than rapidly decomposing, high-quality organic inputs (Fig. 1). The 'C stabilisation potential' could be an equivalent index to the N fertiliser equivalency index used to describe the short-term N release dynamics. The few trials that have shown significant increases in SOM have used farmyard manure as organic input, which may be related to the presence of resistant C in

the manure, as the available C is digested while passing through the digestive track of the animal.

## From Theory to Practice: Implementation of ISFM Practices at the Farm Level

Having focused on the principles and technical issues underlying the ISFM research agenda, these need to be put into the wider context this paper began with. This section looks at ISFM options from the farmer perspective and considers ways to disseminate these options to the various stakeholders.

### Production of organic matter in existing cropping systems: the bottleneck in implementing ISFM practices

Although there is a wide range of potential niches to produce organic resources within existing cropping systems (Table 2), introducing an organic matter production phase in a cropping system creates prob-

lems with adaptability and adoptability of such technologies, especially if this fallow production phase does not yield any commercial product, such as grain or fodder. Although a significant amount of organic matter can potentially be produced in cropping systems with in situ organic matter production, adoption of such cropping systems by the farmer community is low and often driven by other than soil-fertility regeneration arguments. Dual-purpose grain legumes, on the other hand, have a large proportion of their N derived from biological N fixation, a low N harvest index, and produce a substantial amount of both grain and biomass, and thus have a great potential to become part of such cropping systems (Sanginga et al. 2001). Additional advantages to the substantial amount of N fixation from the atmosphere associated with growing high biomass producing legumes in rotation with cereal include potential improvement of the soil available P status through rhizosphere processes operating near the root-zone of the legume crop (Lyasse et al. 2002), reduction in pest and disease pressure by e.g. *Striga* spp., and improved soil physical properties. These processes

**Table 2.** Place and time of production of organic matter (fallow species) relative to crop growth and the respective advantages/disadvantages of the organic matter production systems with respect to soil fertility management and crop growth. ‘Same place’ and ‘same time’ mean ‘in the same place as the crop’ and ‘during crop growth’. Source: adapted from Vanlauwe et al. (2001a).

Place and time of organic matter production – example of farming system	Advantages	Disadvantages
Same place, same time – alley cropping	<ul style="list-style-type: none"> <li>– ‘Safety-net’ hypothesis (complementary rooting depths)</li> <li>– Possible direct transfer from N<sub>2</sub> fixed by legume species</li> </ul>	<ul style="list-style-type: none"> <li>– Potential competition between crop and fallow species</li> <li>– Reduction of available crop land</li> </ul>
Same place, different time – crop residues – legume–cereal rotation – improved tree fallows – manure, derived from livestock fed from residues collected from same field	<ul style="list-style-type: none"> <li>– ‘Rotation’ effects (N transfer, improvement of soil P status...)</li> <li>– Potential inclusion of ‘dual purpose’ legumes</li> <li>– In-situ recycling of less mobile nutrients</li> <li>– No competition between fallow species and crops</li> </ul>	<ul style="list-style-type: none"> <li>– Land out of crop production for a certain period</li> <li>– Decomposition of organic matter may start before crop growth (potential losses of mobile nutrients, e.g. N, K...)</li> <li>– Extra labour needed to move organic matter (manure)</li> </ul>
Different place – cut-and-carry systems – household waste – animal manure, not originating from same field	<ul style="list-style-type: none"> <li>– Utilisation of land/nutrients otherwise not used</li> <li>– No competition between fallow species and crops</li> </ul>	<ul style="list-style-type: none"> <li>– Extra labour needed to move organic matter</li> <li>– No recycling of nutrients on crop land</li> <li>– Need for access to extra land</li> <li>– Manure and household waste often have low quality</li> </ul>

yield benefits to a cereal crop beyond available N but are often translated into N fertiliser equivalency values. Obviously, values greater than 100% should be expected sometimes.

In cut-and carry systems, which involve the transfer of nutrients from one area to another, it is necessary to determine how long soils can sustain vegetation removal before collapsing, especially soils which are relatively poor and where vegetative production can be rapid. Cut-and-carry systems without use of external inputs may be a ‘stay of execution’ rather than a sustainable form of soil fertility management. Of further importance is the vegetation succession that will occur after vegetative removal. It is possible that undesirable species could take over the cut-and-carry field once it is no longer able to sustain removal of the vegetation of the selected species. Where an intentionally planted species is used, the natural fallow species needs to be compared to determine what advantage, if any, is being derived from the extra effort to establish and maintain the planted species.

#### *Soil fertility gradients*

There is a substantial amount of evidence that the soil fertility status of the various fields within a farm can be quite variable, often leading to gradients in which soil fertility decreases as one moves away from the household (Table 3). These gradients are commonly caused by long-term, site-specific soil management by the farmer, and have a considerable influence on crop yield (Fig. 6). Most soil fertility research has been targeted at the plot level, but decisions are made at the farm level, taking into account the production potential of all plots. In Western Kenya, for example, farmers will preferably grow sweet potato on the most degraded fields, while bananas and cocoyam occupy the most fertile fields (Tittonell 2003). As such variations in soil fertility status are likely to affect the use efficiency of mineral

inputs (see above), the potential growth of legumes, and other important processes regulating ISFM options, it is important to take such gradients into account when formulating recommendations for ISFM. One important condition of such recommendations, however, is that these should be related to local classification systems for soil fertility evaluation, as smallholder farmers are unlikely to analyse their soils before deciding on their management. The existence of different fields with varying soil fertility status at the farm level is also likely to determine which are the optimal spatial and temporal niches within a farm to produce organic resources.

#### *Beyond the soil: links with other realms of capital*

So far, this paper has focused mainly on the management of natural capital, with some inclusion of manufactured capital in the form of mineral inputs. However, as stated above, farmers’ livelihoods consist of various realms of capital, all of which contribute to their decision-making about soil fertility management. One obvious factor affecting the way farmers manage their soils is related to their wealth in terms of access to other realms of capital, such as cash, labour, or knowledge. Rommelse (2001) reported that, in villages in Western Kenya, relatively wealthy farmers spend US\$102 on farm inputs per year compared with US\$5 for relatively poor farmers. Besides having an overall impact on the means to invest in soil fertility replenishment, farmers’ wealth also affects the strategies preferred to address soil fertility decline. In two districts in western Kenya, Place et al. (2002) observed that wealthy farmers not only use mineral fertilisers more than do poor farmers, but also use a wider range of soil management practices. Farmer production objectives, which depend on a whole set of biophysical, social, cultural, and economic factors, also take into account the fertility gradients existing within their farm boundaries.

**Table 3.** Soil fertility status of various fields within a farm in Burkina Faso. Home gardens are near the homestead, bush fields furthest away from the homestead and village fields at intermediate distances. Source: Prudencio et al. (1993).

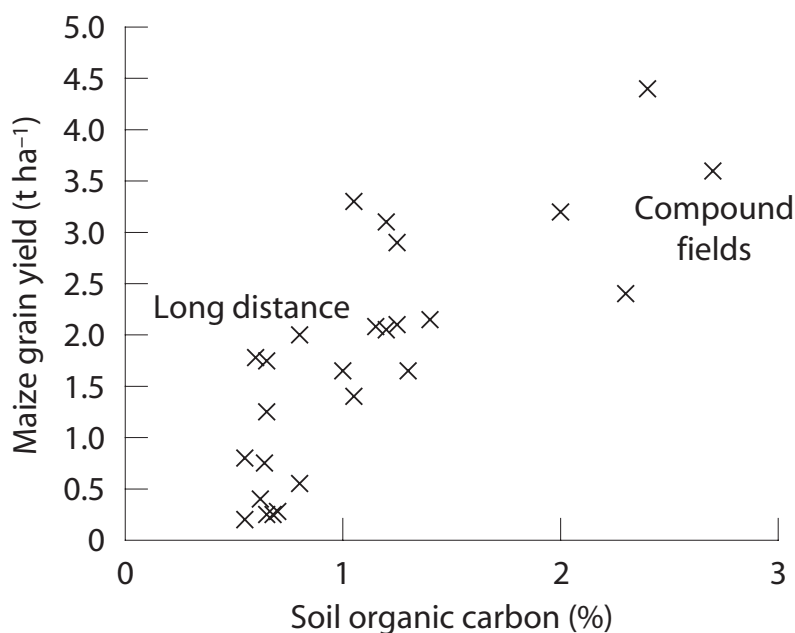
Field	Organic C (g kg <sup>-1</sup> )	Total N (g kg <sup>-1</sup> )	Available P (mg kg <sup>-1</sup> )	Exchangeable K (mmol kg <sup>-1</sup> )
Home garden	11–22	0.9–1.8	20–220	4.0–24
Village field	5–10	0.5–0.9	13–16	4.1–11
Bush field	2–5	0.2–0.5	5–16	0.6–1

Finally, farmers are not the only stakeholders benefiting from proper land management. As stated earlier soils provide and regulate a series of important ecosystem services that affect every living organism and society as a whole, and maintaining those ecosystem service functions may be equally or more vital than maintaining the crop production functions. Unfortunately, little information is available on the potential trade-offs between the use of land for different ecosystem service functions, on the most appropriate way to create a dialogue between the various stakeholders benefiting from a healthy soil fertility status, and on the role policy needs to assume to resolve above questions. The INRM research approach is aiming at creating a basis for such trade-off analysis and stakeholder dialogue.

*Putting it all together: user-friendly decision aids for ISFM*

After having obtained relevant information as described above, two extra steps may be required to complete the development of a user-friendly decision aid: (i) all the above information needs to be synthesised in a quantitative framework, and (ii) that framework needs to be translated into a format accessible to the end users. The level of accuracy of such a quantitative framework is an important point to consider.

The generation of a set of rules of thumb is likely to be more feasible than software-based aids that generate predictive information for a large set of environments, although both tools are needed as they serve different purposes. The level of complexity is another essential point to take into consideration. For instance, if variation between fields within one farm is large and affects ISFM practices, then this may justify having this factor included in decision aids. Other aspects that will influence the way information and knowledge is condensed into a workable package are: (i) the targeted end user community, (ii) the level of specificity required by the decisions to be supported, and (iii) level of understanding generated about the technologies targeted. Van Noordwijk et al. (2001) prefer the term ‘negotiation support systems’ to avoid any connotation that the ‘decision support systems’ has the authority to make decisions that will then be imposed on the various stakeholders. In an INRM context, it is recognised that different stakeholders may have conflicting interests about certain specific soil management strategies, and that a certain level of negotiation may be required. Whatever the terminology, it should be clear that any single ‘decision’ aid is only one source of the wide range of information required by farmers to make their decisions.



**Figure 6.** Relationship between the soil organic carbon content and maize grain yield for a set of fields varying in distance from a homestead in northern Nigeria. Source: Carsky et al. (1998).

In particular, the final format of the decision aid should take into account the realities in the field. Some of these realities are: (i) large-scale soil analyses are not feasible, so local soil quality indicators need to be included in decision aids, as farmers use these to appreciate existing soil fertility gradients within a farm; (ii) conditions within farms vary as does the availability of organic resources and fertiliser, therefore rules of thumb rather than detailed quantitative recommendations would be more useful to convey the message to farmers; (iii) farmers decision-making processes involve more than just soil and crop management; and (iv) access to computers, software and even electricity is limited at the farm level, necessitating hard-copy-based products.

## **Looking Ahead: the Future of the Science of Organic Resource Management**

The following conclusions can be drawn from the material presented in this paper:

- (i) The perceived role for the contribution of organic resources in tropical soil fertility management has changed considerably over the years. Currently, organic resources are valued at a par with mineral inputs, as it is recognised that both inputs play essential but different roles in maintaining or improving soil fertility.
- (ii) ISFM involves the management of three sources of nutrients: soil-derived, organic- resource-derived, and fertiliser-derived. Interactions occur between these, and managing individual inputs and their interactions is an essential component of the ISFM research and development agenda.
- (iii) Organic resources are often not sufficiently available at the farm level. Improved germplasm of commonly grown crops that addresses various constraints to higher yields, is a valid entry point for targeting soil fertility depletion. Germplasm that generates multiple benefits is likely to be adopted more easily and potentially tackles several constraints simultaneously.
- (iv) There are no panaceas or solutions that will be optimal everywhere all the time. There is considerable variability between fields within a farm and between farmers within a community (e.g. different access to resources). Therefore, it is very important to identify the appropriate niches for specific ISFM

interventions. Such niches will have not only biophysical, but also economic and social dimensions.

(v) Any recommendations for ISFM need to have a local soil knowledge basis, as this is the knowledge farmers are using to decide on the management of the resources (labour, fertiliser, organic resources etc.) available to them.

Future legume research and development could emphasise the following:

- (i) A considerable amount of information is available on ISFM interventions. There is an urgent need to synthesise this information to increase the impact of use and avoid duplication of effort. Syntheses should take the form both of databases and predictive models.
- (ii) The role of markets in creating added capital at the farm level is essential. ISFM options will have a greater chance of being adopted if they provide extra resources (labour, improved use efficiency of inputs etc.) to the farmer.
- (iii) It is essential to identify biophysical, social, and economic niches at the farm scale to introduce organic resource production options, as, under most conditions, organic resources are in short supply. Special attention should be given to multipurpose options.
- (iv) Much emphasis is often placed on maintaining the SOM. It remains a big question at what level SOM is needed to maintain the crop production and ecosystem service roles of SOM. To increase SOM usually involves a lot of investment in labour and land and, consequently, efforts to determine such threshold levels are essential. The role of organic resource quality in such endeavours should receive the attention it needs.
- (v) Further exploration of the detail and value of local knowledge systems and how these correlate to formal knowledge is essential in disseminating ISFM interventions.

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## 2.2

# Modelling Release of Nutrients from Organic Resources Using APSIM

M.E. Probert\* and J.P. Dimes†

### *Abstract*

In the context of integrated nutrient management, the performance of a crop model depends mainly on its ability to adequately describe the release of nutrients from diverse inputs and their uptake by the crop. The wide range of input materials found in tropical farming systems brings new challenges for modelling. In particular there are 'quality factors' that influence the decomposition and nutrient-release processes, while the range of manures encountered are quite different, both physically and chemically, from plant residues.

The APSIM modelling framework contains a set of biophysical modules that can be configured to simulate biological and physical processes in farming systems. In terms of the dynamics of both carbon and nitrogen in soil, APSIM SoilN deals with the below-ground aspects, and APSIM RESIDUE with the above-ground crop residues. APSIM MANURE is a recent addition to simulate nutrient availability to crops following addition of materials of highly variable carbon and nitrogen content. It has not been widely tested against measured field-response data.

The objectives of the ACIAR-funded project LWR2/1999/03 'Integrated nutrient management in tropical cropping systems: improved capabilities in modelling and recommendations', were to evaluate and enhance capabilities in APSIM to predict nutrient availability and subsequent crop growth following the addition of organic and inorganic sources of N and P. This paper briefly describes the capabilities of APSIM to simulate the dynamics of N as they existed at the start of the project.

Models that simulate the growth of crops have been around for more than 40 years. In order that they respond sensibly to climate, soil and management, such models tend to have similar features. Notably, they need to represent the processes that are understood to occur. Typically, they operate at a daily time-step, reflecting on the one hand the availability of weather data, and on the other the fact that this is an appropriate time-step for capturing the more important effects of management on the supply of

nutrients and water from the soil and demand by the plant.

Of the many factors that potentially affect the growth of plants, the two that are most responsive to management are water and nitrogen. It is therefore not surprising that most crop models include routines to handle responses to water and nitrogen. Less frequently do models attempt to describe limitations due to other soil constraints (Probert and Keating 2000).

In the context of integrated nutrient management, the performance of a model depends mainly on its ability to adequately describe the release of nutrients from diverse inputs and their uptake by the crop. In many situations, especially in low input agricultural systems in the developing world, crop growth is limited by nutrients other than N, particularly by

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inadequate phosphorus. Accordingly, to be useful for exploring strategies for improving crop nutrition of crops, models need to predict the responses to both N and P. The main objectives of the ACIAR-funded project LWR2/1999/03 ‘Integrated nutrient management in tropical cropping systems: improved capabilities in modelling and recommendations’ were to evaluate and enhance the capabilities in APSIM (McCown et al. 1996; Keating et al. 2003) to predict nutrient availability and subsequent crop growth following the addition of organic and inorganic sources of N and P.

In this paper, we briefly describe the capabilities of APSIM to simulate the dynamics of N as they existed at the start of the ACIAR project. Other papers in these proceedings will report on efforts to improve the ability to describe the release of N from materials typical of those used in many tropical farming systems (Probert et al. 2004), and the new capability to simulate response to P-limiting conditions (Probert 2004).

## The Agricultural Production Systems Simulator (APSIM)

The APSIM modelling framework contains a set of biophysical modules that can be configured to simulate biological and physical processes in farming systems (Keating et al. 2003; web site <www.apsim.info>). The foremost reason for its development was as a modelling framework for sim-

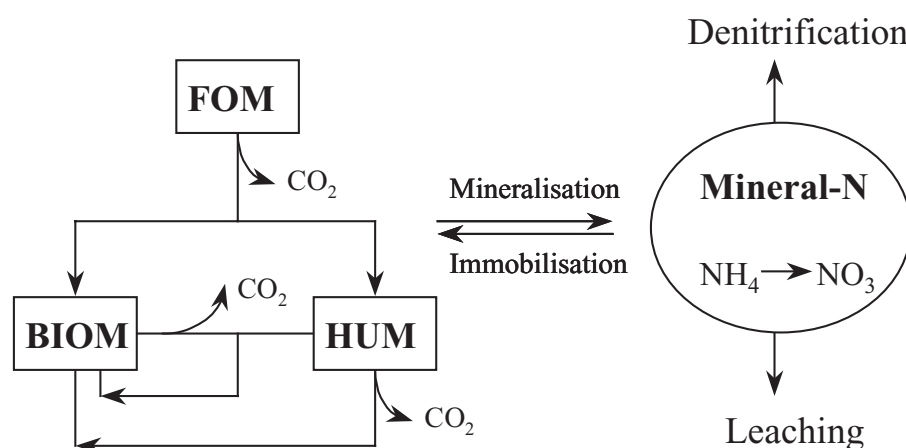
ulation of cropping systems in response to climate and management.

Two modules provide the representation within APSIM of the dynamics of both carbon and nitrogen in soil. APSIM SoilN deals with the below-ground aspects, and APSIM RESIDUE with the above-ground crop residues. These modules have been described by Probert et al. (1998).

### Soil organic matter and nitrogen

APSIM SoilN is the module that simulates the mineralisation of nitrogen and thus the N supply available to a crop from the soil and residues/roots from previous crops. Its development (Probert et al. 1998) can be traced back via CERES models (e.g. Jones and Kiniry 1986) to PAPRAN (Seligman and van Keulen 1981). SoilN provides an explicit balance for carbon and nitrogen so that it is better able to deal with longer-term changes in soil organic matter.

The greatest change from CERES is that the soil organic matter in SoilN is treated as a three pool system, instead of the two pools used in CERES (see Figure 1). The dynamics of soil organic matter is simulated in all soil layers. Crop residues or roots added to the soil comprise the fresh organic matter pool (FOM). Decomposition of FOM results in formation of soil organic matter comprising the soil microbial biomass (BIOM) and HUM pools. The BIOM pool is notionally the more labile organic matter associated with soil microbial biomass; while it makes up a relatively small part of the total soil organic matter, it



**Figure 1.** Schematic representation of the processes affecting soil organic matter and nitrogen transformations in the APSIM SoilN module. FOM = fresh organic matter, i.e. roots and incorporated crop residues; BIOM = labile soil organic matter pool; HUM = remainder of soil organic matter.

has a higher rate of turnover than the bulk of the soil organic matter.

The reasons for introduction of an additional soil organic matter pool were to better represent situations where 'soil fertility' improves following a legume ley (Dimes 1996). A single soil organic matter pool cannot deal realistically with the changes in mineral N supply following the cumulative additions of high N material to soil organic matter. The concepts depicted in Figure 1 have much in common with other models, such as the Rothamsted Nitrogen Turnover Model (Bradbury et al. 1993).

The release of nitrogen from the decomposing organic matter pools is determined by the mineralisation and immobilisation processes that are occurring. The carbon that is decomposed is either evolved as CO<sub>2</sub> or is synthesised into soil organic matter. SoilN assumes that the pathway for synthesis of stable soil organic matter is predominantly through initial formation of BIOM, though some carbon may be transferred directly to the more stable pool (HUM). The model further assumes that the soil organic matter pools (BIOM and HUM) have C:N ratios that are unchanging through time. The C:N ratio of the BIOM pool is typically set at 8, while that of the HUM pool is based on the C:N ratio of the soil, which is an input at initialisation of a simulation. The formation of BIOM and HUM thus creates an immobilisation demand that has to be met from the N released from the decomposing pools and/or by drawing on the mineral N (ammonium and nitrate) in the layer. Any release of N above the immobilisation demand during the decomposition process results in an increase in the ammonium-N.

The FOM pool is assumed to comprise three sub-fractions (FPOOLS), sometimes referred to as carbohydrate-, cellulose- and lignin-like, each with a different rate of decomposition. In this manner, the decomposition of added plant material under conditions of constant moisture and temperature is not a simple first-order process.

The rates of decomposition of the various soil organic matter pools are dependent on the temperature and moisture content of the soil layers where decomposition is occurring. In circumstances where there is inadequate mineral N to meet an immobilisation demand, as can occur where the C:N ratio of the FOM pool is high, the decomposition process is limited by the N available to be immobilised.

Other processes dealt with in SoilN are nitrification, denitrification and urea hydrolysis (following

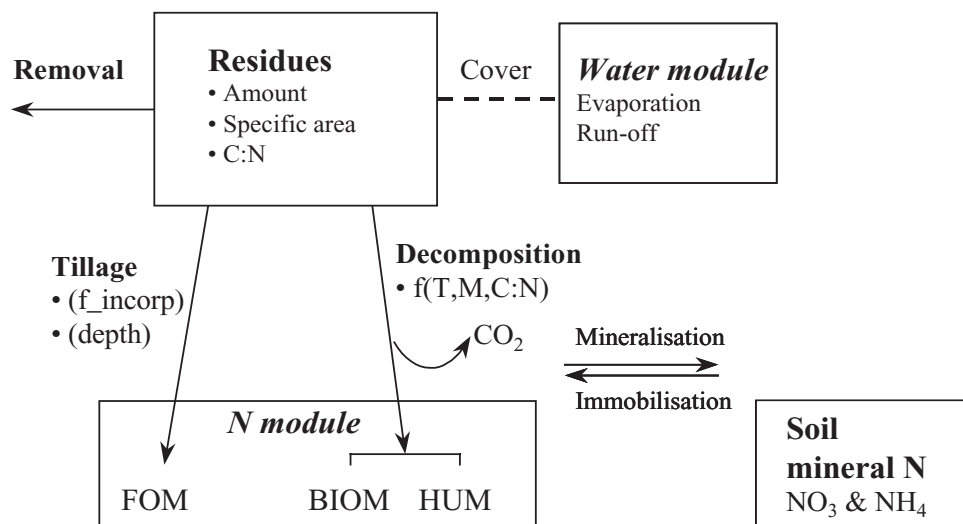
application of urea as fertiliser). Fluxes of nitrate-N between adjoining soil layers are calculated based on movement of water by the water balance module. Ammonium-N and all soil organic matter pools are assumed to be non-mobile.

## Surface residues

In APSIM, crop residues that are on the soil surface are handled by the RESIDUE module (see Figure 2), described by Probert et al. (1998). This has been done so that surface residues can affect the soil water balance through run-off and evaporation.

Crop residues are accounted for as a single surface residue pool that is described in terms of its mass, the cover it provides for the soil surface, and its nitrogen content. When new residues are added, either because of senescence and detachment or at harvest, new weighted (mass) average values are calculated to describe the total amount of residues present.

The amount of residue decreases through one of three processes. Firstly, by removal of residue (for example by burning or collection for animal feed); such action does not alter the C:N ratio of the residues. Secondly, through the incorporation of residues into the soil. A tillage event transfers a specified proportion of the surface residues into the soil FOM pools to a nominated depth. Finally, by decomposition *in situ*. The decomposition routine is similar to that used for the soil organic matter pools in the SoilN module in order to maintain balances of both carbon and N. Any immobilisation demand is met from the uppermost soil layer, while the soil organic matter formed and ammonium-N mineralised are added to the uppermost soil layer. The temperature dependency for decomposition of residues is related to daily ambient temperature. As the soil water balance does not include the litter layer, the moisture dependency is assumed to be unconstrained immediately after a rainfall event, with decomposition rate declining as litter dries, based on potential evaporation. The rate of decomposition is also sensitive to the amount of residues on the soil surface. A 'contact' factor accounts for the opposing effects of mulch separation from the soil surface and a modified moisture environment in the mulch layer as the amount of surface material increases. Thorburn et al. (2001) have investigated the importance of the contact factor for sugarcane systems that involve large amounts of surface residues (up to 20 t ha<sup>-1</sup>).



**Figure 2.** Schematic representation of the processes dealt with in the APSIM RESIDUE module. Note the linkage with the water module whereby the amount of residues will influence components of the water balance.

## Manures

In many low-input systems, manures are the sole source of nutrients applied to croplands. These manures are often of low quality. Studies in eastern Kenya (Probert et al. 1995) have shown that the manures being used on farms are grossly inadequate as a source of nitrogen, and are probably being used inefficiently as a source of phosphorus. This is true also in other parts of the semi-arid tropics.

In these environments, improved management of soil fertility calls for efficient use of scarce supplies of manure, integrating its use with other sources of nutrients in crop residues (particularly where legumes are grown) and augmenting these sources where necessary with purchased fertilisers. It is the location of this complexity of nutrient supply investments in a climate with high rainfall uncertainty that makes a simulation model a valuable tool for comparing management options. But, to be useful, the simulation model must adequately represent the nutrient value of the manures, involving their decomposition patterns and the availability of the nutrients for crop growth.

The development of the APSIM MANURE module has progressed towards filling this need. It should be noted that the concern has been with farming systems employing generally low quality manure that is normally incorporated into soil before sowing. Had the interests evolved elsewhere, with

higher quality manures and slurries, say, as occur in intensive livestock systems, the approaches taken may have been different (e.g. volatilisation losses as ammonia).

Manures vary greatly in composition (Lekasi et al. 2003), being a complex mixture of animal excreta and plant residues that has undergone varying degrees of composting/decomposition and might have been mixed with considerable amounts of soil (as in the Kenyan boma system; Probert et al. 1995). Some of the nutrients are in forms that are immediately available for uptake by plants, and some will have to undergo decomposition before they become available. This concept of nutrient availability implies a time dimension, with the nutrients in manure exhibiting a wide range of availabilities, ranging from components that are water soluble to very recalcitrant.

A simple characterisation is to divide each nutrient into two fractions: one part that is immediately available with the rest being treated as an initially unavailable, organic input that must decompose in order for its nutrients to become available. The concept for the organic portion has obvious similarities with how APSIM represents decomposition of crop residues and roots, but with two important differences. In crop residues, carbon content varies little (Palm et al. 2001), and for most plant material APSIM assumes 40% in the dry matter; this is not so for manures.

Also, APSIM SoilN assumes that the carbon in crop residues and roots added to the soil FOM is distributed between the three FPOOLS in the ratio 20:70:10; one suspects that this would not hold true for manures.

The schema for the APSIM MANURE module is shown in Figure 3. An application of manure is specified in terms of its mineral N components and the organic portion. For a surface application, it is assumed that the mineral components are leached into soil in response to rainfall, and the organic portion will decompose *in situ* in an analogous manner to decomposition of surface residues. Incorporation of the manure transfers both the mineral and organic components into the soil to the specified depth, with the organic portion becoming part of the FOM in the APSIM SoilN module.

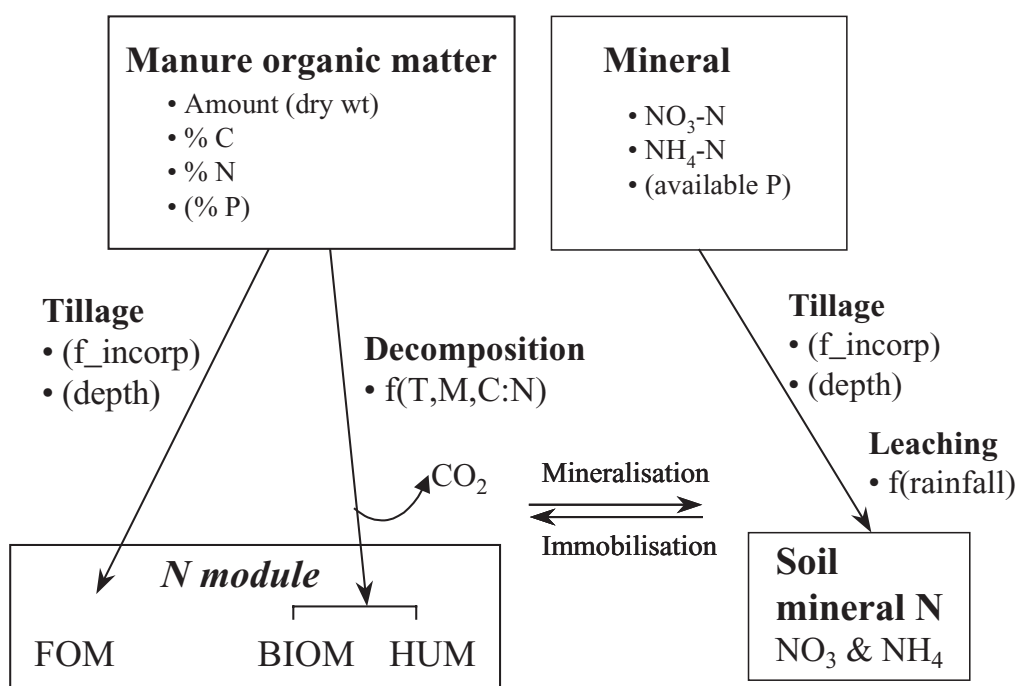
In early tests of the sensibility of the MANURE module it was supposed that different quality manure could be represented by variation in the FPOOLS comprising the organic fraction (e.g. Carberry et al. 2002). The paper by Probert et al. (2004) explores the extent to which this is feasible.

## Discussion

Models have evolved as they have been applied to different agricultural systems, and this is particularly true for the simulation of nutrient dynamics. It is instructive to reflect on the relatively short history that covers the development of APSIM to its present capability.

The early modelling experiences of those who were to become the developers of APSIM were with models of the CERES family, particularly CERES-Maize (Jones and Kiniry 1986). These models had been developed primarily to simulate the growth of crops in high-input systems. As long as N fertiliser inputs met a substantial proportion of the crop nutrient needs there was not much pressure on the model to accurately predict N mineralisation from soil.

However, attempts to apply such models to low-input systems exposed this problem, and efforts were made to improve the soil mineralisation routines (Probert et al. 1998). In particular, it was recognised that a full accounting of both C and N was needed,



**Figure 3.** Diagram showing processes considered in the APSIM MANURE module. Manure on the surface of the soil can have an effect on the water balance in similar manner to surface residues (not shown). The schema has provision for manure to also contain phosphorus, which would be transferred to the APSIM SoilP module when manure is incorporated into soil or decomposes.

and that all soil organic matter was not the same with respect to its susceptibility to decomposition (this latter effect being particularly important with soil organic matter in subsoil layers).

Modelling the growth of single crops, with the soil being initialised just before sowing, masked the ability of the models to adequately represent crop residues and roots. Indeed, many crop models can do a satisfactory job in predicting crop yields without considering roots (e.g. the RESCAP model of Monteith et al. (1989)). The desire to model sequences of crops (i.e. a true farming system rather than a single crop) exposes such inadequacies. The amount of roots and residues remaining, and their quality, have major effects on the N supply to following crops. These might be positive in the case of a legume–cereal sequence, or detrimental when cereal residues with a high C:N ratio cause immobilisation of N. For the materials encountered in typical arable cropping systems, the mineralisation/immobilisation of N can be represented as the outcome of the decomposition of the organic sources and the synthesis of soil organic matter. In such materials, the carbon concentration is close to 40%, and concentrations of lignin and polyphenols are generally small. Thus, N concentration (or C:N ratio) is the dominant factor controlling N release.

Most recently there has been recognition of the need to simulate the nutrient release from a wider range of organic inputs, especially manures. For example, Palm et al. (1997) asserted

... current simulation models do not yet fully meet the needs of research and extension workers in developing countries ... The major issues that need attention are the capacity to simulate P dynamics and the decomposition of the range of crop residues and organic materials that are encountered in tropical farming systems.

The wider range of materials found in tropical systems brings new challenges for modelling. In particular, there are other ‘quality factors’ that influence the decomposition and nutrient release processes (Heal et al. 1997), while the manures encountered are quite different, both physically and chemically, from plant residues. The purpose of the project reported in these proceedings was to evaluate current predictive performance of APSIM in these tropical farming systems, and to implement further improvements to the model based on understanding of the experimental data.

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## 2.3

# Linking Simulation Modelling to Participatory Research in Smallholder Farming Systems

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### *Abstract*

Simulation models have proven beneficial to commercial farmers in Australia when applied within a participatory action research approach. This paper reports on an attempt to combine a participatory research approach and computer-based simulation modelling to engage smallholder farmers in Africa on issues of soil fertility management. A three-day interaction with farmers in one village in Zimbabwe provided evidence that the farmers found the simulation outputs to be credible and meaningful in a manner that allowed ‘virtual’ experiential learning to take place. The paper concludes that simulation applied within an action research framework may have a role in direct interventions with smallholder farmers in such regions

Simulation modelling has struggled for relevance in real-world agriculture and for impact on farmer decision-making, as outlined in two recent reviews. McCown et al. (2002) reflected on the impacts and learning in developing and applying computerised decision-support systems (DSS) through the collated experiences from nine substantive efforts of researchers in delivering DSS to farmers. All case studies were from developed countries (Australia, USA, Europe), and most incorporated dynamic simulation models within the applied DSS. Based on these experiences, McCown (2002) concluded ‘the DSS has fallen far short of expectations in its influence on farm management’.

Matthews and Stephens (2002) reviewed the application of simulation models in developing countries and sought examples of where such models

have been useful in smallholder farming systems. Unfortunately, this extensive review largely failed to identify any noteworthy examples of where crop simulation models had impacted on the practices of smallholder farmers. The 11 examples presented to demonstrate possible impact (Matthews et al. 2002) were mostly via influence on research direction, e.g. designing new rice plant types to increase yield potential or weed competitiveness (Dingkuhn et al. 1997), or in the training of local researchers, e.g. the SARP project (ten Berge 1993).

In the past, model applications have generally meant abstract analyses whereby researcher-designed management scenarios are tested under hypothetical situations, and recommended actions are suggested on what managers should do, generally without any reference to real-world testing. Most attempts to justify modelling approaches refer to multitudes of such context-free analyses (Meinke et al. 2001; Hammer et al. 2002; Matthews and Stephens 2002), but few examples are provided on where farming practices have benefited from such modelling studies.

Given past failures in DSS implementation and the increasingly unenthusiastic reaction of journals and

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research peers to such simulation analyses, which are easily generated and relate to no place in particular, the future for many modellers has been to retreat from 'trying to be practical' and seek a 'market' elsewhere. Some argue that models used in a normative manner could have input into public policy (Goldsworthy and Penning de Vries 1994), but again there are few reported examples of where models have actually influenced policy implementation. More recently, Hammer et al. (2002) have promoted a new hope for modelling in directing plant breeding, through identifying and assessing plant traits through gene-to-phenotype modelling. Modelling input into setting research directions or in plant breeding, in education and training, or as input into public policy probably does provide sufficient rationale for the continued development and application of models. But what of simulation modelling as an aid to farm decision-making?

While realistic about the past impacts of simulation modelling, both McCown (2002) and Matthews and Stevens (2002) are not dismissive of the prospects of modelling contributing to improved farmer decision-making. Both suggest that simulation modelling using a participative approach may be the future. Farmer participatory research stresses the co-learning of researchers and farmers who work together to explore the different options open to farmers through conducting experiments to test new agricultural inputs and practices. Participatory approaches allow researchers and farmers to jointly learn about farmer conditions in order that both can help each other design sustainable development interventions (Ashby and Sperling 1994; Okali et al. 1994).

A substantive example indicating possible success with a participatory application of simulation modelling is the FARMSCAPE experience (Carberry et al. 2002). FARMSCAPE (Farmers, Advisers, Researchers, Monitoring, Simulation, Communication And Performance Evaluation) is a program of participatory research with Australian farming communities that explicitly researched whether farmers and their advisers could benefit from simulation modelling. Carberry et al. (2002) provide performance indicators of impact on farming practices and reflect on what was learnt from this experience. They suggest that the active participation of farmers and their advisers, who work with researchers in the context of their own farming operations, was the key ingredient in the

design, implementation and interpretation of the FARMSCAPE approach to decision support.

Dimes et al. (2003) agree that there can be synergies between simulation models and participatory research and suggest that, for smallholder farming systems, there are four areas of possible application: (i) the interpretation of on-farm experiments, (ii) exploration of investment options and risk analysis, (iii) assessment of new technologies and (iv) engaging farmers directly with simulation models in order to create virtual 'experiential learning' opportunities that are difficult or risky in real life. While the first three areas are consistent with past proposals for model applications, it is the fourth suggestion which may surprise, especially in the case of smallholder farmers. Dimes et al. (2003) briefly reported on an experience of using models with a group of smallholder farmers in Zimbabwe. The purpose of this paper is to provide greater detail and analysis of this experience of engagement of researchers with smallholder farmers in semi-arid Zimbabwe.

## Background

In October 2001, a workshop was convened at ICRIAT-Bulawayo in Zimbabwe to explore the complementarities between farmer participatory research approaches and computer-based simulation modelling in addressing soil fertility management issues at the smallholder level (Twomlow 2001). To test the complementarities of these two approaches, six teams were assembled, made up of computer simulation modellers trained in the use of the cropping systems model APSIM (Keating et al. 2003), participatory researchers (agronomists, economists and social scientists) trained in participatory rural appraisal and rapid rural appraisal tools and methods, and local researchers knowledgeable on African farming systems. The six teams then worked with farmers in six villages in the Tsholotsho and Zimuto districts, Zimbabwe, for three days. They used participatory tools to build realistic farm scenarios for the computer simulations, which were then run for the farmers to get their reactions and suggestions for improvements. This paper is the report on what happened and what was learnt from one of those teams which interacted with 30 farmers in the village of Mkhubazi, Tsholotsho, Zimbabwe.

The APSIM cropping systems model was selected for use in this study because it had been previously tested in simulating crops in smallholder farming



systems in Zimbabwe (Robertson et al. 2000; Shamudzarira and Robertson 2000; Shamudzarira et al. 2000). Likewise, soil and agronomic data were available to parameterise APSIM for the analyses to be undertaken in this study (Dimes et al. 2003). Climate data collected at Tsholotsho (less than 20 km from Mkhubazi) were used in the subsequent simulation scenarios.

## Farmer Focus Group Meeting

On the first of the three days of interaction with a group of farmers in the village, a focus group meeting was held. About half the group were women. Over the three days, the number of farmers increased from 21 on day 1 to over 30 on day 3. All group discussions were mediated by a local interpreter. Some farmers in the group had a degree of English language competence.

The facilitator started the discussion by eliciting the local taxonomy of soils in the village. The smallholders in Mkhubazi recognise four types of soil. They crop two most frequently: *ihlabathi* soils, which are whitish sandy soils that do not hold water well and need large amounts of manure to be productive, and *iphane* soils, which are sodic, don't store much water and are prone to waterlogging, sometimes leaving maize plants standing in water for a week at a time. The less-fertile *ihlabathi* soils are the more common of the two. All villagers present at the focus group discussion have and plant crops on *ihlabathi* soils, whereas only 7 or 8 of the 20 villagers have *iphane* soils.

Given this picture of the local soil constraints, an agricultural activity calendar was then elicited from farmers, showing the details of dates of planting, weeding, and harvesting for different crops grown on both kinds of soils. It showed, for instance, that farmers plant crops of maize and sorghum first on *iphane* soils, if they have them, because they get poor germination on these soils if they plant late. Moreover, they plant early on these soils so that the plants are established to survive the waterlogging when the 'main rains' come in December. If *iphane* soils are planted after the main rains come, farmers might not be able to enter the ponded fields to plough. This means, for farmers with both kinds of soils, that maize and sorghum are planted first on *iphane* soils, followed by millet and legumes (groundnuts, cowpeas, and bambara nuts) on *ihlabathi* soils, as farmers

report a striga problem with sorghum and maize planted on *ihlabathi* soils. Farmers with only *ihlabathi* soils can be expected to plant when 'the rains come' in the sequence specified by the activity calendar: maize and groundnuts in November, followed by sorghum and pearl millet and groundnuts in mid-December. Cowpeas can be planted from mid-November to mid-January.

Farmers say they weed maize, groundnuts, and bambara nuts twice, the first being 2 weeks after planting and the second depending on the amount of weed infestation. Millet and sorghum, however, are weeded once, four weeks after emergence. Different patterns of crop rotations on the same plot or portion of a big plot are reported, e.g. small 1 acre (1 acre = 0.4 ha) plots of legumes (groundnuts, cowpeas, bambara nuts) followed by 1–5 acre plots of maize followed by larger plots (4–8 acres) of millet followed by smaller plots (1–2 acres) of sorghum. Crops are also rotated in the homestead field or garden managed by women.

An hour's discussion ensued about inorganic and organic fertiliser use. Farmers say they do not buy chemical fertiliser from the trade store for use on grain crops; but all have been exposed to the nutrient advantages of chemical fertiliser. Farmers apply manure if they have cattle and/or goats, preferably on land planted to maize and then sorghum. Yet, when asked which soil should they put manure on, more farmers said *ihlabathi* (sandy) soils than *iphane* (sodic-like) soils. The amount of manure applied varied a great deal, from 3 to 8 scotch-carts (about 600 kg) hectare<sup>-1</sup> every 2–5 years. These discussions were followed by small-group discussions with the eight team members interviewing small groups of four to five farmers. Some team members asked individual farmers about their individual farming practices, household food security, and household composition.

Work resumed on day 2 with a short summary by the team. The group then broke into small groups of four to five farmers to develop resource allocation maps (RAM) (Defoer and Budelman 2000). The RAM for each farm provided a diagrammatic representation of the farm infrastructure and assets and the seasonal flows of materials and labour between farm units (household, garden, fields etc.). A well-specified RAM for an individual farm enabled specification of actual and planned crop production strategies.

## Describing a Computer Model to Smallholder Farmers

In the afternoon of day 2, the concept of a computer model was introduced to the farmers. Although many of the farmers had not previously seen a computer, a number had lived and worked in the city and had some understanding of a computer and its ability to calculate. These few provided valuable support to the interpreter in describing what followed.

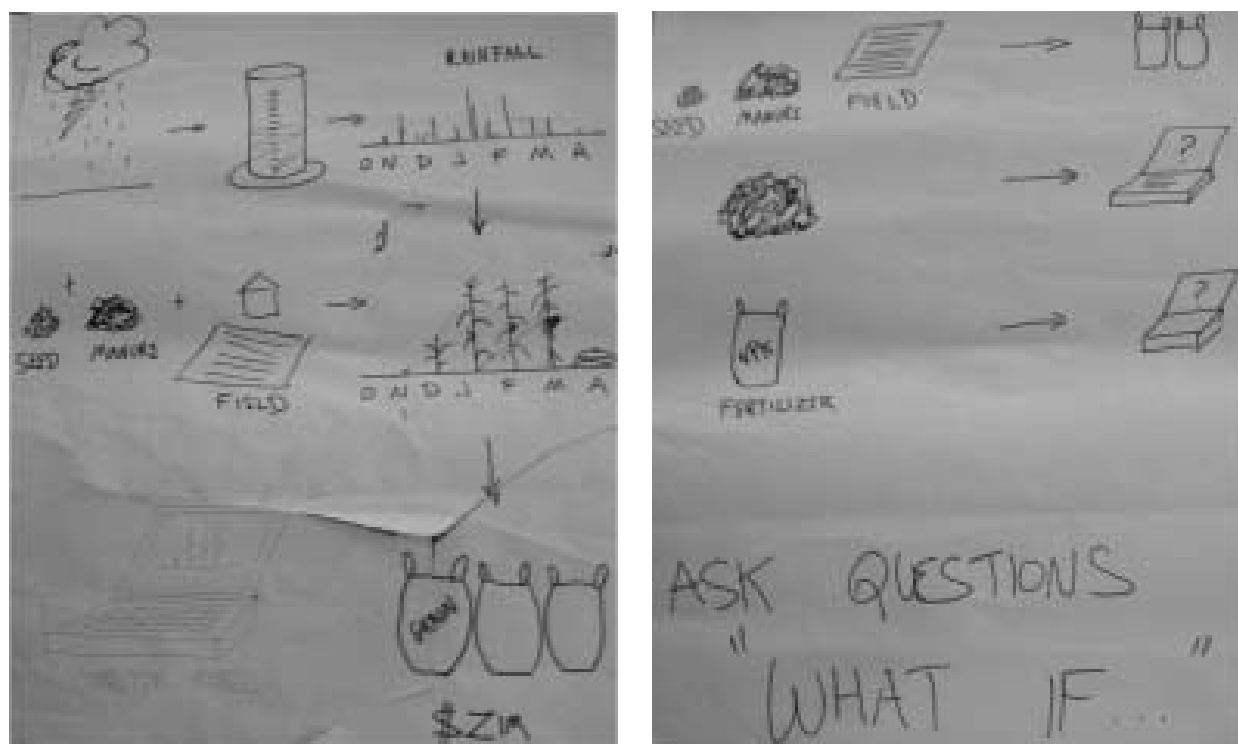
Hand-drawn diagrams on flipcharts were used to help describe a computer model (Fig. 1). Firstly, the concept of measuring daily rainfall was discussed, with its accumulation representing what rain falls throughout the cropping season. Good and bad seasons were related to frequency and amount of rainfall events. Next, the process of growing a maize crop was discussed, starting with inputs of seed and manure applied to a particular field and the subsequent development and growth of the maize from seedlings to maturity. The linkage between rainfall events and crop growth was discussed.

Growing the same crop ‘on the computer’ was then proposed by providing it with the same information as what happened in real-life; i.e. what rain fell, how many seeds were planted to what field and soil type,

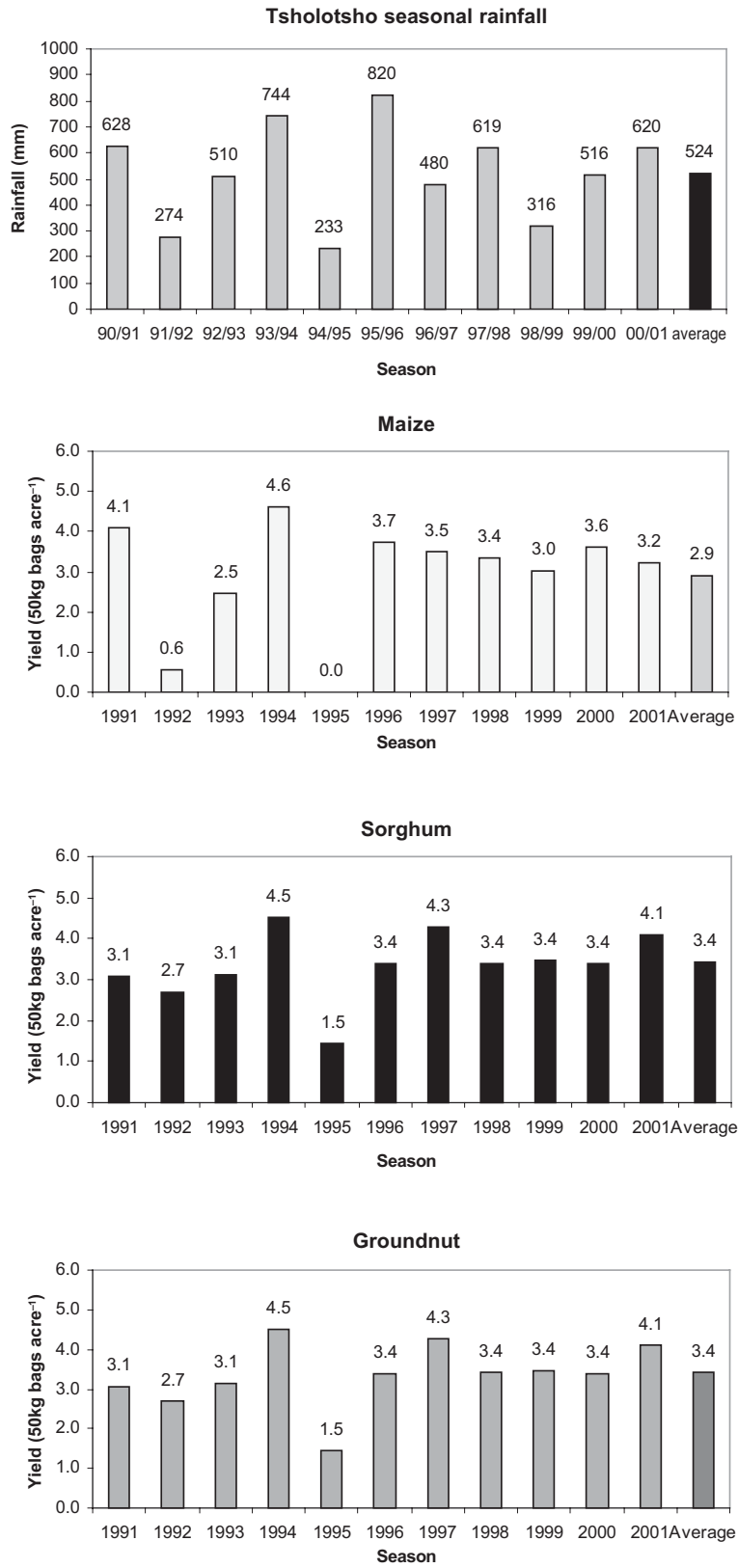
how much manure was applied etc. A notebook computer, as drawn in Figure 1a, was displayed to the group. Once the interpreters and the few farmers with some knowledge about computers had completed long discussions with the less aware farmers, the idea of using the computer to ask ‘What if?’ questions was proposed (Figure 1b). If maize was planted in a field with a small amount of manure and yielded two bags, what yield would the computer suggest with more manure? Or with inorganic fertiliser?

In attempting to better relate computer simulation to the reality of farming at Tsholotsho, actual rainfall and simulated crop yields for maize, sorghum, and groundnut from 1991–2001 were presented as hand-drawn graphs (Figure 2). Yields were represented as number of 50 kg bags of grain acre<sup>-1</sup>, units that appeared to be understood by the farmers during the RAM interviews. Crop management rules were aligned with information collected in interviews on the previous day, and soil characteristics were likewise informed by farmer information supplemented by local researcher knowledge. These simulations were completed before the meeting and the notebook computer was not used during this session.

Immediately after the Figure 2 graphs were presented, Sevi, a female farmer, asked the question:



**Figure 1.** Photos of hand-drawn diagrams on flip charts used to help describe a computer model.



**Figure 2.** Seasonal rainfall for Tsholotsho and simulated crop yields for maize, sorghum, and groundnut for 1991–2001.

why was the simulated sorghum yield in a year with >800 mm rainfall (1995–96) less than the yield in a year of only 480 mm rainfall (1996–97)? This one unsolicited question was the catalyst for increased engagement between the researchers and the farmers. It ‘broke the ice’ for discussion about a range of issues on which both farmers and researchers had knowledge, the former with local knowledge, the latter with scientific knowledge.

Subsequent discussion concentrated around the matching of seasonal rainfall, simulated yields and farmer experience over the previous 11 years. We initially concentrated on the previous season (2000–01) by presenting the season’s daily rainfall, and benchmarked simulated yields of maize and groundnut against experiences volunteered by a few farmers. Closest consensus was reached in relation to the simulated drought-affected maize yields in years 1992 and 1995. It was concluded that three types of years could be distinguished between 1989 and 1998: one very bad year (1992), four bad years and five normal years.

This second day’s interaction ended without significant indicators that many farmers had understood the description of computing or crop modelling. The farmers were polite but mostly reserved. Some in the group did engage in comparing their experience over recent years with that presented by the researchers.

## **Running Simulation ‘What If?’ Discussions with Smallholder Farmers**

Day 3 began with an intention to engage the farmers with simulation output. Preparation for the day involved selection of four case-study farmers and issues which emerged from the focus group meeting and the RAM exercise. Using these data, initial simulations were conducted overnight and results transferred to flip charts as pre-meeting preparations.

This day’s meeting at Mkhubazi commenced without a concise agenda on how the farmers would be engaged using the simulation output. While some in the research group were sceptical of progressing beyond simple presentation of simulation results, all were hopeful of achieving higher levels of interaction. Therefore, the subsequent farmer–researcher engagement was guided by two hypotheses: that an action research approach, whereby what to do next would be informed by what was learnt from previous

actions, could inform the engagement process, and that the engagement process employed in the FARM-SCAPE experience (Carberry et al. 2002) would be a sensible framework for initiating the interactions with smallholder farmers using simulation output.

The selected case studies were conducted for four farmers:

- *Samuel*, the leader of the farmer group and a relatively wealthy farmer when judged by land area, cattle number and wives. Samuel had access to 14 scotch carts of manure year<sup>-1</sup> which could be applied to 2.5 ha of cropland. Baseline simulations for Samuel covered the issue of the benefit of application of manure.
- *Sevi*, one of the leading and younger women farmers with modest farm resources. Sevi was clearly someone thinking about her farming system and she was an initiator of questions and contributed freely to discussions.
- *Derrick*, a farmer with less resources in the group with few cattle and low production.
- *Ester*, an older woman farmer with limited resources and cattle.

Each of these case studies and the interactions between farmers and researchers are described in the following section, with greater detail supplied on the first example.

### **(i) Samuel**

The meeting started with presentation of simulated results from the overnight runs for the first case study farmer (Samuel). This baseline simulation, using climate data for Tsholotsho for 11 years (1991–2001), was for maize cultivar sc501 grown on *ihlabathi* soil with no applications of manure or inorganic fertiliser. Also presented was the same simulation but with 14 scotch carts (8000 kg ha<sup>-1</sup>) of good quality manure (C:N ratio of 20) applied to the maize crop before planting (results not shown).

This first presentation of hand-drawn graphs started as a lecture without feedback sought from nor volunteered by farmers during its interpretation by the presenting researcher. When asked for their reaction after presentation, Samuel and the other farmers remained detached and non-committal. The meeting was heading towards an early and frustrating ending! Then one of the older, clearly respected farmers stood up and, through the interpreter, commented that the maize cultivar sc501 was poorly adapted to the region and few in the village now used this variety. In

his opinion, the results were not relevant to his farm. This was the opportunity needed to engage. Let's redo the simulations using the variety you recommend, was the suggestion put to the farmers. They agreed and chose cultivar sc401, a shorter season variety. The new runs were completed within minutes and the changes in bags acre<sup>-1</sup> (relative to cultivar sc501) were presented on flip charts for each year of simulation and for the average. Figure 3(a,b) presents these simulation results, but with the baseline simulation using cultivar sc401.

The initiating farmer volunteered his reaction; that he expected sc401 to perform better than sc501 in most years and he was pleased that the presented results were now better aligned with his experience. Other farmers agreed and good discussion followed on why this was the case. The 1999 and 2000 seasons were remembered as low rainfall years when a short season variety was advantaged but last season (2001) had sufficient rainfall to support the longer season sc501. The farmers also seemed satisfied with the simulated yields — they expected to produce in the order of 5–6 bags acre<sup>-1</sup> year<sup>-1</sup>, but have had years with no production (1995 was well remembered as a bad drought) and other years when 9–10 bags acre<sup>-1</sup> were produced.

The alignment of farmer experience with simulated output for a common experience (a change in maize cultivar) seemed to generate considerable credibility with the farmers and a subsequent willingness to proceed with further simulations. Let's see what difference other changes would make to the outcome was the suggestion accepted by the more proactive members of the group. When asked, Samuel asked that the impacts of manure application next be redone with the variety sc401.

The FARMSCAPE experience (Carberry et al. 2002) helped guide the process here. While the new simulations were being run, the farmers were asked to nominate what change they would expect from the manure application. Each farmer was asked in turn to nominate how many extra bags of grain would be produced with the application of 14 scotch carts of high quality manure (Table 1). The simulated yield change ranged from 0–1.5 extra bags acre<sup>-1</sup> (Figure 3c), with an expected (average) value of 0.8 bags acre<sup>-1</sup>. This result was less than the experience of most farmers. Comment was sought from those farmers who nominated the larger benefits (5–9 bags acre<sup>-1</sup>) and it appeared that they included farmers without access to such large quantities of manure and so without relevant experience. Active discussion

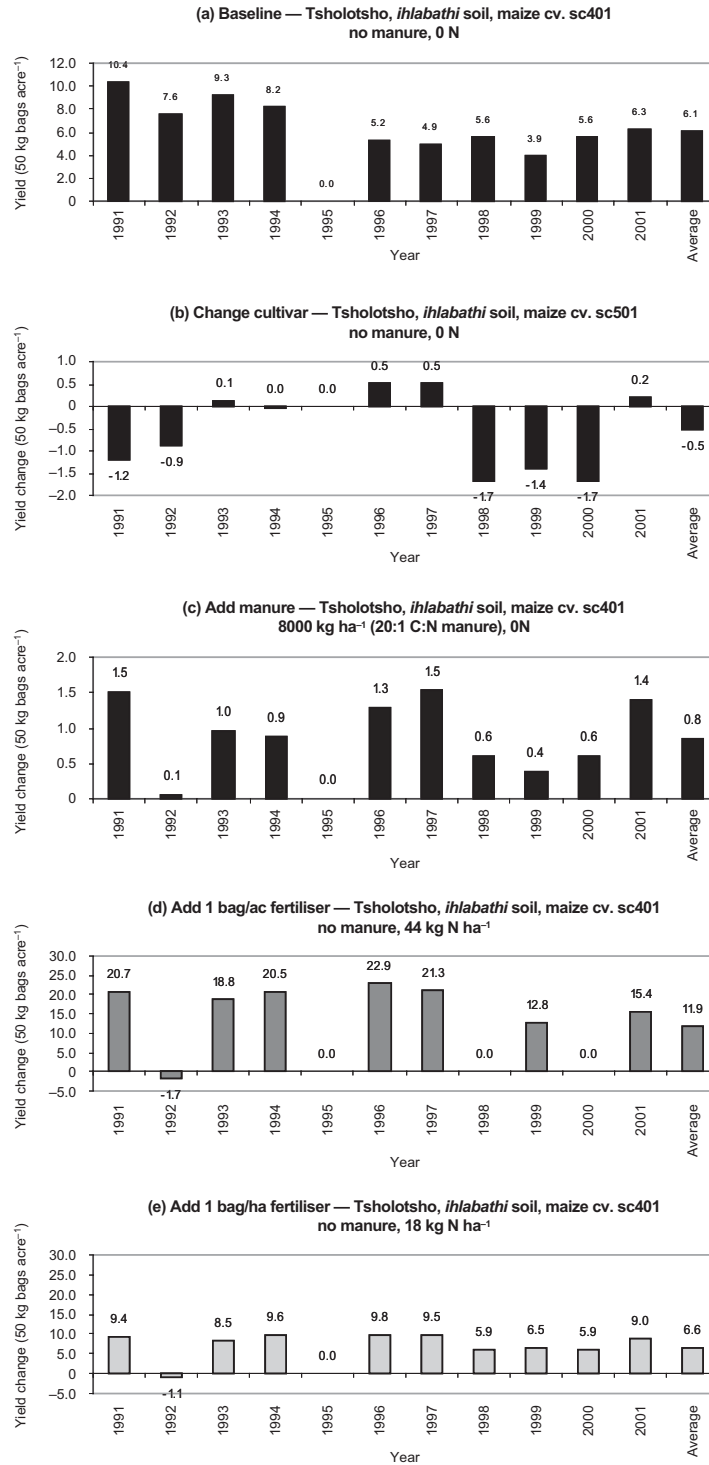
ensued for some time between the local farmers and the researchers on manure and its use within their farming systems. This discussion led to the possible use of inorganic fertilisers (undoubtedly introduced by the researchers). At this point, the question was asked whether the farmers wanted to redo the simulation with applied fertiliser. The response was an enthusiastic yes. Samuel nominated applying 1 bag of fertiliser acre<sup>-1</sup> (44 kg N acre<sup>-1</sup>).

**Table 1.** Number of farmers who nominated changes in bags acre<sup>-1</sup> from manure and N fertiliser applications in case study 1.

	Yield difference (bags acre <sup>-1</sup> )									
	0	1	2	3	4	5	6	7	8	9
Manure application	0	2	14	10	1	2	1	0	0	0
N fertiliser application	0	2	6	4	8	4	0	0	2	1a

<sup>a</sup> This difference was volunteered by the modeller before he ran the simulation.

The same procedure was followed, whereby farmers were asked by a show of hands before presentation of simulation results to nominate their expectations for the change in yield with applied fertiliser (Table 1). At this point the engagement became more light-hearted, animated and inclusive of more farmers. Many started debating amongst themselves the likely outcome and several changed their nomination as a result. The modeller gained a great laugh by joining in and nominating a changed yield larger than anyone else — the farmers accused him of cheating through 'insider-knowledge'! As the changes in yield were read out and recorded— plus 22 bags acre<sup>-1</sup>, -1, 19, 21 ... (Figure 3d) — the farmers' reactions were a mix of amazement, disbelief and excitement. The simulated yield changes were significantly greater than any farmer had imagined. Great debate ensued, with most farmers asking if such returns could really be possible. One female farmer volunteered that she had once achieved 16 bags acre<sup>-1</sup> and so she believed such yields were achievable. This discussion enabled input from several researchers on the mechanism of crop response to soil N and on-farm experimental evidence with fertilisers. The variability in yield change, with even a negative response, had to be emphasised by the researchers — high yields were not assured with applied fertiliser.



**Figure 3.** (a) Baseline simulation, using climate data for Tsholotsho for 11 years (1991–2001), was for maize cultivar sc401 grown on *ihlabathi* soil with no applications of manure nor inorganic fertiliser, and the changes in maize yields (bags acre<sup>-1</sup>), (b) for cultivar sc501 relative to sc401, (c) for manure application, (d) for applying 1 bag fertiliser acre<sup>-1</sup> (44 kg N ha<sup>-1</sup>), and (e) for 18 kg N/ha applied as fertiliser.

When asked his reaction, Samuel said he found it too difficult to believe such high yields were possible and, besides, he could not afford such a high fertiliser rate. He asked what if he spread one bag of fertiliser over his whole farm ( $44 \text{ kg N acre}^{-1}$  over 2.5 acres)? The simulations were rerun with  $18 \text{ kg N ha}^{-1}$  applied as fertiliser (Figure 3e). This result (expected return of 7 bags  $\text{acre}^{-1}$ ) greatly interested Samuel and other farmers. Small applications of N fertiliser could return significant benefits in most seasons. More requests were proposed, to try even lower rates of fertiliser, but close to 2 hours had been spent on the one case and three other farmers were waiting for their results. It was decided to change cases.

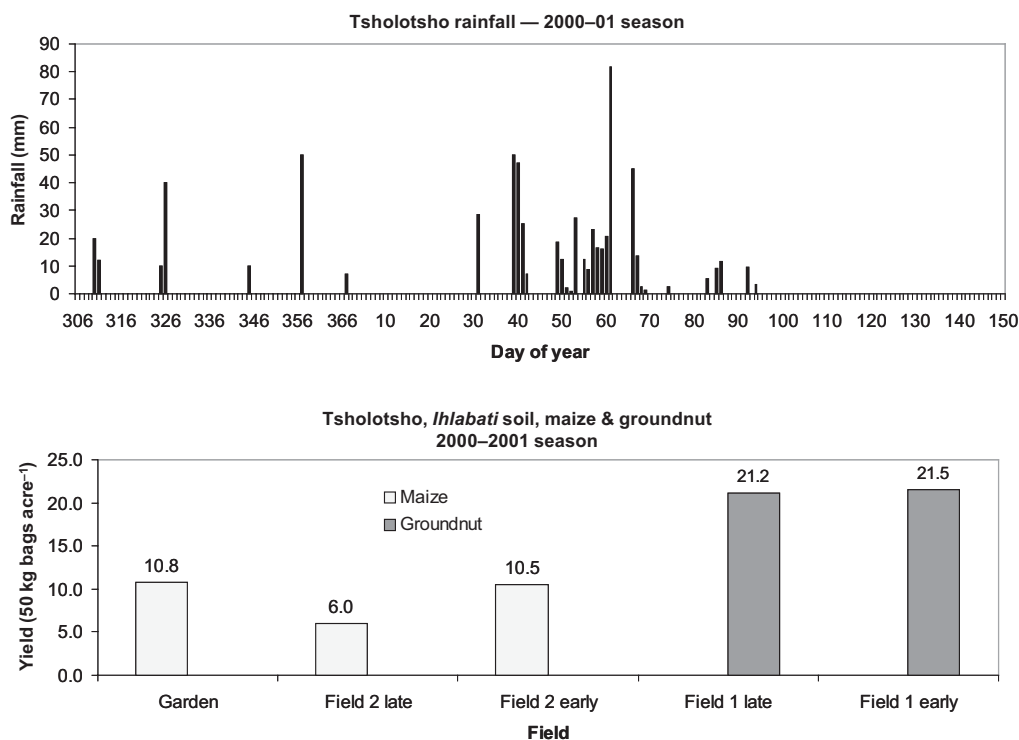
By the close of the first case study, the farmers seemed to now have little difficulty in participating in our evolved process: i.e. initially present the overnight runs for each case study as bags  $\text{acre}^{-1}$  for a baseline and a new practice, calculate the difference in yield, discuss suggestions for alternative options, ask the farmers to nominate their answers, run the new simulations, write changes in bags  $\text{acre}^{-1}$ , discuss results in a manner which leads to the next iteration of simulations. Indicators of a consensual process were: not having to re-explain the request for

their estimates, the ready volunteering of estimates with animated debate on likely outcomes between farmers, and the unsolicited queries on what the next simulation should be from different farmers.

## (ii) Sevi

The second case study, for Sevi, aimed at benchmarking the performance of her maize and groundnut crops grown on *ihlabathi* soil in the previous 2001 season. On the first rainfall events in early November, Sevi was able to plant her garden plot to maize and field one to groundnut. However, due to labour shortages and delayed rainfall, she was not able to plant maize in field two until early December. The question, which had emerged through discussions the previous day, was: What if she had given priority to planting her main crop of maize in field two on the early rains and delayed planting the groundnut until December?

The simulation used rainfall data for Tsholotsho for the 2001 season (Figure 4a) and showed simulated yields for the late-sown maize crop to be significantly less than for the crop sown early in the garden plot (Figure 4b). The simulation suggested that, if



**Figure 4.** (a) Daily rainfall for Tsholotsho for the 2001 season, and (b) simulated yields for the garden plot and early and late sown maize and groundnut crops.

Sevi had given priority to sowing all her maize early, she would have achieved greater maize production without significant effect on the production of groundnut sown later (Figure 4b).

This case study challenged the planting priority for different crops, with the objective of planting the main maize crop before the lesser-priority groundnut crop. While this action appeared attractive to the researchers, as it did not involve additional resources, one farmer commented that early planted maize, outside the fenced garden plot, ran the risk of being grazed by cattle due to the scarcity of alternative feed.

### (iii) Derrick

In the RAM interviews on day two, Derrick indicated that he did not use manure or fertiliser as he owned only two cattle and had few spare resources. His initial question was to ask about the value of four scotch carts (2500 kg) of low quality manure (C:N ratio of 35) applied to 1 acre of maize grown on a *ipane* soil.

Interestingly, during case study 1, where large returns from fertiliser were simulated, compared with small returns from manure, Derrick volunteered that his interest had shifted from manure to fertiliser (*'the effort from manure is not worth it'*). The first runs for Derrick's farm initially confirmed his new view that there was no return from the application of low quality manure (Figure 5a,b). The facilitated discussion then addressed why there was so little response to manure application and what he could do about it. All farmers joined this discussion with the researchers, on the N immobilisation phenomenon of such manure. The farmers and researchers together reached consensus to rerun the simulation but to concentrate the available 1000 kg manure on a smaller area (1/2 acre) and improve its quality (Figure 5c,d). These new runs showed modest returns to manure (0–2 bags acre<sup>-1</sup>) which was attractive to Derrick as it involved no higher dollar investment and it was something new that he could do himself. He could collect manure in a manner that maintained its quality and this was something he could start on tomorrow. Derrick stated that *'this is what I will do'*.

### (iv) Ester

The first three case studies had consumed close to five hours of discussion and lunch was ready. Even so, the fourth case study farmer, Ester, asked for her simulations. These were discussed over lunch with a

smaller group of farmers huddled around the notebook computer. Ester wanted to explore the application of low versus high quality manure for her own circumstance (results not presented). These runs were undertaken and discussed one-to-one with Ester but limited time prevented exploration of further scenarios.

## Farmer Meeting Conclusion

After lunch, the farmers and researchers reconvened to conclude the meeting, despite enthusiasm by some farmers for continuation – a female farmer interjected *'since this is our last day, we want to learn more'*. Samuel (our first case study farmer) gave a speech thanking the researchers for visiting him and his neighbours over the past three days. He identified record keeping by farmers of their yields and rainfall as an important learning from the meeting. He also asked for access to fertiliser and seed so that the village's farmers could increase their productivity in ways discussed over the previous days.

The leader of the research visitors responded with gratitude to the village farmers for attending the three days of the workshop and for their attention and interest. He offered to return the following week to discuss with interested farmers opportunities for follow-up, on-farm trials on issues raised during the discussions. He therefore asked that the farmers be proactive and meet themselves to discuss options for collaborative on-farm trials in the coming season.

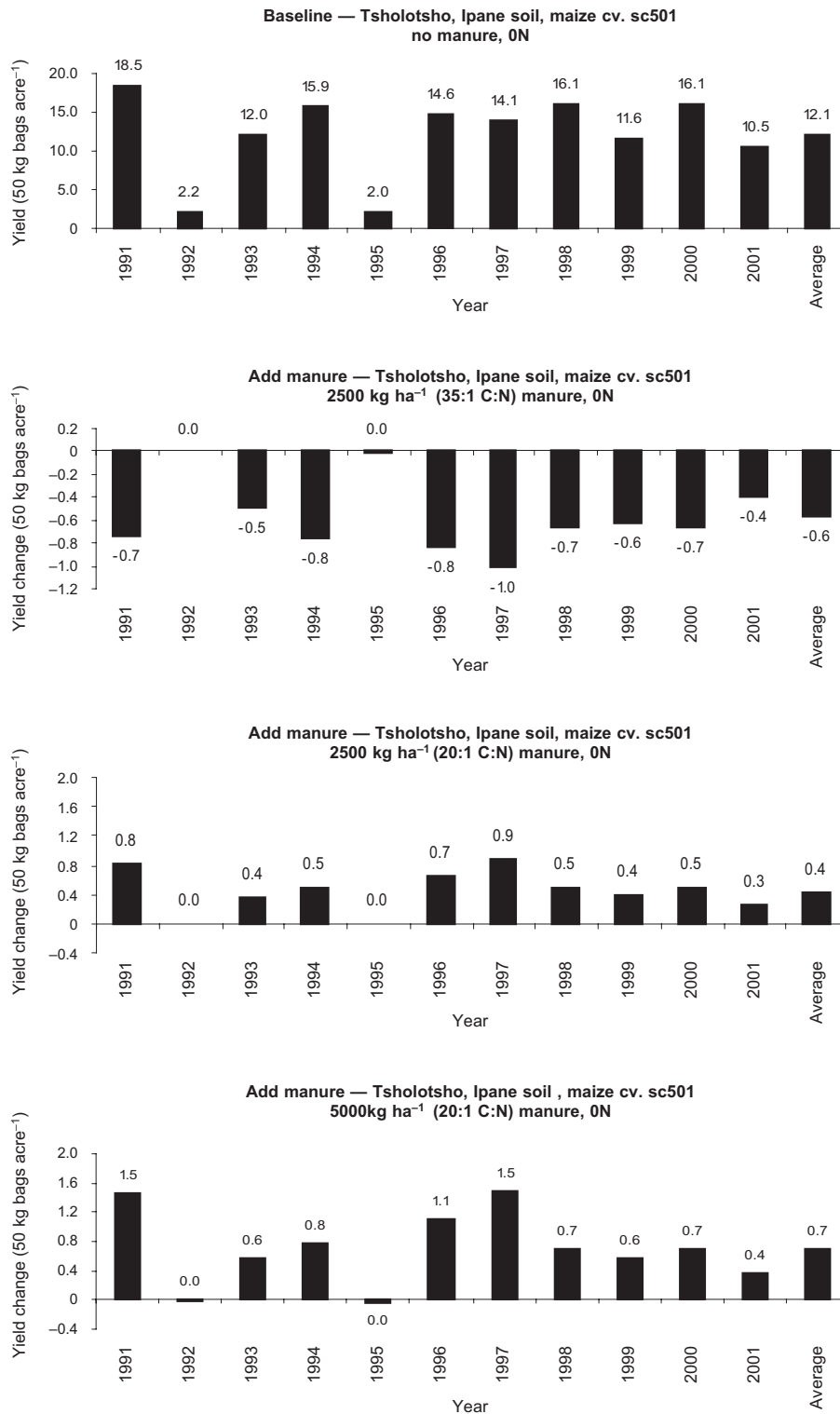
The day was concluded with the villagers singing and dancing for the departing researchers.

## Follow-up Activities

A week following the simulation workshop, ICRISAT researchers returned to the village of Mkhubazi to negotiate on-farm trials with interested farmers. The meeting started with a recap of what had been discussed during the simulation workshop. The farmers were then asked to present what they wished to do as a follow-up activity.

The discussions focused on the modelling results from the previous week's workshop and what could be done during the current season. Some of wealthier farmers referred to the huge potential benefit that the model showed when 1 bag of ammonium nitrate was applied acre<sup>-1</sup> compared with the normal practice of no N fertiliser. However, this was quickly dismissed





**Figure 5.** (a) Baseline simulation, using climate data for Tsholotsho for 11 years (1991–2001), was for maize cultivar sc501 grown on *ipane* soil with no applications of manure or inorganic fertiliser; and the changes in maize yields (bags acre<sup>-1</sup>); (b) for the application of low quality manure; (c) for the application of high quality manure; and (d) for the application of high quality manure concentrated on a smaller area (0.5 acre).

as a possible experimental treatment, as the farmers agreed that they could not afford to apply such high rates. In addition, such high returns to N fertiliser may not be achievable in these systems if other constraints were also evident (e.g. P deficiency, weeds etc.). When the rate of fertiliser was reduced to a realistic  $10 \text{ kg acre}^{-1}$ , the simulations had showed a yield advantage of an additional 3–4 bags  $\text{acre}^{-1}$  indicating that investment in fertiliser pays in many years.

During this discussion, the issue of the cost of fertiliser was approached by suggesting that 10 kg of fertiliser at then current prices equated to seven bottles of beer. The beer comparison posed the question, is beer an investment in the future? Women farmers responded by saying that it would be better to invest in crops than in beer, while some male farmers were not keen to answer the question, although they did make it clear that inorganic fertilisers were not available locally and asked could ICRISAT help? A local trade store owner was subsequently identified by the group and ICRISAT included him in an agents program supplying ammonium nitrate fertiliser in 10 kg bags rather than the standard 50 kg bags.

The ICRISAT team now referred to the workshop, at which farmers had indicated an interest to do trials on manure and fertiliser interactions. From the ideas farmers had suggested in discussions, five researchable areas emerged:

- how much manure?
- how much nitrogen?
- seed variety?
- anthill soil?
- ash?
- legume responses to phosphorus?

The farmers then broadly divided themselves into three groups. Eleven farmers would look at manure and inorganic nitrogen interactions; eleven would look at legumes (groundnuts or bambara) and their responses to various forms of phosphorus; and five would continue with their original ideas.

Despite a significant drought in Zimbabwe and the political upheavals associated with the 2002 presidential elections, which severely restricted travel by researchers, the farmers in Mkhubazi implemented and managed the trials that had been agreed (Twomlow 2003). These results support the southern African teams investment in participatory approaches linked with simulation modelling, and the empowerment it gives to rural communities and change agents.

## What Did We Learn?

The experience recounted here centred around the use of a cropping systems simulator with smallholder farmers in Zimbabwe as a way of allowing the farmers to experiment with alternative management options for their own farms. While this approach has proved successful with commercial farmers in Australia (Carberry et al. 2002), it was a surprise that computer simulation was apparently relevant to smallholder farmers in Zimbabwe. Evidence of relevance included the ready participation of farmers in specifying questions to be simulated, in volunteering likely outcomes, in rationalising their expectations with simulated outputs and in re-specifying the question for the next simulation run. The farmers in this engagement were not passive participants, rather they acted as experts in their own domain, using the simulator to explore possible consequences of altered management. All the researchers left the focus meeting with the feeling that real engagement and learning had occurred.

## What Process for Engagement?

The farmer meeting commenced with a feeling amongst the researchers of being uncomfortable about planning to use APSIM with farmers, of whom few would have prior knowledge of computers let alone a cropping systems model. However, by day 3, the researchers were readily engaging with the farmers using the model. The approach was to ensure that simulations were presented in a manner that facilitated thinking by all participants—the process was equivalent to playing a farming game. Using a particular farmer for the runs, eliciting his questions, getting other farmers' views, confirming the specifics of the run to be done, asking for their assessment of the outcome, revealing the results and debating what had happened, appeared an appropriate process for this engagement.

Asking the farmers for their estimate of the simulation outcome before presentation worked very well. This process had the farmers thinking about the question. In trying to rationalise the presented attributes of the simulation, it maintained involvement of all farmers, as opposed to just the case study farmer, and it provided them with a challenge which was mildly competitive with their peers. There appeared little sign that a consensus view dominated, as answers varied among groups and between simulations.

Once, when not all views were recorded for an upcoming simulation, the farmers drew attention to their answer for recording. On many occasions, farmers were volunteering their answers before being asked. Answers for early runs (range 1–4 bags, no zeros, no high returns) showed a far narrower range in distribution than the later simulations (0 to >10 bags, included low and high returns). Initially, the farmers seemed to be reluctant to risk being too different from prevailing views, but later this attitude dissipated as they started to think more about the outcomes; they became caught up in the questions being asked rather than worrying about the views of others. These observations were regarded as indicators of learning and confidence in the simulation approach.

Using recent historical rainfall, simulations for each year and asking questions such as ‘*what is your expected (average) benefit?*’ and ‘*how often one would win or lose?*’ worked well. Presentation of the yield difference between the base practice and a new practice worked better than just presenting yields for both practices and expecting farmers to visualise the contrast from graphs and assuming that all will do their own calculations on the difference. The presentation process evolved into not presenting the yields for added simulations but just presenting the differential in bags acre<sup>-1</sup> and this worked well.

### **Why Did Farmers Give the Simulations Credibility?**

The participating farmers had no prior knowledge of computer modelling, yet appeared to readily engage in a process of using the model to explore their farming practices. Initially they undoubtedly accommodated the visit because the researchers came to the village as ICRISAT representatives and were joined by the local extension person who was known to the farmers. However, the energy and eagerness of farmers to participate, the ready emergence of new questions, the willingness of farmers to predict the likely results and to explain why certain results occurred, were indicators of real engagement and acceptance of the process.

The process of ‘credibility generation’ commenced by concentrating on last season (2000–01) as a benchmark. The general pattern of daily rainfall was depicted and the performance of maize and groundnut crops was simulated, with simulated yields matching farmer experience impressively

well. Next, the past 11 years of annual rainfall amounts were presented and the focus of discussion was on correspondence of rainfall and simulated yields with farmer experience (e.g. the 1992, 1995 droughts). Again, simulated yields generally conformed with farmer experience.

The meeting changed dramatically from a traditional presentation approach to one of inquiry and discovery-learning during the first case study, when one game farmer challenged the relevance of the information being presented due to use of an inappropriate cultivar in the analyses. By shifting from cultivar sc501 to sc401 at the request of the farmers, rerunning the simulation and simulating their expected change, significant approval seemed to be created, both in giving legitimacy to local knowledge and in demonstrating a process for using the simulator interactively in a discussion.

Farmers’ behaviour indicated that, in addition to finding the simulation outputs to be credible, they found them *meaningful*, apparently because the simulations were specified in the context of a particular farmer and a relevant question. A process in which they could ask questions and related results were available immediately and in a manner where follow-on queries could be addressed was clearly appreciated by the farmers and effective in achieving the researchers’ aims. Researchers to whom this approach was new were comparing this to field experimentation, which often relates to no individual farmer and where results are not available for months and are biased by the influence of one season.

As the meeting progressed the farmers tended to be less critical, accepting the simulation results without due questioning. For example, after the 50 kg fertiliser simulation (yields simulated > 20 bags acre<sup>-1</sup>), the farmers had to be reminded to be sceptical of simulated results and to reflect on whether such yields are indeed possible and why. The researchers’ intent was to instil in the farmers a view that the simulations were not truth but rather an approximation that is close enough to allow ‘virtual’ experiential learning to take place. Even if such learning were only tentative, it might play an important role in farmers’ future adaptation of their practices.

### **The Role of Researchers**

There can be a clear difference between the approach of external experts trying to think of solutions for farmer clients and an alternative approach of facili-

tating farmers to explore their own options. Some researchers in the group initially wanted to recommend practices in response to simulations rather than ask farmers for their reaction and encourage them to explore the results by questioning them. The idea of such engagements is to make it interactive and an opportunity to learn using the simulator to gain 'virtual experience'. For some research experts, unaccustomed to a facilitation approach, to see the power of this approach and not jump too quickly into lecturing mode proved to be a significant learning experience.

The issue of what is a relevant question emerged as important and problematic amongst the researchers during the farmer interaction. One view was that the high fertiliser option (44 kg N acre<sup>-1</sup>) in the first case study was not appropriate, as it was beyond the resources of all the participating farmers. Yet, the farmer, Samuel, nominated this option. This simulated scenario actually sparked significant interest and debate amongst the farmers (see description in case study one). Here was an example of taking advantage of simulations which created discrepancies between farmer expectation of results (return on fertiliser 1–5 bags acre<sup>-1</sup>) and simulated output (1–30 bags acre<sup>-1</sup>). This helped facilitate discussion and learning about the issue of investing scarce cash resources in fertiliser. It also highlighted the importance of allowing the dialogue among farmers and researchers to *unfold* in accordance with farmers' inquiry, rather than to be overly designed and directed by scientists.

### **A Learning About the 'Best Place' for the Computer**

Over lunch the offer of doing more runs for individual farmers did not create great demand. While one farmer requested an additional run, which was undertaken with her and several other observers, the interaction was clearly not as rich as when the simulations were undertaken as part of a group activity. The results were also presented on the computer rather than transferred to flip charts. This created a distraction of the computer, with the farmers wanting to touch the computer themselves (e.g. to write their name). Having the computer central to running and presenting the results clearly distracted from the results themselves. The process of transferring simu-

lation outputs to flip charts avoided the problem of the computer getting in the way.

## **Conclusions**

Why does a short, three-day interaction warrant such reporting? As a group of research and extension professionals coming from a range of disciplines and perspectives, we started this activity all sceptical that simulation could be directly relevant to smallholder farmers. Our three-day interaction tested this hypothesis and provided evidence that challenges the prevailing view that models may be relevant only as an implement for policy research in smallholder systems (Lynam 1994). Our engagement of smallholder farmers with simulation modelling provided a unique, surprising and exciting experience from which there is opportunity to rethink the role of simulation within an action research framework for direct intervention with farmers in such regions.

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**Characterisation of Organic Sources,  
and Relevance to Model Parameterisation**

# 3.1

## Chemical Characterisation of a Standard Set of Organic Materials

Catherine N. Gachengo,\* Bernard Vanlauwe,\* Cheryl A. Palm<sup>†</sup> and George Cadisch<sup>§</sup>

### Abstract

This paper reports on the chemical characterisation of a standard sample set prepared for a cross-methods analysis to identify potential proximate analysis methods for the parameterisation of simulation models. In the subsequent sections, these samples are analysed using aerobic incubations, in vitro dry matter digestibility and near infrared reflectance spectrometry. Thirty-two organic materials were collected from various locations in Kenya, comprising plant samples (leaves, stems, leaflets), sawdust and cattle manure. Data obtained from chemical analysis of the materials were used to group the materials into the following quality classes: Class I, %N >2.5%, lignin <15% and soluble polyphenols <4%; Class II, %N > 2.5%, lignin >15% and soluble polyphenol >4%; Class III % N <2.5%, lignin <15%; and Class IV %N <2.5%, lignin >15%. Results showed that materials high in %N were also high in other nutrients (P, Ca, Mg), but potassium was not correlated with N concentration. Class I materials were mainly leaves of leguminous species. Class II comprise mainly *Calliandra calothyrsus* from different locations, as they had polyphenol contents higher than the critical value of 4% and had high protein-binding capacities. They were also low in K concentration (< 1%). Materials in quality class II were subdivided into three categories depending on their polyphenol and lignin contents. Class III materials were crop residues (except for one sample) and were generally low in N, polyphenols and lignin, while class IV (low in N and high in lignin) comprise stems and leaf-litter materials.

Organic materials play a critical role in both short-term nutrient availability and longer-term maintenance of soil organic matter in most smallholder farming systems in the tropics. Over the last decade, the formulation of research hypotheses related to residue quality and N release has led to a vast amount of research aimed at validation of these hypotheses.

Based on much of this work, a minimum data set of resource quality parameters has been proposed for the purpose of identifying robust plant quality indices that provide improved prediction of decomposition, nutrient release and soil organic matter factors which can be coupled with decomposition models (Palm and Rowland 1997).

Plant materials containing at least 2.5% N are usually described as being of high quality, where the application of these materials to soil is likely to result in net release of nitrogen if lignin and polyphenol are <15% and <4%, respectively. On the other hand, plant materials containing less than 2.5% N are considered to be of low quality as they are likely to temporarily immobilise N during decomposition (Palm et al. 2001).

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Representation of these quality parameters in simulation modelling is limited, with C:N and lignin content the only parameters presently used by most models. Also, lack of standardisation of analysis has to date not identified robust and cheap methods that can be used to generate the data required for simulation model parameterisation. Therefore, 32 organic materials commonly used in soil fertility management in Kenya, and that covered the four resource categories of Palm et al. (2001) (see Figure 1 of Vanlauwe and Sanginga (2004)), were collected (Table 1) and characterised as an initial step in the process of describing their nutrient supply characteristics.

This paper reports on the proximate analysis conducted by the Tropical Soil Biology and Fertility Institute of CIAT and the analyses of protein-binding capacity conducted by Imperial College at Wye.

## Materials and Methods

### Total nutrient analysis

Materials were oven dried at 30–35°C and ground to pass through 1 mm sieve. Plant nutrients (N, P, K, Ca and Mg) were analysed through complete oxidation of 0.3 g of material by Kjeldahl digestion using

**Table 1.** Organic materials and their place of collection.

	Sample name	Place of collection
1	<i>Zea mays</i> stover	W. Kenya
2	<i>Croton megalorapus</i> leaves	W. Kenya
3	<i>Senna spectabilis</i> leaflets	W. Kenya
4	<i>Lantana camara</i> leaves	W. Kenya
5	<i>Calliandra calothyrsus</i> leaflets	W. Kenya
6	<i>Senna siamea</i> leaflets	W. Kenya
7	<i>Crotalaria ochroleuca</i> leaflets	W. Kenya
8	<i>Crotalaria grahamiana</i> leaflets	W. Kenya
9	<i>Tithonia diversifolia</i> leaves	W. Kenya
10	<i>Gliricidia sepium</i> leaflets	W. Kenya
11	<i>Gliricidia sepium</i> leaflets	Machakos
12	<i>Senna siamea</i> leaflets	Machakos
13	<i>Flemingia congesta</i> leaflets	Machakos
14	<i>Senna spectabilis</i> leaflets	Machakos
15	<i>Calliandra calothyrsus</i> leaves	KARI-Embu (Embu provenance)
16	<i>Calliandra calothyrsus</i> leaflets	KARI-Embu (Embu provenance)
17	<i>Calliandra calothyrsus</i> leaves	KARI-Embu (Patalul provenance)
18	<i>Calliandra calothyrsus</i> leaflets	KARI-Embu (Patalul provenance)
19	<i>Calliandra calothyrsus</i> leaves	KARI-Embu (San Ramon Provenance)
20	<i>Calliandra calothyrsus</i> leaflets	KARI-Embu (San Ramon Provenance)
21	<i>Saccharum officinarum</i> stover	Nairobi
22	<i>Lantana camara</i> leaves	Nairobi
23	<i>Lantana camara</i> stems	Nairobi
24	Cattle manure	W. Kenya
25	<i>Tithonia diversifolia</i> leaves	Nairobi
26	<i>Gliricidia sepium</i> stems	Muguga
27	<i>Senna spectabilis</i> leaves	Muguga
28	<i>Sesbania sesban</i> leaves	Muguga
29	<i>Gliricidia sepium</i> leaflets	Muguga
30	<i>Sesbania sesban</i> stems	Muguga
31	<i>Eucalyptus saligna</i> leaf litter	Muguga
32	Sawdust	Muguga



sulfuric acid, hydrogen peroxide and selenium digestion mixture (Anderson and Ingram 1993). Nitrogen and potassium were determined from 5 mL of aliquot of the digestion mixture using an autoanalyser. Phosphorus was determined by adding ammonium molybdate/antimony potassium tartrate solution and ascorbic acid and the absorbance read at 880 nm. Calcium and magnesium were determined by adding 10 mL of 0.15% lanthanum chloride and analysis in an atomic absorption spectrophotometer.

## Total carbon analysis

Total carbon was determined by oxidation with concentrated sulfuric acid and 1 M aqueous potassium dichromate mixture with external heating, followed by titration against 0.2 M ferrous ammonium sulfate solution using 1,10 phenanthroline ferrous sulphate indicator (Anderson and Ingram 1993).

**Table 2.** Quality parameters of organic materials (grouping adapted from Palm et al. (2001)).

Sample name	Plant part	%N	%P	%K	%Ca	%Mg	%C	%PP	% lignin	% soluble carbon	C:N	Protein Binding capacity BSA mg/g plant material
Quality class I (High N, low lignin and PP*)												
<i>Croton megalorapus</i>	leaf	3.38	0.14	1.96	1.54	0.57	41.63	3.09	8.68	7.54	12.3	35.9
<i>Senna spectabilis</i>	leaflets	4.18	0.22	1.56	1.61	0.21	44.25	2.73	8.20	11.94	10.6	18.9
<i>Crotalaria ochroleuca</i>	leaflets	5.32	0.24	1.57	0.91	0.44	45.46	3.13	3.55	10.44	8.6	22.1
<i>Crotalaria grahamiana</i>	leaflets	3.42	0.16	0.64	1.84	0.53	37.82	2.77	4.85	10.12	11.1	21.0
<i>Gliricidia sepium</i>	leaflets	3.79	0.16	0.90	1.89	0.81	43.67	2.87	10.77	13.80	11.5	29.2
<i>Senna spectabilis</i>	leaflets	3.42	0.17	1.27	1.88	0.18	46.45	3.68	9.64	12.85	13.6	11.5
<i>Senna spectabilis</i>	leaf	4.58	0.23	2.04	1.33	0.17	45.46	1.89	11.27	9.94	10.0	26.1
<i>Sesbania sesban</i>	leaf	4.48	0.24	1.13	5.34	0.49	37.02	2.30	2.54	15.10	8.3	30.2
Quality class II ( High N, high PP, high lignin)												
<i>Calliandra calothyrsus</i>	leaflets	3.53	0.13	0.50	1.82	0.58	41.90	10.04	14.53	9.21	11.9	117.8
<i>Calliandra calothyrsus</i>	leaflets	3.20	0.10	0.49	1.23	0.39	44.48	9.46	15.79	9.46	13.9	197.8
<i>Flemingia congesta</i>	leaflets	2.90	0.18	0.46	1.64	0.41	40.41	8.63	16.11	11.35	14.0	171.3
Quality class II( High N, high PP, low lignin)												
<i>Lantana camara</i>	leaf	3.45	0.21	2.26	1.53	0.44	41.00	6.15	11.60	8.38	11.9	47.9
<i>Calliandra calothyrsus</i>	leaflets	4.09	0.16	0.60	1.38	0.55	44.45	9.54	8.84	7.60	10.9	163.8
<i>Senna siamea</i>	leaflets	2.93	0.13	0.53	2.39	0.13	44.85	7.23	11.27	9.78	15.3	24.1
<i>Tithonia diversifolia</i>	leaf	3.29	0.27	3.36	1.95	0.48	39.82	5.97	8.16	9.21	12.1	29.3
<i>Calliandra calothyrsus</i>	leaf	3.03	0.12	0.49	1.35	0.47	43.83	14.01	9.78	11.43	14.5	294.7
<i>Calliandra calothyrsus</i>	leaf	3.03	0.11	0.61	0.91	0.40	46.40	14.48	6.21	12.75	15.3	287.6
<i>Calliandra calothyrsus</i>	leaflets	3.10	0.10	0.49	0.89	0.35	46.28	14.77	12.09	12.04	14.9	322.0
<i>Calliandra calothyrsus</i>	leaf	2.61	0.08	0.48	0.99	0.41	45.08	12.26	12.93	10.42	17.3	280.4
<i>Lantana camara</i>	leaf	4.51	0.33	2.59	1.49	0.66	43.67	5.15	6.20	8.51	9.70	12.6
<i>Tithonia diversifolia</i>	leaf	4.25	0.26	4.03	1.93	0.41	37.68	4.85	4.56	9.53	8.9	24.1
Quality class II (High N, high lignin, low PP)												
<i>Gliricidia sepium</i>	leaflets	3.58	0.16	1.44	3.23	0.73	40.53	2.56	15.68	11.86	11.3	21.1
<i>Cattle manure</i>		2.54	0.62	3.56	1.08	0.68	36.98	1.05	17.27	3.74	14.6	48.3
<i>Gliricidia sepium</i>	leaflets	3.78	0.16	2.12	1.85	0.48	40.68	3.50	16.67	11.59	10.8	33.6
Quality class III (Low N, low lignin)												
<i>Zea mays</i>	stover	0.59	0.03	0.80	0.33	0.34	41.30	1.06	4.62	4.84	70.9	14.7
<i>Senna siamea</i>	leaflets	1.99	0.10	0.62	3.25	0.28	43.56	8.14	10.45	11.90	21.8	22.1
<i>Saccharum officinarum</i>	stover	1.22	0.15	2.18	0.28	0.10	40.16	1.51	4.72	4.85	33.4	18.9
<i>Lantana camara</i>	stems	0.95	0.07	1.33	0.32	0.11	42.57	1.48	16.40	3.11	45.0	21.0
Quality class IV (Low N, high lignin)												
<i>Gliricidia sepium</i>	stems	1.64	0.09	2.67	0.97	0.36	42.08	1.30	20.44	5.01	25.7	26.1
<i>Sesbania sesban</i>	stems	0.82	0.04	0.76	0.62	0.12	44.38	0.84	15.09	3.24	54.4	25.2
<i>Eucalyptus saligna</i>	leaf litter	1.03	0.03	0.43	0.95	0.13	46.13	10.83	23.68	8.94	44.8	182.9
saw dust		0.14	0.01	0.05	0.08	0.02	48.57	1.74	29.45	1.40	348.8	19.9

### Water-soluble carbon analysis

Water-soluble carbon was obtained by wet oxidation using potassium dichromate. Twenty mL of deionised water was added to 0.03 g plant material in a glass bottle followed by hand shaking. The bottles were placed in a water bath at 100°C for 1 hour with occasional shaking. After filtration, 2 mL of 0.16 M potassium dichromate was added to 10 mL extract in digestion tubes. Another 10 mL of concentrated sulfuric acid was added while mixing on a vortex mixer. The digestion tubes were placed in a pre-heated block at 150°C for 30 minutes, then let cool. Samples were read on a spectrophotometer at 600 nm to obtain carbon concentration.

### Total soluble polyphenols

Total soluble polyphenols were determined by the Folin-Ciocalteu method (Constantinides and Fownes 1994). This involved extraction of 0.1 g material with 50% methanol in a water bath at a temperature of 77–80°C for 1 hour. The extract was filtered into a 50 mL conical flask and made to volume with distilled water. Folin-Ciocalteu reagent (2.5 mL) and 10 mL of 17% sodium carbonate was added to 1 mL extract in a 50 mL conical flask, made to volume and left to stand for 30 minutes for colour development. Standard samples of known tannic acid concentration were treated in the same way, and absorbance of the standards and samples was read in a spectrophotometer at 760 nm. Concentration of samples was obtained by plotting absorbance against concentration of standard samples. Percent polyphenol (expressed as tannic acid equivalent) was calculated as:

$$\% \text{ total soluble polyphenols} = (C \times 250)/W$$

where  $C$  = corrected concentration of sample in mg mL<sup>-1</sup>

$W$  = moisture corrected weight of sample in g  
250 = a dilution factor.

### Lignin content analysis

Lignin was determined through acid detergent fibre (ADF) via Ankom Technology. Plant materials (0.5 g) were placed into fibre bags that were then sealed with a heat sealer. These were placed in an Ankom Machine into which was added 2 litres of extracting solution (solution of sulfuric acid and centyltrimethyl ammonium bromide). Extraction was done for 1 hour at

100°C. The samples were then washed with boiling water, followed by repeated washing with acetone to remove plant pigments. They were then oven dried at 80° C and weighed to determine ADF. The samples were further hydrolysed with 72% sulfuric for 3 hours and washed repeatedly with boiling water followed by drying at 80° C to obtain lignin plus ash. Ashing was done in a muffle furnace at 550°C for 3 hours to destroy lignin and obtain ash. Lignin was then obtained by weight loss upon ashing, using the following formula:

$$\% \text{ lignin} = (W2 - W3)/W1 \times 100$$

where  $W1$  = moisture free weight of sample

$W2$  = lignin plus ash weight

$W3$  = ash weight.

### Protein-binding capacity

Protein binding capacity of polyphenols was determined by extracting the material using 50% aqueous methanol at 95°C. The extract was centrifuged and applied to chromatographic paper, followed by reaction with bovine serum albumin (BSA). Bound BSA was stained with Ponceou S and its absorbance read at 525 nm followed by conversion of absorbance to protein units using a calibration curve (Handayanto et al. 1994).

## Results and Discussion

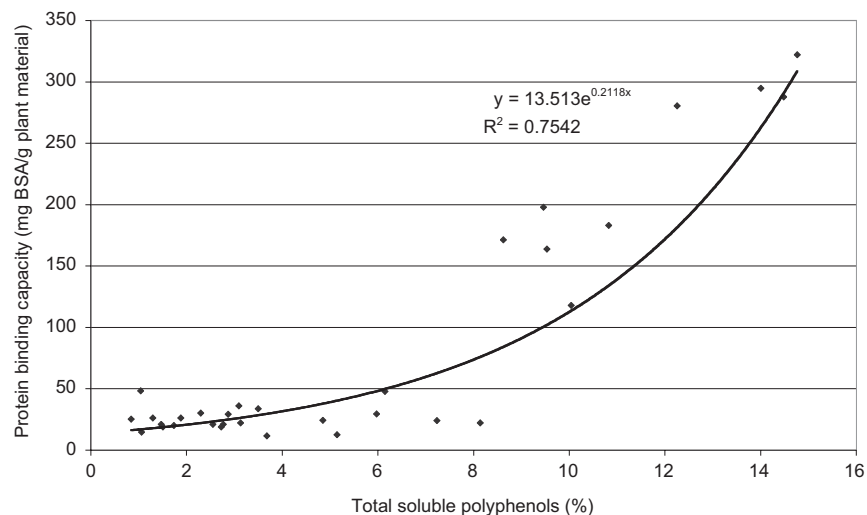
The proximate analysis enabled the differentiation of the standard sample set into different quality classes depending on their nitrogen, lignin and polyphenol contents (Table 2). Materials in quality class II were further grouped into three categories depending on their polyphenol and lignin contents.

Nitrogen was linearly correlated with all parameters except K and PBC (Table 3). Thus, materials high in N (classes I and II) were also high in phosphorus, calcium and magnesium concentrations, but low in lignin concentration. Potassium concentration was, however, not correlated with N content. Class II materials (mainly *Calliandra calothyrsus*) were generally high in polyphenol contents, and had high protein-binding capacity. Class III materials were low in soluble carbon, polyphenols and protein-binding capacity (except for one material). Class IV materials comprised mainly stems and were generally low in nutrients but high in lignin.

**Table 3.** Simple linear correlation coefficients for quality parameters.

	%C	%N	%P	%K	%Ca	%Mg	% PP	% Lignin	% Soluble carbon	C:N	PBC
%C	1.00	-0.166	-0.518**	-0.554**	-0.419*	-0.455**	0.001	0.326	0.001	0.366*	0.353
%N		1.00	0.510**	0.275	0.500**	0.556**	0.683**	-0.539**	0.683**	-0.580**	-0.009
%P			1.00	0.687**	0.234	0.480**	0.073	-0.265	0.073	-0.352*	-0.250
%K				1.00	0.041	0.241	-0.173	-0.218	-0.173	-0.277	-0.464**
%Ca					1.00	0.371*	0.662**	-0.313	0.662**	-0.365*	-0.202
%Mg						1.00	0.364*	-0.267	0.364*	-0.443*	0.068
% PP							1.00	0.011	0.419*	-0.210	0.902**
% Lignin								1.00	-0.421*	0.561**	0.106
% Soluble carbon									1.00	-0.542**	0.278
C:N										1.00	-0.133
PCB											1.00

\* and \*\* refer to significance at 5 and 1% confidence levels, respectively; PCB = protein-binding capacity of polyphenols; PP = total soluble polyphenols.



**Figure 1.** Relationship between total soluble polyphenols and protein binding capacity.

The relationship between protein-binding capacity and total soluble polyphenols is twofold (Fig. 1). From the data, it appears that the relationship can best be described using broken-stick models (see also Handayanto et al. (1997)), with an initial phase (up to about 8% total soluble PP) with few active polyphenols, followed by a linear relationship between total extractable PP and PBC. Polyphenol contents below ~8% resulted in protein-binding capacity < 50 mg BSA g<sup>-1</sup>.

On the other hand, polyphenol contents above 10% resulted in PBC > 100 mg BSA g<sup>-1</sup>. Correlation between soluble polyphenols and protein binding capacity ( $r = 0.90$ ) was highly significant (Table 3).

## Conclusion

Proximate analysis of the 32 organic materials showed that they covered the four resource quality classes that relate to nutrient release. Materials high in N were low in lignin and high in other nutrients (except K) and, as expected, the soluble polyphenols correlated significantly with protein-binding capacity at higher levels.

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## 3.2

# Mineralisation Patterns of Selected Organic Materials

Catherine N. Gachengo,\* Bernard Vanlauwe\* and Cheryl A. Palm†

### *Abstract*

Thirty-two standard organic materials were mixed with a sandy soil (at 40% field capacity) at a rate equivalent to 5 t ha<sup>-1</sup> and incubated aerobically under controlled conditions at 25°C for 28 days. Sampling for mineral N determination and CO<sub>2</sub> evolution was conducted at 3, 7, 14 and 28 days. Released CO<sub>2</sub> was related to resource quality, with those materials high in N, low in lignin and low in polyphenol concentrations releasing higher percentages of their initial C. In vitro dry matter digestibility (IVDMD) was linearly correlated with carbon breakdown, with correlation coefficients of 0.91, 0.92, 0.92 and 0.84 for sampling times of 3, 7, 14 and 28 days, respectively. Initial N concentration was significantly positively correlated with C breakdown at all sampling times. Nitrogen mineralisation was influenced mainly by initial N concentration of the materials, with materials having at least 2.3% N releasing N throughout the 28-day period.

Organic materials constitute a major soil input in many agricultural systems in the tropics. The effect of these materials on crop production is mainly through their contribution to soil available nutrients, improvement in soil moisture status, especially in relatively dry areas, contribution to organic matter build-up in the soil and enhancement in soil microbial populations that improve nutrient release and availability to plants. Most soils in the tropics are deficient in major plant nutrients such as nitrogen, phosphorus and potassium. The contribution of these materials to soil nutrient availability is subject to nutrient release during the process of decomposition. This process is influenced by several factors, among them quality of the material (Swift et al. 1979). Among the major quality parameters influencing

nutrient release, are nitrogen (N), lignin and soluble polyphenol concentrations. Materials rich in N, and low in soluble polyphenols and lignin, generally readily release nutrients once incorporated into the soil, subject to favourable environmental conditions. Materials low in nitrogen and high in lignin and polyphenol concentrations are likely to immobilise nitrogen during decomposition.

A study was carried out to determine nutrient release patterns of organic materials collected from different parts of Kenya. These materials comprised 30 plant materials (different parts), one cattle manure and one sample of sawdust.

### **Materials and Methods**

Thirty-two organic materials were collected from different parts of Kenya, oven dried at 30–35°C and ground to pass through a 1 mm sieve (Gachengo et al. 2004). Fifty grams of oven-dry soil (78% sand, 4% clay, 8% silt, pH (in water) 5.4, total carbon 0.48%, total N 0.04%) was used. The soil was brought to 40% of field capacity and kept at room temperature

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for 2 weeks. The organic materials were thoroughly mixed with the soil at a rate of 5 t ha<sup>-1</sup> dry weight basis in 60 mL bottles. These were placed in 250 mL incubation jars containing 10 mL of distilled water to maintain moisture levels during the incubation.

A vial containing sodium hydroxide (10 mL of 0.5 N) was placed in each incubation jar to trap CO<sub>2</sub> released during decomposition of the materials. The jars were tightly sealed with masking tape to avoid leakage of CO<sub>2</sub> produced by the respiring soil and kept in a temperature controlled room at 25° C. Each treatment was replicated three times in a completely randomised design.

Sampling for CO<sub>2</sub> and mineral N determination (nitrate plus ammonium) was done at 3, 7, 14 and 28 days. Determination of mineral N was also done at the beginning of the experiment (time 0). N mineralisation was calculated as net N mineralisation, where the sum of nitrate and ammonium N for each treatment was corrected by subtraction of the control.

Carbon dioxide trapped in the sodium hydroxide solution was determined by titration with 0.5 N hydrochloric acid. Ammonium and nitrate-nitrogen in the soil were determined by extraction using 100 mL of 2 N KCl (Dorich and Nelson 1984).

The amount of carbon released was calculated as:

$$\text{CEVOL} = (\text{BLNKTIT} - \text{SAMTIT}) \times 6 \times N_{\text{HCL}}$$

where CEVOL = evolved C (mg C)

BLNKTIT = volume of standard HCl used to titrate the NaOH in containers from positive controls (mL)

SAMTIT = volume of standard HCl used to titrate the NaOH in containers exposed to the soil atmosphere (mL)

N<sub>HCL</sub> = normality of standard HCl.

## Results and Discussion

### Carbon breakdown

The 32 organic materials analysed have been grouped into 6 quality classes depending on their N, lignin and polyphenol contents as described in Gachengo et al. (2004). During the incubation experiment, the high-quality materials (Class I) released the highest amounts of their initial C (Figure 1 (a)). By the end of 28 days, materials high in N, high in lignin and high in polyphenols (Figure 1(b)) had released the least amount of their initial C. It appears that there may be interaction between polyphenols and lignin in their

influence on carbon breakdown. Materials high in either lignin or polyphenols alone but high in N (Figure 1(c) and (d)) released more of their initial carbon than those high in both lignin and polyphenols (Figure 1(b)). However, polyphenols appear to play a bigger role in limiting C breakdown than lignin. Materials low in both N and lignin (Figure 1(e)) released more of their initial carbon than those low in N and high in lignin (Figure 1(f)).

Carbon breakdown correlated well (Table 1) with most chemical constituents of the materials (Gachengo et al. 2004). Carbon released at 14 days by various materials linearly correlates well with in vitro dry matter digestibility (data reported by Barrios et al. (2004)). Correlation between the two parameters resulted in four clusters of materials (Figure 2). Cluster 1 represents materials with initial N > 2.5%, lignin and soluble polyphenol contents <15 and < 4%, respectively (quality class I). Cluster 2 comprise materials both low and high in N, lignin and polyphenols (classes I, II, III), while cluster 3 consists of materials with N <2.5% and low lignin or polyphenol contents (class III). Cluster 4 is primarily made up of materials of low quality with N < 2.5% and lignin > 15% (class IV). Sawdust would be expected to fall within this cluster, but it lies on its own, probably due to its very high lignin content (29%) and low initial N (0.14%).

Significant positive linear correlation was also found between C released and N concentration. Lignin concentration showed significant negative correlation, while polyphenol concentration had no significant correlation with carbon release. However, on leaving out polyphenol data for stems, manure and stover materials (these are usually very low in polyphenols and nutrients, but high in lignin (Palm et al. 2001), there was a high negative correlation ( $r = -0.86$ ) between carbon release and polyphenol concentration for leaf materials (Figure 3). The same applies to protein-binding capacity.

Multiple linear regression to determine the contribution of N, lignin and polyphenols resulted in the equation with an  $R^2$  value of 0.6598:

$$\text{C28} = 49.69 + 1.687\text{N} - 1.406\text{PP} - 1.144\text{Lignin}$$

where C28 = percentage of initial carbon evolved by 28 days

N = per cent N in material

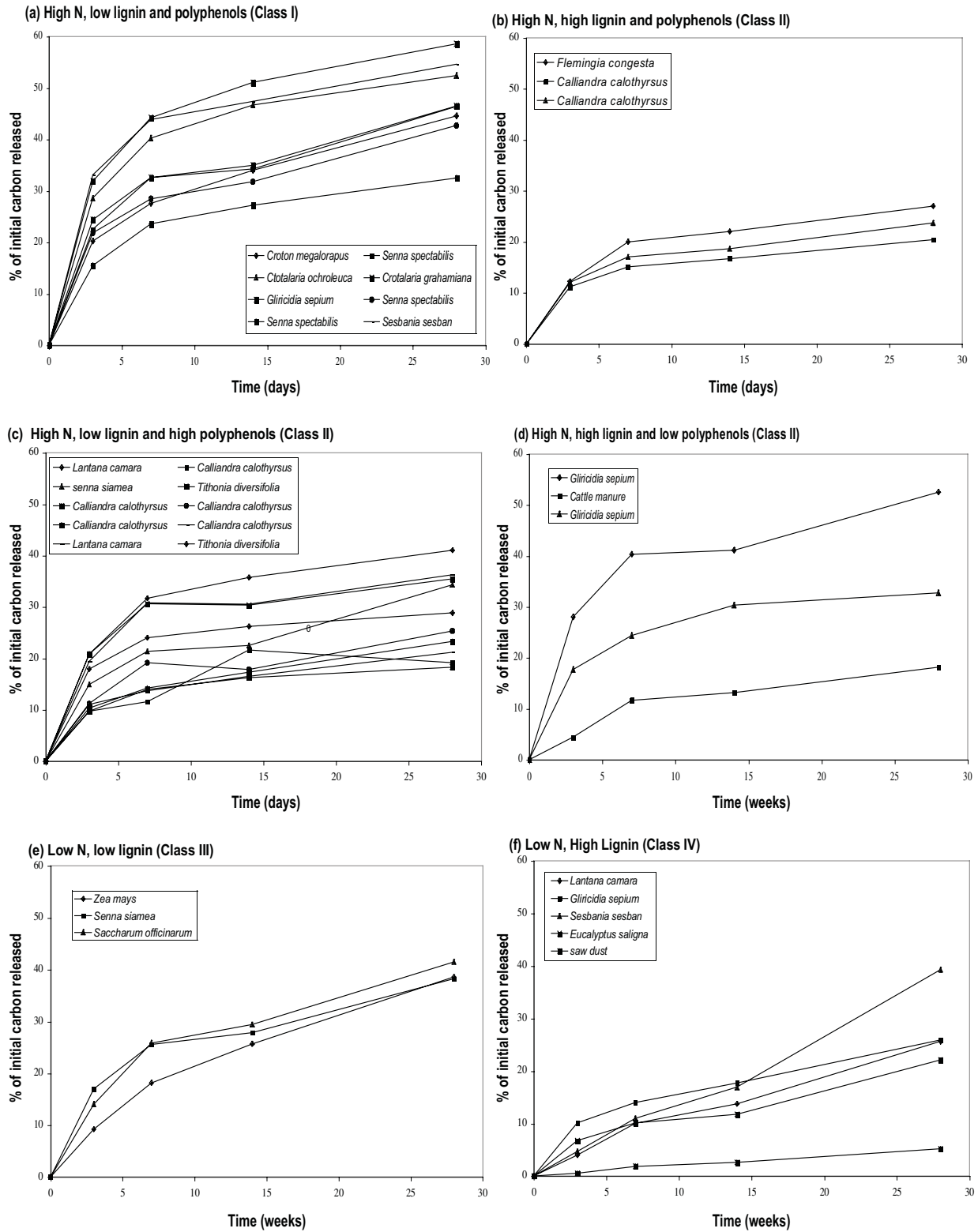
Lignin = per cent lignin in material

PP = per cent polyphenol in material.

**Table 1.** Simple linear correlation coefficients for mineralisation of N and C.

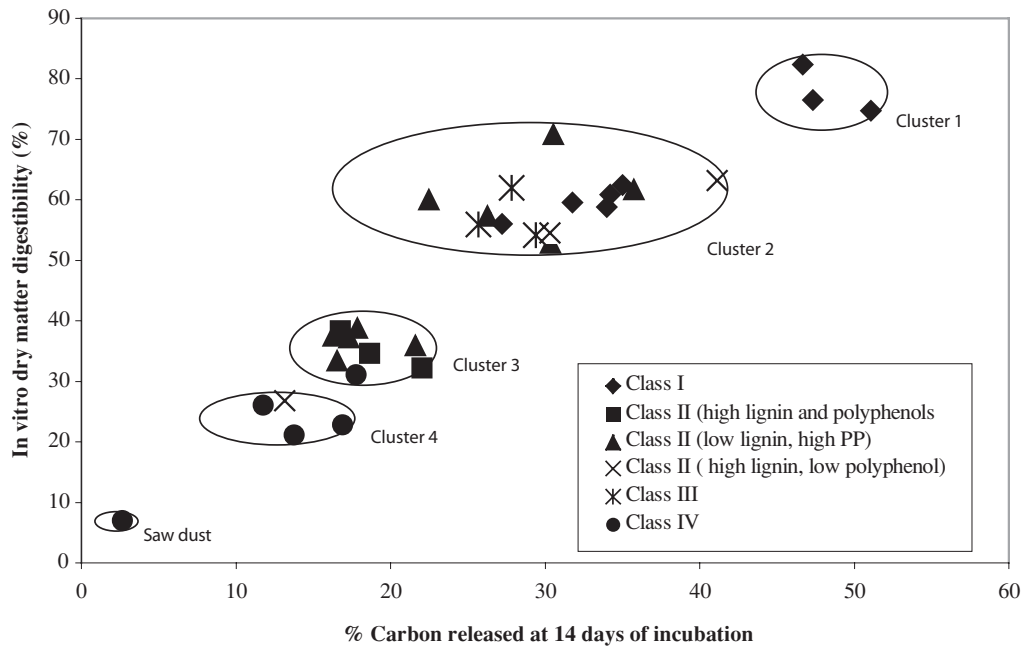
	%N	%P	%K	%Ca	%Mg	% total soluble polyphenols	% lignin	% soluble carbon	C:N	% in vitro dry matter digestibility	Protein-binding capacity BSA mg/g plant material
<b>Nitrogen</b>											
Day 3	0.826**	0.445*	0.297	0.510**	0.593**	-0.005	-0.181	0.524**	-0.393	0.414*	-0.038
Day 7	0.836**	0.450*	0.299	0.526**	0.579**	0.022	-0.183	0.563**	-0.407*	0.429*	-0.026
Day 14	0.896**	0.506**	0.351*	0.581**	0.615**	0.065	-0.334	0.651**	-0.589**	0.554**	-0.021
Day 28	0.915**	0.526**	0.352*	0.570**	0.648**	0.109	-0.415*	0.690**	-0.636**	0.621**	0.001
<b>Carbon</b>											
Day 3	0.709**	0.271	0.214	0.681**	0.435*	-0.233	-0.626**	0.662**	-0.449**	0.910**	-0.365*
Day 7	0.656**	0.328	0.290	0.631**	0.408*	-0.310	-0.673**	0.588**	-0.451**	0.925**	-0.432*
Day 14	0.639**	0.279	0.267	0.579**	0.395*	-0.362*	-0.706**	0.523**	-0.458**	0.923**	-0.454**
Day 28	0.418*	0.147	0.205	0.502**	0.225	-0.471**	-0.651**	0.409*	-0.423*	0.848**	-0.538**

\* and \*\* refer to significance at 5 and 1% levels, respectively.

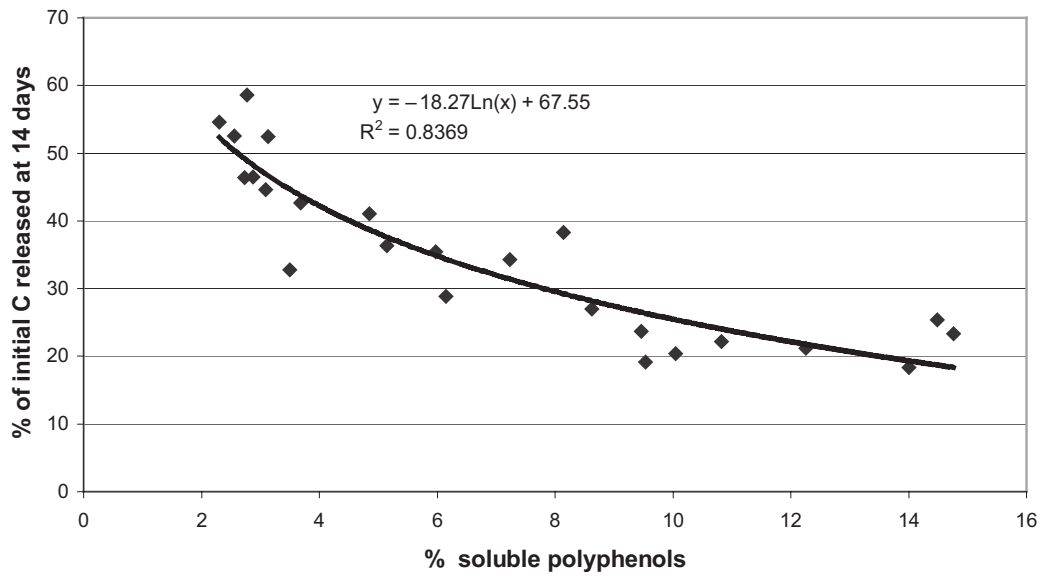


**Figure 1.** Carbon mineralisation patterns of different quality classes.





**Figure 2.** Relationship between in vitro dry matter digestibility and carbon release.



**Figure 3.** Effect of soluble polyphenols on carbon release of organic materials.

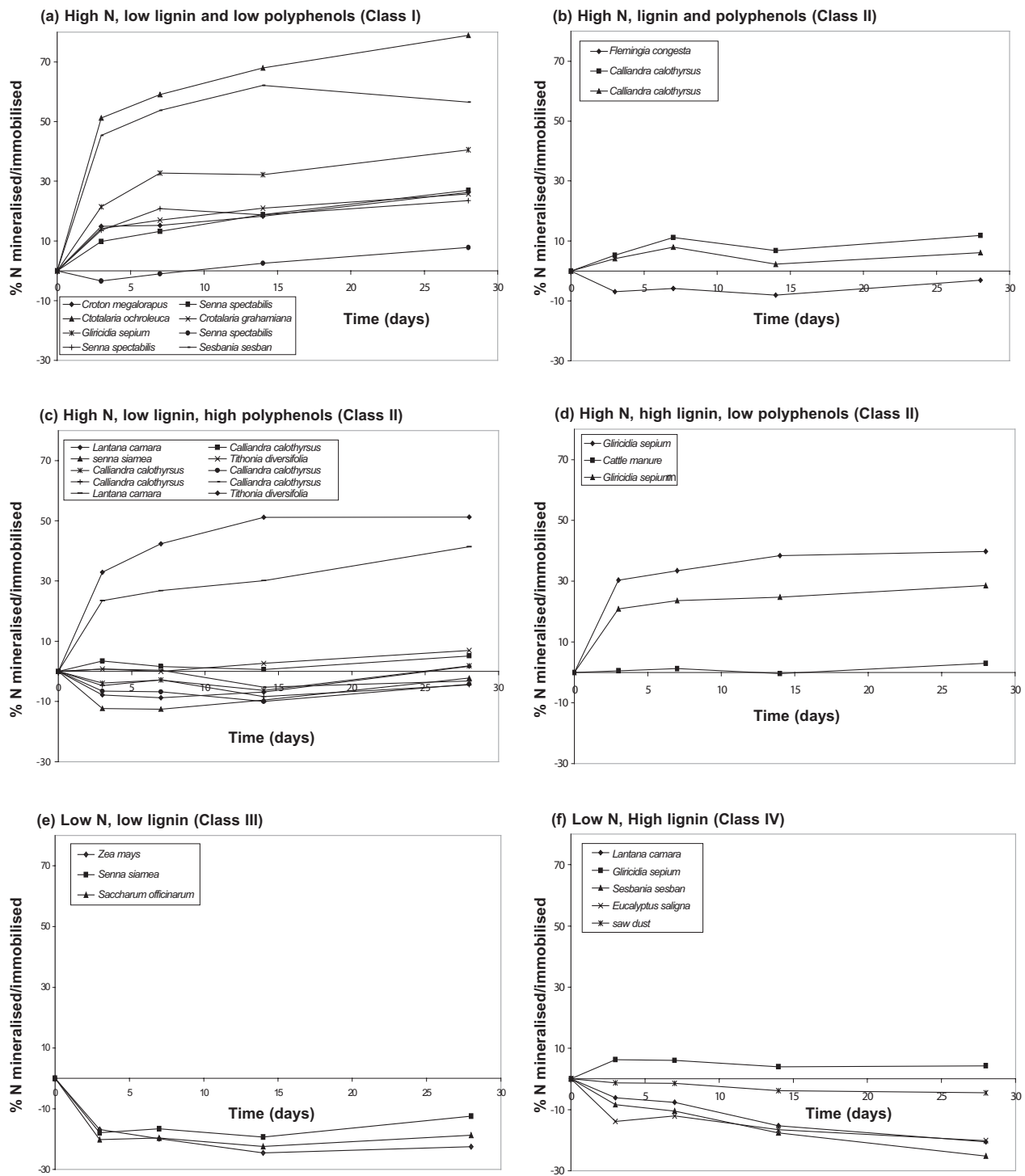
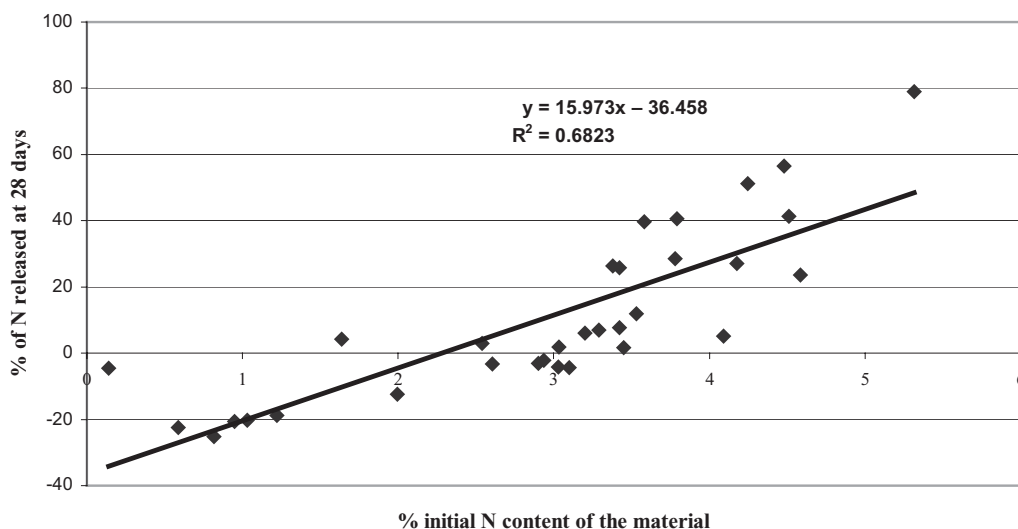


Figure 4. Nitrogen mineralisation patterns from organic materials.



**Figure 5.** Effect of initial N content on N mineralisation.

Thus, about 66% of variation in carbon mineralised by 28 days was accounted for by N, lignin and polyphenols contents of the materials.

### Nitrogen mineralisation

Organic materials in Class I released N through the 28-day period except for one material that immobilised N during the first 7 days of incubation (Figure 4 (a)). This may be explained by its polyphenol content (3.81%), which was very close to the critical level (4%) required for net N mineralisation to occur. Most materials high in both N and polyphenol (but low in lignin) (Figure 4(c)) immobilised N for some time or throughout the 28 days, while those high in N and lignin (but low in polyphenols) (Figure 4(d)) mineralised N throughout the study period. Thus, polyphenols had a higher influence in limiting N mineralisation than lignin. Materials in class III immobilised N throughout the 28 days due to their low initial N content. However, there was a reduction in immobilisation after 14 days of incubation. Materials in class IV immobilised N, increasingly with time. The trend does not show any indication of net mineralisation taking place in the near future (Figure 4(f)).

The most significant positive correlation for nitrogen release at 28 days was with the N concentration of the materials (Table 1). Most materials whose nitrogen concentration was at least 2.3% released nitrogen (Figure 5). Materials with %N above 2.3% but soluble polyphenol above 4% immo-

bilised N. *Gliricidia sepium* stems, though low in N (1.64%) and high in lignin (20.44%), did not immobilise N probably due to their low polyphenol concentration (1.3%). This suggests that N mineralisation of the materials was controlled mainly by their N and polyphenols contents.

Multiple regression analysis showed N mineralisation was mainly influenced by N concentration in the materials (Table 1), the following equation having an  $R^2$  value of 0.846:

$$N_{28} = -97.81 - 0.00021PP + 28.85N + 0.698Lignin$$

where  $N_{28}$  = percentage of initial N mineralised by 28 days.

### Conclusion

Mineralisation is a complex process that is governed by several factors, among them quality of the material. During the early stages of decomposition, it appears that N and polyphenol contents are the main quality parameters that determine mineralisation of nitrogen. For net N mineralisation to take place during the early stages of decomposition, a combination of low polyphenol and high nitrogen concentrations is required. Carbon breakdown was also influenced by the presence of lignin, with materials high in both lignin and polyphenols releasing less C. However, lignin did not appear to influence N mineralisation significantly, at least during the first 28 days of decomposition.

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## 3.3

# The In Vitro Dry Matter Digestibility (IVDMD) Method

Edmundo Barrios\*

### Abstract

In vitro dry matter digestibility (IVDMD) is reported for a standard set of organic materials. IVDMD ranged from 82% for leaflets of the legume *Crotalaria ochroleuca* to 7% for sawdust.

In a review by Chesson (1997) it was proposed that decomposition processes in the rumen and in the soil, although different, were sufficiently similar to be considered for comparative plant tissue studies. Studies by Tian et al. (1996) supported this hypothesis, by showing that plant degradation during in situ ruminant nylon bag assay correlated with decomposition in a litter-bag study. More recently, Cobo et al. (2002) showed that the in vitro dry matter digestibility (IVDMD) method, which simulates in vitro processes taking place in the rumen of cattle during plant digestion, was closely related with decomposition processes for 12 plant materials with different tissue qualities (Figure 1).

The highly significant ( $P < 0.001$ ) correlations obtained during this study between IVDMD and plant decomposition suggested that laboratory-based IVDMD tests could be used as surrogates for decomposition of plant tissues in the field (Cobo et al. 2002). In the present study, the importance of this finding to model parameterisation was further evaluated by assessing their IVDMD values of 32 standard organic materials covering a wider range of tissue qualities.

### Method

The IVDMD is a laboratory test used as a plant quality index for animal feed by animal nutritionists (Tilley and Terry 1963; Harris 1970). The method includes two consecutive digestion phases. During the first digestion phase in this study, plant materials were incubated under anaerobic conditions with rumen microorganisms for 48 hours at 39°C. This was followed by a 24 hour acid-pepsin digestion phase at 39°C, under anaerobic conditions. Following this 72 hour incubation, residual plant materials were collected and oven dried (105°C for 12 hours). Ash contents were determined by combustion (550°C for 2 hours) and these data used to correct plant sample weight for potential contamination with soil.

Calculations were made using the following equation:

$$\%IVDMD = (1 - wd - wb/ws) \times 100$$

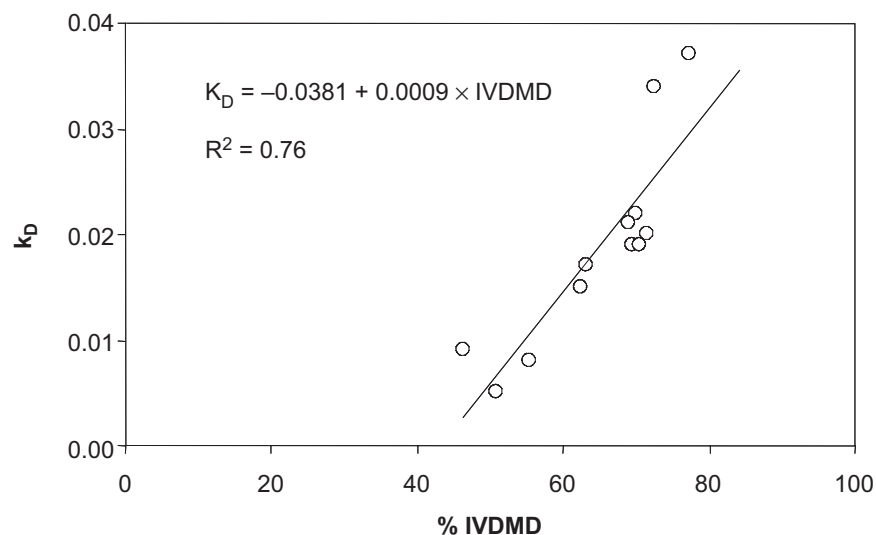
where wd = weight of dry plant residue, wb = weight of dry residues from blank, and ws = dry weight of original plant sample.

### Results and Discussion

The IVDMD method showed a wide range of qualities in the 32 plant materials tested related to their differing chemical compositions (Table 1). The highest IVDMD value (82.4%), corresponding to

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**Figure 1.** Linear regression between in vitro dry matter digestibility (IVDMD) of plant materials and their respective rates of decomposition ( $K_D$ ). N=12. Reproduced from Cobo et al. (2002).

**Table 1.** In vitro dry matter digestibility (IVDMD) values for 32 standard organic materials.

Lab ID	Plant name	Plant part	IVDMD (%)
TSBF1	<i>Zea mays</i>	Stover	55.91
TSBF2	<i>Croton megalocarpus</i>	Leaf	58.78
TSBF3	<i>Senna spectabilis</i>	Leaflets	60.88
TSBF4	<i>Lantana camara</i>	Leaf	57.36
TSBF5	<i>Calliandra calothyrsus</i>	Leaflets	35.88
TSBF6	<i>Senna siamea</i>	Leaflets	60.03
TSBF7	<i>Crotalaria ochroleuca</i>	Leaflets	82.37
TSBF8	<i>Crotalaria grahamiana</i>	Leaflets	74.73
TSBF9	<i>Tithonia diversifolia</i>	Leaf	52.85
TSBF10	<i>Gliricidia sepium</i>	Leaflets	62.48
TSBF11	<i>Gliricidia sepium</i>	Leaflets	63.21
TSBF12	<i>Senna siamea</i>	Leaflets	61.94
TSBF13	<i>Flemingia congesta</i>	Leaflets	32.21
TSBF14	<i>Senna spectabilis</i>	Leaflets	59.59
TSBF15	<i>Calliandra calothyrsus</i>	Leaves	37.51
TSBF16	<i>Calliandra calothyrsus</i>	Leaflets	38.36
TSBF17	<i>Calliandra calothyrsus</i>	Leaves	38.85
TSBF18	<i>Calliandra calothyrsus</i>	Leaflets	37.18
TSBF19	<i>Calliandra calothyrsus</i>	Leaves	33.41
TSBF20	<i>Calliandra calothyrsus</i>	Leaflets	34.64
TSBF21	<i>Saccharum officinarum</i>	Stover	54.12
TSBF22	<i>Lantana camara</i>	Leaves	70.83
TSBF23	<i>Lantana camara</i>	Stems	21.15
TSBF24	Cattle manure		26.84
TSBF25	<i>Tithonia diversifolia</i>	Leaves	61.67
TSBF26	<i>Gliricidia sepium</i>	Stems	31.08
TSBF27	<i>Senna spectabilis</i>	Leaflets	58.06
TSBF28	<i>Sesbania sesban</i>	Leaves	76.48
TSBF29	<i>Gliricidia sepium</i>	Leaflets	54.52
TSBF30	<i>Sesbania sesban</i>	Stems	22.80
TSBF31	<i>Eucalyptus saligna</i>	Leaf litter	26.02
TSBF32	Sawdust		6.99

rapid decomposition rates, was found for leaflets of the legume *Crotalaria ochroleuca*. Intermediate values were found for leaves of *Calliandra calothyrsus* (38.9%). The lowest IVDMD value (7%), corresponding to slow decomposition rates, was measured for sawdust.

The IVDMD results were consistent with expected results based on existing information in the literature and in our databases. This observation further confirms the potential of this test to save time and variability associated with decomposition studies in the field. This finding could also be of practical importance for screening plant materials for different farm uses and could be linked to decision-tree schemes similar to those reported by Palm et al. (2001).

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## 3.4

# Predicting Decomposition Rates of Organic Resources Using Near Infrared Spectroscopy

Keith D. Shepherd\*

### *Abstract*

Organic resources constitute a major source of nutrient inputs to both soils and livestock in smallholder tropical production systems. Information on decomposition characteristics is needed for sound management of organic resources. Measurement of C and N mineralisation rates and dry matter digestibility using current laboratory methods is both time-consuming and costly. This study tested near infrared (wavelengths from 1.0 to 2.5  $\mu\text{m}$ ) reflectance spectroscopy (NIRS) for rapid prediction of C and N mineralisation rates and in vitro dry matter digestibility for a diverse range of organic resources ( $n = 32$ ). The organic resource samples were aerobically incubated in a sandy soil and amounts of C and N mineralised determined after 28 days. Organic resource attributes were calibrated to first derivative reflectance using partial least squares regression. Cross-validated  $r^2$  values for actual versus predicted values were 0.82 for percentage of added C mineralised, 0.84 for percentage of added N mineralised, and 0.88 for in vitro dry matter digestibility. NIRS can be used for routine prediction of decomposition and nutrient release characteristics of organic resources. Construction of spectral calibration libraries in central laboratory facilities would greatly increase the efficiency of NIRS use for routine organic resource characterisation in laboratories throughout the world.

Organic resources constitute a major source of nutrient inputs to both soils and livestock in smallholder tropical production systems. The quality of organic resources regulates the potential rate of decomposition and availability of those nutrients, both in the soil and the rumen. Although the actual rate and degree of decomposition are moderated by the local activity of the decomposer organisms and the environmental conditions, plant litter quality is the factor most amenable to management in agricultural systems (Giller and Cadisch 1997; Heal et al. 1997). Recently, efforts have been undertaken to compile global information on decomposition and resource quality attributes as a basis for more systematic experimentation and development of predictive models (Palm et al. 2001). Using this diverse

collection, Shepherd et al. (2004) demonstrated that near infrared spectroscopy (NIRS) can be used as a non-destructive method for rapid analysis of N, total soluble polyphenol and lignin concentration in organic resources. These quality attributes of organic resources largely determine their decomposition and nutrient release rates. The objectives of this study were to test the robustness of NIRS for direct prediction of C and N mineralisation rates and in vitro dry matter digestibility for a diverse set of samples from the organic resource database.

### Methods

Thirty-two samples were selected from the organic resource database to represent a range of N, total soluble polyphenol and lignin concentrations (Gachengo et al. 2004b). The plant materials were aerobically incubated in sandy soil for 28 days as

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described by Gachengo et al. (2004a). The total amounts of C and N mineralised after 28 days were expressed as a percentage of their respective initial amounts added. The incubations were conducted in triplicate. In vitro dry matter digestibility was determined on the same materials in duplicate using standard methods (Barrios 2004). Diffuse reflectance spectra were recorded for each sample using a FieldSpec™ FR spectroradiometer (Analytical Spectral Devices Inc., Boulder, Colorado) at wavelengths from 1.0 to 2.5  $\mu\text{m}$ , with a spectral sampling interval of 0.001  $\mu\text{m}$ . Dried and ground (<1 mm) plant material was placed into 7.4 cm diameter Duran glass Petri dishes to a thickness of about 1 cm. The samples were scanned through the bottom of the Petri dishes using a high intensity source probe (Analytical Spectral Devices Inc., Boulder, Colorado). The probe illuminates the sample (4.5 W halogen lamp giving a correlated colour temperature of 3000 K; WelchAllyn, Skaneateles Falls, NY) and collects the reflected light from a 3.5 cm diameter sapphire window through a fibre-optic cable.

To sample within-dish variation, reflectance spectra were recorded at two positions, successively rotating the sample dish through 90° between readings. The average of 25 spectra (the manufacturer’s default value) was recorded at each position to minimise instrument noise. Before reading each sample, 10 white reference spectra were recorded using calibrated spectralon (Labsphere®, Sutton, NH) placed in a glass Petri dish. Reflectance readings for each wavelength band were expressed relative to the average of the white reference readings. With this method, a single operator can comfortably scan 500 samples a day.

The raw spectral reflectance data were pre-processed before statistical analysis as follows. Relative reflectance spectra were resampled by selecting every hundredth-micrometre value from 1.0 to 2.5  $\mu\text{m}$ . This was done to reduce the volume of data for analysis and to match it more closely to the spectral

resolution of the instrument (0.003–0.01  $\mu\text{m}$ ). The reflectance values were then transformed with first derivative processing (differentiation with second-order polynomial smoothing with a window width of 0.02  $\mu\text{m}$ ) using a Savitzky-Golay filter, as described by Fearn (2000). Derivative transformation is known to minimise variation among samples caused by variation in grinding and optical set-up (Marten and Naes 1989). Multiplicative scatter correction (used to compensate for additive and/or multiplicative effects in spectral data) and normalisation (sample-wise scaling) of the reflectance data (both described in Vandeginste et al. (1998)) did not improve calibrations and so were not used. Wavebands in regions of low signal-to-noise ratio or displaying noise due to splicing between the individual spectrometers (Analytical Spectral Devices Inc. 1997) were omitted leaving 148 wavebands for analysis. The omitted bands were 1.00–1.01  $\mu\text{m}$ , and 2.50  $\mu\text{m}$ .

The data from the laboratory reference methods were calibrated against the reflectance wavebands using partial least squares regression, using ‘The Unscrambler’ (Camo ASA, Oslo) software. Hold-out-one full-cross validation was used to evaluate the stability of the calibrations. Jack-knifing was performed to eliminate unreliable (non-significant) wavebands, in order to simplify the final model and make it more reliable. Prediction success was evaluated on reference and actual observations using the coefficient of determination ( $r^2$ ), root mean square error (RMSE) and bias.

## Results and Discussion

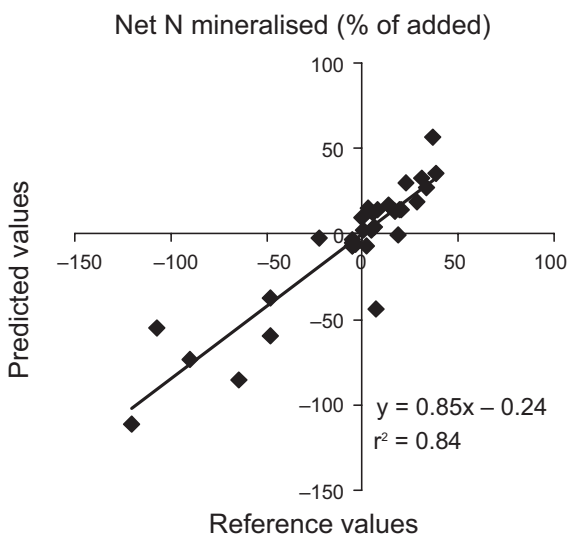
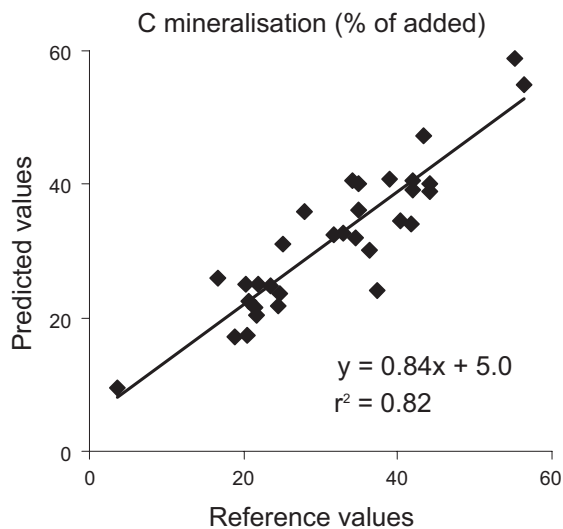
Robust partial least squares calibrations were obtained for all the three reference methods (Table 1). There was more scatter in the calibration at low than high nitrogen mineralisation values (Figure 1), most likely reflecting imprecision in the laboratory

**Table 1.** Statistics for calibration and full-cross validation models for predicting decomposition reference values from near infrared reflectance.

Reference method	Calibration			Validation		
	$r^2$	RMSE	Bias	$r^2$	RMSE	Bias
C mineralisation	0.92	3.2	-8.9E-7	0.84	4.6	0.08
N mineralisation	0.89	13	1.7E-6	0.84	16	0.22
IVDM digestibility	0.95	3.9	-9.3E-7	0.88	6.3	-0.15

RMSE = root mean square error of calibration.  
IVDM = in vitro dry matter digestibility.

measurements at very low plant nitrogen concentrations. The lowest calibration point for in vitro dry matter digestibility (sawdust sample) was underestimated in the cross-validated predictions (Figure 2). Having more samples with low digestibility in the calibration data set would improve the calibration.



**Figure 1.** Spectrally predicted values versus laboratory reference values for amount of carbon and nitrogen mineralised from organic materials incubated in soil. The results are based on predictions using hold-out-one, full cross-validation.

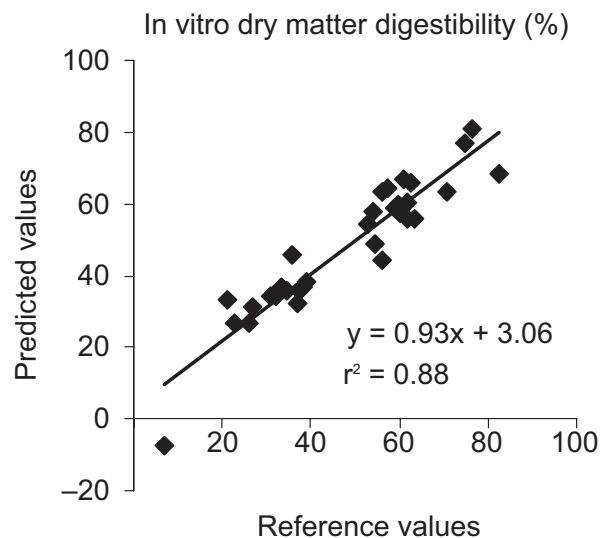
## Conclusion

NIRS shows promise for direct prediction of decomposition and nutrient-release characteristics of

organic resources, obviating the need for tedious determination of organic resource attributes in the laboratory and the development of predictive models based on these attributes. Large spectral calibration libraries (Shepherd and Walsh 2002) for organic resources decomposition and nutrient-release characteristics should be built up in central laboratories. Then sets of standards will be all that is needed to cross-calibrate individual laboratory spectrometers to the central laboratory spectrometer. In this way, the efficiency of analysis of organic resource quality can be greatly increased. Further work should compare the accuracy and precision of the NIRS predictions of decomposition rates with predictions derived from attributes of organic resource quality determined by conventional laboratory methods, or with actual breakdown and related soil changes or growth responses in the field. The potential for widespread use of NIRS of measuring residue quality will increase as the laboratory uses for NIRS increase and the relative cost declines.

## Acknowledgments

I thank Elvis Weulow for technical support on spectroscopy, Andrew Sila for assistance with data management, and gratefully acknowledge financial support from the Rockefeller Foundation.



**Figure 2.** Spectrally predicted values versus laboratory reference values for in vitro dry matter digestibility of organic materials incubated in soil. The results are based on predictions using hold-out-one, full cross-validation

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## 3.5

# Analysis of Organic Resource Quality for Parameterisation of Simulation Models

B. Vanlauwe\*

### *Abstract*

Updating of simulation models to incorporate new thinking on parameters that influence decomposition and hence nutrient release in the soil has been slow, with most models relying on N and lignin contents as determinants of decompositions. In addition, these analyses are expensive and time-consuming. This paper summarises the papers on analysis of the standard sample set of 32 different quality organic materials and how this can be linked to parameterisation and improvement of simulation models.

From this cross-method analysis, the minimum data set to assess organic resource quality consists of N, lignin and soluble polyphenol content, which is consistent with conclusions from earlier efforts. When considerations of cost and speed are included in the analysis, aerobic incubation is one of the cheapest, but also it's the slowest method. NIR, on the other hand, is the fastest method, but also most expensive until it is used for routine assessments.

Class III resources needed solely N content measured, whereas for Classes I and II there were no single quality indices. For Class III resources that show positive mineralisation with time, including polyphenol content in the decomposition routines of simulation models would increase the accuracy of prediction.

During the 1990s, the formulation of research hypotheses related to residue quality and N release led to a vast amount of projects aiming at validation of these hypotheses. Based on all this information, Palm et al. (2001) compiled the 'organic resource database' (ORD), which contains information on organic resource quality parameters including macronutrients, lignin and polyphenol contents of fresh leaves, litter, stems and/or roots from almost 300 species found in tropical agroecosystems. In addition, it contains many records of animal manures and livestock feed species. The database is available for downloading from the Internet at <http://www.ciat.cgiar.org/catalogo/producto.jsp?codigo=P0215>.

Following careful analysis of a large number of N-mineralisation studies using a wide range of organic resources, Palm et al. (2001) proposed a conceptual decision-support system (DSS) for organic N management. The DSS proposes four classes of organic resources, each having specific management options. Class I contains materials with high N (> 2.5%), low soluble polyphenol (< 4%), and low lignin (< 15%) content, and it is proposed that they be applied directly to a growing crop. The proposal for classes II and III is that they be mixed with either fertiliser or class I materials, as they have either a high N and high polyphenol content (class II) or a low N, low polyphenol and low lignin content (class III). Class IV materials have a low N and high lignin content and the recommendation is that they be applied as surface mulch.

Over the years, the range of organic resource quality characteristics found to affect the decomposition and mineralisation process has broadened.

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Originally, the C/N ratio was seen to relate well with N availability. Mellilo et al. (1982) showed that the N and lignin content of hardwood leaf litter residues significantly affected their decomposition. Palm et al. (1997) introduced the soluble polyphenol content in organic resource quality–N-mineralisation relationships, while Handayanto et al. (1994) showed that the content of soluble polyphenols that were actively binding proteins was better related to decomposition than the total soluble polyphenol content itself. One of the ‘traditional’ assessments for C and N mineralisation is an aerobic incubation under controlled conditions for a number of weeks. Recently, some efforts have been made to short-cut this procedure by adapting *in vitro* approaches used by animal nutritionists (Tian et al. 1996; Cobo et al. 2002).

Description of a standard method(s) to establish resource quality characteristics that can be used to parameterise simulation models is needed. Therefore, the objectives of this work were to use a large and well-chosen range of organic resources covering the complete organic resource quality spectrum (Class I to Class IV) to measure resource quality and decomposition, in order to: (i) explore relationships between aerobic incubation, *in vitro* digestibility and near-infrared reflectance spectrometry approaches for assessing short-term organic resource decomposition; (ii) to evaluate relationships between short-term decomposition dynamics and organic resource characteristics; and (iii) to reflect on the minimum data set needed to predict short-term N mineralisation dynamics.

## Materials and Methods

Organic materials were collected from different parts of Kenya (Gachengo et al. 2004b), and their resource quality was determined using a variety of standard and less commonly used characteristics. The C and N mineralisation of all organic resources was measured in an aerobic incubation experiment (Gachengo et al. 2004a) and through an *in vitro* dry matter digestibility (IVDMD) method (Barrios 2004). Near infrared reflectance spectroscopy (NIRS) (wavelengths from 1.0 to 2.5  $\mu\text{m}$ ) was used for rapid prediction of C and N mineralisation rates and IVDMD (Shepherd 2004).

## Data analysis

Simple and multiple regression (STEPWISE method) techniques (SAS 1985) were used to relate decomposition dynamics with various organic resource characteristics. For C mineralisation and IVDMD data, a single multiple-regression model was used, while for the N mineralisation data, separate models were run for the treatments with negative and positive percentages of applied N mineralised. This was done because the ‘traditionally’ used calculation procedure results in a discontinuity when the percentage N mineralised is zero.

## Results

Simple linear regression analysis shows that cumulative C release after 28 days is linearly related to especially the lignin content, the polyphenol/N ratio and the PBC/N ratio of the organic resources, where PBC is the protein-binding capacity (Table 1). Cumulative N release after 28 days is highly significantly related to the N content, soluble C content, and soluble C/N ratio of the organic materials. For the IVDMD, the resource quality parameters yielding the most significant relationships are the N content, the lignin content, and the PBC:N ratio.

NIRS first calibrated the organic resource attributes to first derivative reflectance using partial least squares regression. Cross-validated  $r^2$  values for actual versus predicted values were 0.84 for percentage of added C mineralised, 0.84 for percentage of added N mineralised, and 0.88 for IVDMD (Shepherd 2004).

Multiple regression analysis shows that soluble C, polyphenol, and lignin content of the organic resources explain 86% of the variation in cumulative C mineralisation (Table 2). When using IVDMD data, soluble C and lignin content and PBC explain 89% of its variation. For residues with positive N-mineralisation values, the N and polyphenol content of the organic resources explain 60% of the variation in N mineralisation at day 28. For all other residues, 90% of the variation was explained by their N content (Table 2).

Figure 1 showed three classes of organic resources: one class with N-mineralisation values significantly above 0 (Class I), one class with values not different from 0 (Class II), and a third class with values significantly below 0 (Class III). When considering only Class III data, a highly significant

linear relationship was observed between N mineralisation and the N content of the organic resources (Figure 2a). For Class I data, no significant relationships between N mineralisation and any specific organic resources quality parameter were observed. Excluding the *Gliricidia* samples, however, N mineralisation was linearly related with the lignin/N ratio of the organic resource (Figure 2b).

For organic resources with high polyphenol or lignin content, the IVDMD assay-based assessment of decomposition correlated well with the aerobic incubation assay (Figure 3). This was, however, not true for organic resources with low polyphenol and

lignin content. This may not be surprising, as the IVDMD assay is based on an anaerobic microbial decomposition phase and an enzyme digestion phase. Both phases are unlikely to be affected by lack of N for optimal decomposition of the organic resources with low biochemical resistance against decomposition. In the aerobic decomposition process, however, lack of mineral N may hamper the decomposition of organic resources with low N. For organic resources with either high polyphenol or lignin content, the organic resources themselves show some biochemical protection against decomposition, independent of the availability of N.

**Table 1.**  $R^2$  values of the simple linear regressions between selected decomposition parameters and commonly used organic resource characteristics.

Organic resource characteristic	Cumulative C release after 28 days (%)	Cumulative N release after 28 days (%)	In vitro dry matter digestibility (%)
N content (% DM <sup>a</sup> )	0.21 <sup>**b</sup>	0.82 <sup>***</sup>	0.45 <sup>***</sup>
C:N ratio	0.21 <sup>**</sup>	0.38 <sup>***</sup>	0.24 <sup>**</sup>
Polyphenol content (%DM)	0.21 <sup>**</sup>	0.01	0.06
Lignin content (% DM)	0.48 <sup>***</sup>	0.15 <sup>*</sup>	0.59 <sup>***</sup>
Soluble C content (% DM)	0.18 <sup>*</sup>	0.46 <sup>***</sup>	0.32 <sup>***</sup>
Protein-binding capacity (mg BSA g <sup>-1</sup> DM)	0.29 <sup>**</sup>	0.00	0.19 <sup>*</sup>
Soluble C:N ratio	0.12	0.56 <sup>***</sup>	0.15 <sup>*</sup>
Polyphenol:N ratio	0.45 <sup>***</sup>	0.25 <sup>**</sup>	0.35 <sup>***</sup>
Lignin:N ratio	0.24 <sup>**</sup>	0.25 <sup>**</sup>	0.25 <sup>**</sup>
(Lignin+Polyphenol):N ratio	0.26 <sup>**</sup>	0.26 <sup>**</sup>	0.26 <sup>**</sup>
Protein binding capacity:N ratio	0.50 <sup>***</sup>	0.19 <sup>*</sup>	0.46 <sup>***</sup>

<sup>a</sup> DM = dry matter.

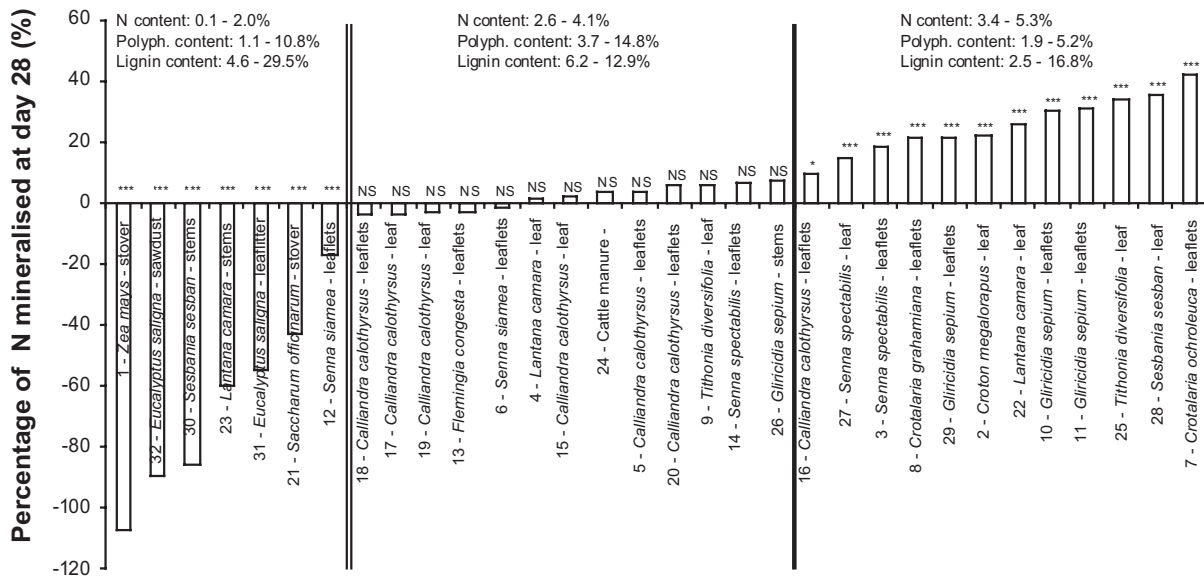
<sup>b</sup> \*, \*\*, and \*\*\* indicate significance at the 5, 1, and 0.1% level, respectively.

**Table 2.** Multiple regression analysis using selected decomposition parameters as dependent variables and C, N, P, polyphenol, lignin, and soluble C content and protein-binding capacity as independent variables.

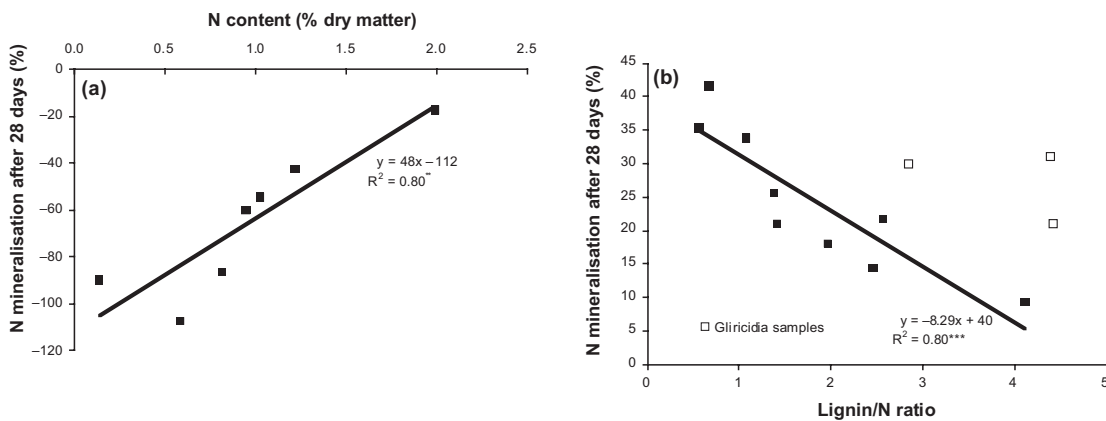
Dependent variable	Multiple regression equation <sup>b</sup>	R <sup>2</sup>
Cumulative C mineralisation at day 28 (%)	$37^{***} - 1.84 \times (\text{polyphenol content})^{***} - 0.92 \times (\text{lignin content})^{***} + 1.80 \times (\text{soluble C content})^{***}$	0.86
In vitro dry matter digestibility (% DM <sup>a</sup> )	$49^{***} - 1.51 \times (\text{lignin content})^{***} + 2.69 \times (\text{soluble C content})^{***} - 0.10 \times (\text{protein binding capacity})^{***}$	0.89
Cumulative N mineralisation at day 28 (%) for treatments with positive values	$-11 + 9.84 \times (\text{N content})^{***} - 1.59 \times (\text{polyphenol content})^*$	0.60
Cumulative N mineralisation at day 28 (%) for treatments with negative values	$-100^{***} + 34.1 \times (\text{N content})^{***}$	0.90

<sup>a</sup> DM = dry matter.

<sup>b</sup> \*, \*\*, and \*\*\* indicate significance of coefficients of regression at the 5, 1, and 0.1% level, respectively.



**Figure 1.** The percentage of added organic resource N mineralised after 28 days. ‘\*\*\*’, ‘\*’ and ‘NS’ signify significance at the 0.1%, the 5% level and not significant, respectively, as calculated with the LSMEANS option of the MIXED procedure (SAS 1992). The vertical bars delineate three groups of organic resources: a first group that has values significantly less than 0, a second group with values not different from 0, and a third group with values significantly larger than 0. The range of N, polyphenol, and lignin contents presented for the middle group excludes sample numbers 24 (cattle manure: 2.5% N, 1.1% polyphenols and 17.3% lignin) and 26 (*Gliricidia* stems: 1.6% N, 1.3% polyphenols and 20.4% lignin).

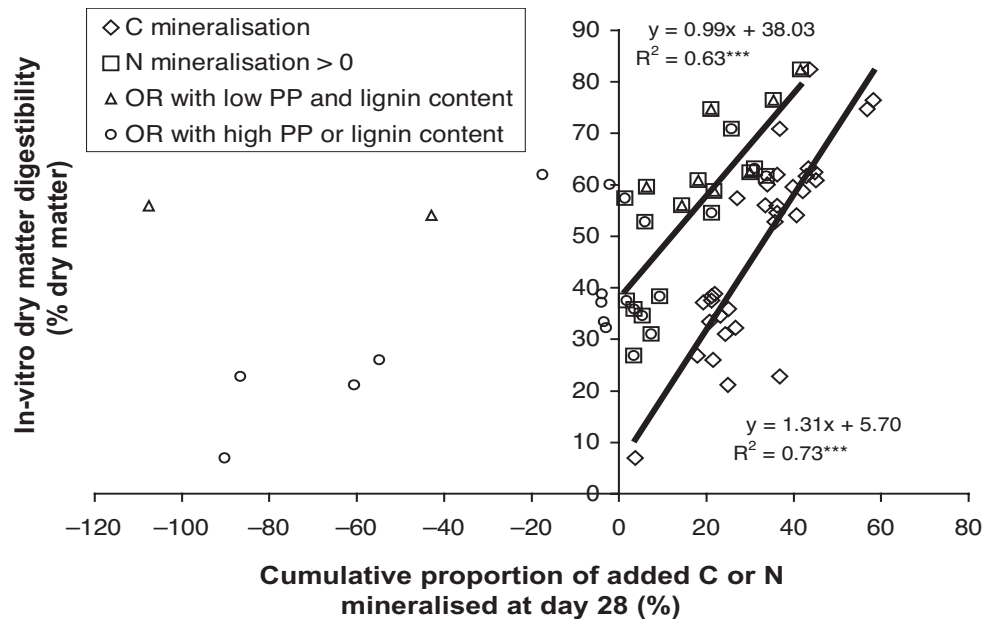


**Figure 2.** Relationship between the percentage of added N mineralised after 28 days and (a) the N content for organic materials with values significantly below 0, and (b) the lignin/N ratio for the organic materials with values significantly above 0. In Figure 2b, the *Gliricidia* leaves (samples 10, 11, and 29) were excluded from the regression.

## Discussion

From the different methods used in this cross-method analysis, the minimum data set to assess organic resource quality appears to consist of N, lignin, and soluble polyphenol content, a finding that

is consistent with conclusions from earlier efforts. The various methods used to assess short-term mineralisation produced significant correlations to N and C mineralised after 28 days, with at least one of the three aforementioned characteristics.



**Figure 3.** Relationships between C and N mineralisation as assessed using the aerobic incubation technique and the in vitro dry matter digestibility assay.

Cost and speed also need to be compared where more than one method is available. Aerobic incubations are one of the cheapest but slowest methods, compared with NIR, which is the fastest. Although NIR is expensive to purchase, for routine analysis of many samples it would be cost effective. Construction of spectral calibration libraries in central laboratory facilities would greatly increase the efficiency of NIRS use for routine organic resource characterisation in laboratories and dramatically reduce the costs of this analysis.

An issue that this analysis has raised is the inclusion of other parameters that should be included in simulation models to enhance their predictions of decomposition. This applies to only certain classes of resource quality. Only N content needs to be measured for Class III resources, whereas for Classes I and II there were no single quality indices.

For Class III resources that show positive mineralisation with time, including polyphenol content in the decomposition routines would increase the accuracy of prediction. Whitmore and Handayanto (1997) developed algorithms to include the polyphenol effect in decomposition and hypothesised the direct transfer of C and N to the stable soil organic matter, without any decomposition and loss of C.

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**4**

**Simulating N and P Release  
from Organic Sources**

## 4.1

# The APSIM Manure Module: Improvements in Predictability and Application to Laboratory Studies

M.E. Probert,\* R.J. Delve,† S.K. Kimani§ and J.P. Dimes¶

### *Abstract*

Existing models are able to capture the pattern of N release from plant materials based on their C/N ratios. However, these models are unable to simulate the more complex pattern of N release reported for some animal manures, especially for manures that exhibit initial immobilisation of N even when the C/N ratio of the material suggests it should mineralise N.

This paper reports on progress towards developing a capability within the APSIM SoilN module to simulate nitrogen release from these manures. The SoilN module was modified so that the three pools that constitute added organic matter can be specified in terms of both the fraction of carbon in each pool and also their C/N ratios. The previous assumption that all pools have the same C/N ratio fails to adequately represent the observed behaviour for release of N from some organic inputs. By associating the model parameters with measured properties (the pool that decomposes most rapidly equates with water-soluble C and N; the pool that decomposes slowest equates with lignin-C) the model performed better than the unmodified model in simulating the N mineralisation from a range of livestock feeds and manure samples.

In the soil fertility management of many tropical farming systems, organic sources play a dominant role because of their short-term effects on nutrient supply to crops (Palm et al. 2001). Considerable literature exists reporting decomposition and nutrient-release patterns for a variety of organic materials and this information has been drawn together and used for improvement of soil fertility through better man-

agement of organic inputs (e.g. Giller and Cadisch 1997; Palm et al. 2001).

If simulation models are to be useful in helping to design farming systems that use various nutrient sources more effectively, it is a requirement that the models be able to reliably describe the release of nutrients from these different organic sources. Palm et al. (1997) pointed out that there is little predictive ability for making recommendations on combined use of organic and inorganic nutrient sources. One reason for this is the inability of models to adequately capture the short-term dynamics of the release of nutrients from organic materials.

The manner in which the dynamics of soil carbon and nitrogen are modelled in APSIM's SoilN module (Probert et al. 1998; Probert and Dimes 2004) is similar to what is found in many other models — see reviews by Ma and Shaffer (2001) and McGechen and Wu (2001). Briefly, crop residues and roots

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added to the soil are designated fresh organic matter (FOM) and are considered to comprise three pools (FPOOLS), sometimes referred to as the carbohydrate-like, cellulose-like and lignin-like fractions of the residue. Each FPOOL has its own rate of decomposition, which is modified by factors to allow for effects of soil temperature and soil moisture. For inputs of crop residues and roots, it has usually been assumed that the added C in the three FPOOLS is always in the proportions 0.2:0.7:0.1. In this manner, the decomposition of added residues ceases to be a simple exponential decay process as would arise if all residues were considered to comprise a single pool.

Although the three fractions have different rates of decomposition, they do not have different compositions in terms of C and N content. Thus, while an input might be specified in terms of the proportion in each of the FPOOLS, thereby affecting its rate of decomposition, the whole of the input will decompose without change to its C:N ratio. The model further assumes that the soil organic matter pools (BIOM and HUM) have C:N ratios that are unchanging through time. The formation of BIOM and HUM thus creates a gross immobilisation demand that has to be met from the N released from the decomposition of the FOM and/or by drawing on the mineral N (ammonium- and nitrate-N) in the system.

However, changing the pool sizes alone cannot alter whether a source exhibits initial net N mineralisation or immobilisation (since this is determined by the C:N ratio of the substrate). In studies of the mineralisation of N from various manures, Kimani and co-workers (unpublished) and Delve et al. (2001) encountered situations where there was an initial immobilisation of N, despite the fact that the overall C:N ratio of the material was such that it would be expected to result in net mineralisation. This behaviour cannot be modelled without assuming that the three FPOOLS also differ in their C:N ratios.

## Modifications to the Model

Modifications were made to the APSIM SoilN module so that any input of organic material could be specified in terms of both its fractionation into the three FPOOLS, and the C:N ratios of each FPOOL. In the modified model, each FPOOL is assumed to decompose without changing its C:N ratio. The rates of decomposition of the three FPOOLS were not changed from the released version of APSIM (viz.

0.2, 0.05 and 0.0095 day<sup>-1</sup>, respectively, under non-limiting temperature and moisture conditions).

Using the modified model, we explored three different approaches to simulate how an organic input decomposes:

1. using the released version of ASPIM SoilN (v 2.0)
2. changing the FPOOLS to have different fractional compositions and different C:N ratios, in the first instance with FPOOL1 differing from a common value for FPOOLS 2 and 3
3. with the fractional composition and C:N ratios differing between all three FPOOLS.

## Materials and Methods

### Simulation of mineralisation from hypothetical sources

The model was configured to simulate a simple incubation study, involving a single layer of soil under conditions of constant temperature (25°C) and at a soil water content that ensured there was no moisture restriction on decomposition. Initial nitrate-N concentration in the soil was 20 mg N kg<sup>-1</sup>. The effect of different organic inputs was investigated by incorporating materials that contained a constant amount of N (100 mg N kg<sup>-1</sup> soil) but with varying C:N ratio. A control system was also simulated without any added organic input.

### Simulation of laboratory incubation studies

The experimental data reported by Delve et al. (2001) were used to investigate whether the analytical data for a range of livestock feeds and manure samples can be used to specify the model to simulate the N mineralisation measured in a laboratory incubation experiment.

Using a leaching-tube incubation procedure (Stanford and Smith 1972), they measured net N mineralisation for feeds and manure samples resulting from cattle fed a basal diet of barley straw alone, or supplemented with 15 or 30% of the dry matter as *Calliandra calothyrsus*, *Macrotyloma axillare* or poultry manure. The soil used was a humic nitisol with organic C content of 31 g kg<sup>-1</sup>, C/N ratio of 10 and pH (in water) of 5.9. The incubations were conducted at 27°C.

Kimani and co-workers (unpublished data) carried out a mineralisation study, using the same method-

ology as Delve et al. (2001), for a selection of manure samples collected on-station and from farms in central Kenya. Analytical data for these materials included total and water soluble C and N, but not fibre analyses.

## Results

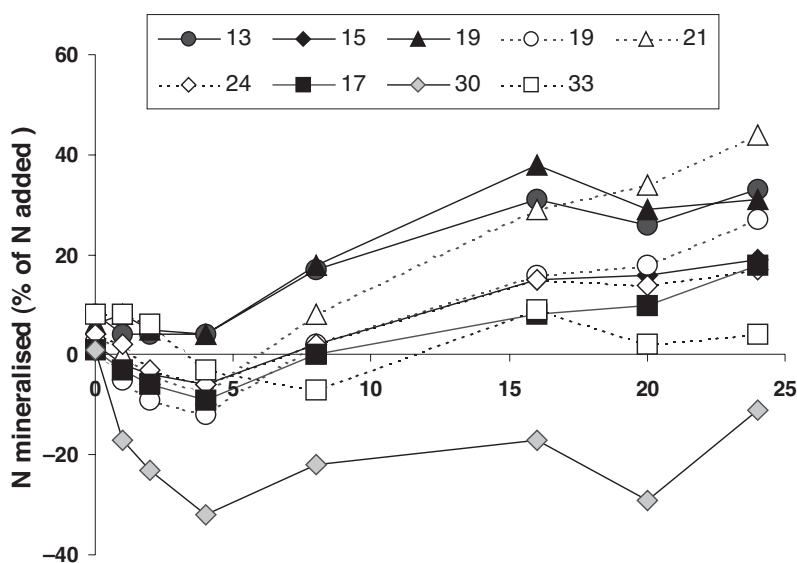
Experimental data (S.K. Kimani et al., unpublished data) that indicated the need to reconsider how N mineralisation from organic inputs is modelled are illustrated in Figure 1. For a wide range of manures, their results consistently show an initial immobilisation or delay in mineralisation lasting several weeks, even for materials that have overall C:N ratios of less than 20. This pattern of response is noticeably different to studies of N mineralisation from plant materials (e.g. Constantinides and Fownes 1994), where plant materials with low C:N typically exhibit positive net mineralisation from the start of the incubation period.

The manure samples studied by Delve et al. (2001), with C:N ratios in the range 20–27, had even more complex patterns of mineralisation; some materials showed initial net mineralisation before an extended period of immobilisation lasting for at least 16 weeks of incubation (see below).

## Modelling N mineralisation from hypothetical sources

Simulation of mineralisation for sources with different C:N ratios using the released version of APSIM SoilN is shown in Figure 2. The results are in general agreement with experimental studies for plant materials where net N mineralisation is closely related to the N content and hence C:N ratio (e.g. Constantinides and Fownes 1994; Tian et al. 1992). For sources with C:N < 20, net mineralisation occurs from the outset. However, with C:N > 20, there is initially immobilisation of mineral-N and it is only as newly formed soil organic matter is re-mineralised that mineral-N in the system begins to increase.

Effects of changing the composition of the input by modifying the C:N ratios of the different FPOOLS are shown in Figures 3 and 4. In Figure 3, all materials have the same overall C:N ratio, but the C:N ratio of FPOOL1 is now greater than for the material in pools 2 and 3. The result is that the material in FPOOL1, which decomposes most rapidly, creates an immobilisation demand, and the higher the C:N ratio of FPOOL1 the greater the initial immobilisation. If, however, the C:N of FPOOL1 is higher, there must be compensating falls in the C:N ratios of the other pools. As incubation time increases, the differences between different materials decrease, so that there is little longer-term

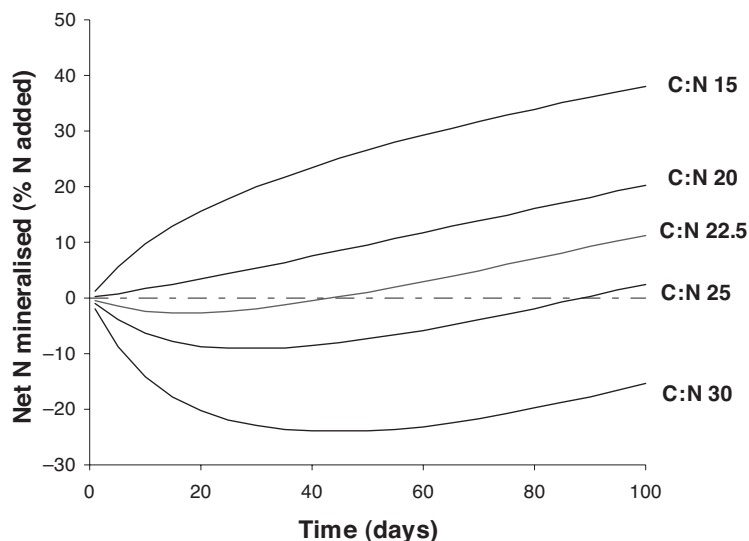


**Figure 1.** Net nitrogen mineralised from different manures in an incubation study lasting 24 weeks. C:N ratios of the manures are shown in the legend. Source: S.K. Kimani et al., unpublished data.

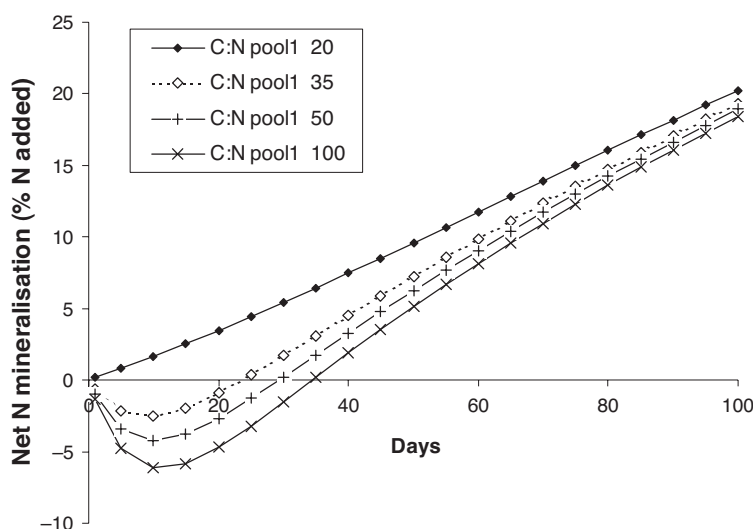
effect of the C:N ratios of the FPOOLS on net mineralisation, which is determined largely by the overall C:N ratio.

In Figure 4 the effect of varying the C:N ratios of FPOOLS 2 and 3 is shown. Again all materials have the same overall C:N ratio, with the C:N of FPOOL1 fixed at 10. With the low C:N in the rapidly decom-

posing pool, there can be an initial net mineralisation, especially when the C:N of FPOOL2 is also relatively low. However, as FPOOL1 is depleted, there can be a switch from net mineralisation to net immobilisation. Increasing the C:N of FPOOL2 results in increasing immobilisation and immobilisation persists for longer.



**Figure 2.** Simulation of nitrogen mineralisation from organic inputs with different C:N ratios using the released version of APSIM SoilN. The model assumes that all inputs have the same fractional composition in terms of the three FPOOLS (0.2:0.7:0.1), and that, for a given source, all FPOOLS have the same C:N ratio.



**Figure 3.** Effect of changing the composition of organic inputs by modifying the C:N ratios of the FPOOLS. In this example, the inputs have fractional composition of 0.2:0.7:0.1, overall C:N ratio of 20, and C:N ratio of FPOOL1 as shown in the legend (with C:N ratios of FPOOLS 2 and 3 being equal).

## Modelling the mineralisation study of Delve et al. (2001)

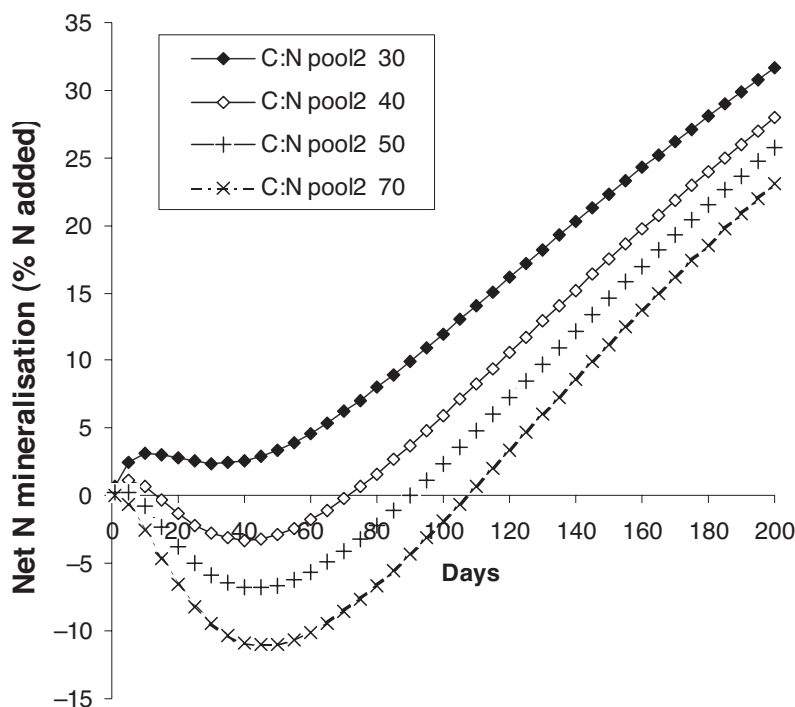
The modelled net mineralisation from hypothetical sources display patterns of N release that are similar to experimental data. Notably, the several weeks delay before mineralisation became positive, as exhibited by several of the manures studied by Kimani and co-workers (Figure 1), is consistent with variation in the C:N ratio of FPOOL1 (Figure 3). On the other hand, the longer delay reported by Delve et al. (2001) is more like the pattern shown in Figure 4 associated with variation in FPOOL2 and 3.

We have attempted to use the analytical data reported by Delve et al. (2001) to specify the 'quality' aspects of organic inputs represented in the model. We assume the soluble components of C and N equate to FPOOL1; thus the analytical results are sufficient information to determine the proportion of total C in this pool and its C:N ratio. Also, we assume that acid detergent lignin (ADL; Van Soest et al. 1987), which is a proximate measure of lignin, equates to FPOOL3, permitting the fraction of C in

this pool to be estimated; the fraction of C in FPOOL2 is found by difference. Since the overall C:N ratio (on a total dry matter basis) is also known, the only missing information is the distribution of non-water soluble N between pools 2 and 3. A series of simulations was carried out for each source with different combinations of C:N in the two pools (constrained by the C:N of the total DM). This enabled selection of the C:N giving an acceptable fit to the observed data (see Figure 5).

The net N mineralisation for the feeds and a selection of the manure samples studied by Delve et al. (2001) is shown in Figure 6. The outputs from two simulations are compared, these being the outputs from the modified and unmodified versions of the model. The input data used for the modified model are set out in Table 1.

For most of the materials, the goodness of fit is substantially better for the modified than for the unmodified model. Using the analytical data to specify the fraction of C in each of the FPOOLS and the C:N ratio of FPOOL1, it was possible to choose

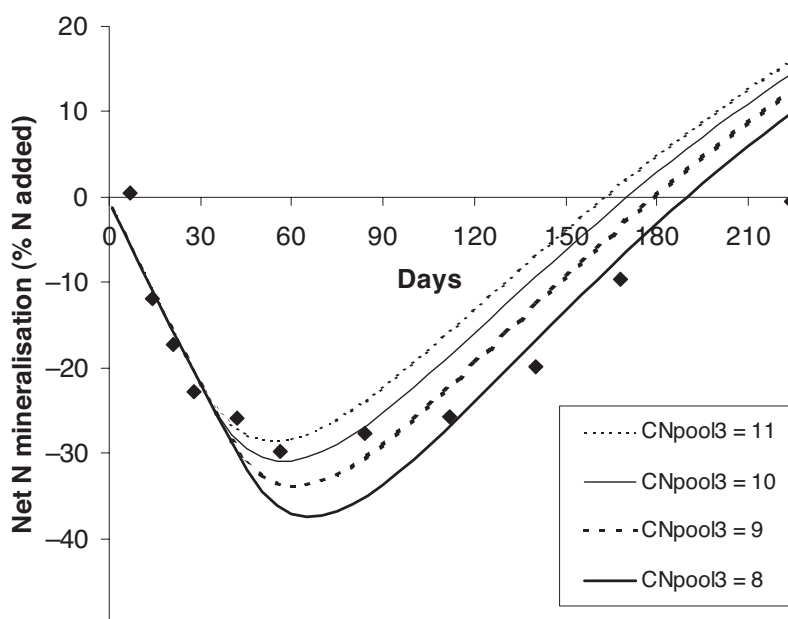


**Figure 4.** Effect of changing the quality of organic inputs by varying the C:N ratios of the FPOOLS. In this example, the inputs have fractional composition of 0.1:0.7:0.2, overall C:N ratio of 20 and C:N ratio of FPOOL1 of 10, with C:N of FPOOL2 as shown in the legend.

values for the C:N ratios of FPOOL2 and FPOOL3 to obtain satisfactory fits with the measured data.

In general, the fit is better for the manure samples than for the feeds, with the poorest fit for the poultry waste. The pattern of net mineralisation measured for the poultry waste, which had an overall C:N ratio of

17, is different from the other materials in that the change from immobilisation to mineralisation that occurred after about 50 days was not maintained, and further net immobilisation occurred later in the incubation. Delve et al. (2001) could not explain the behaviour of this material.



**Figure 5.** Illustration of how appropriate values for the C:N ratios of FPOOL2 and 3 were selected. In this example, the observed data for manure derived from the straw diet are compared with model output with different C:N ratios. Choice of a “best” value is a compromise between the maximum immobilisation and the longer-term mineralisation.

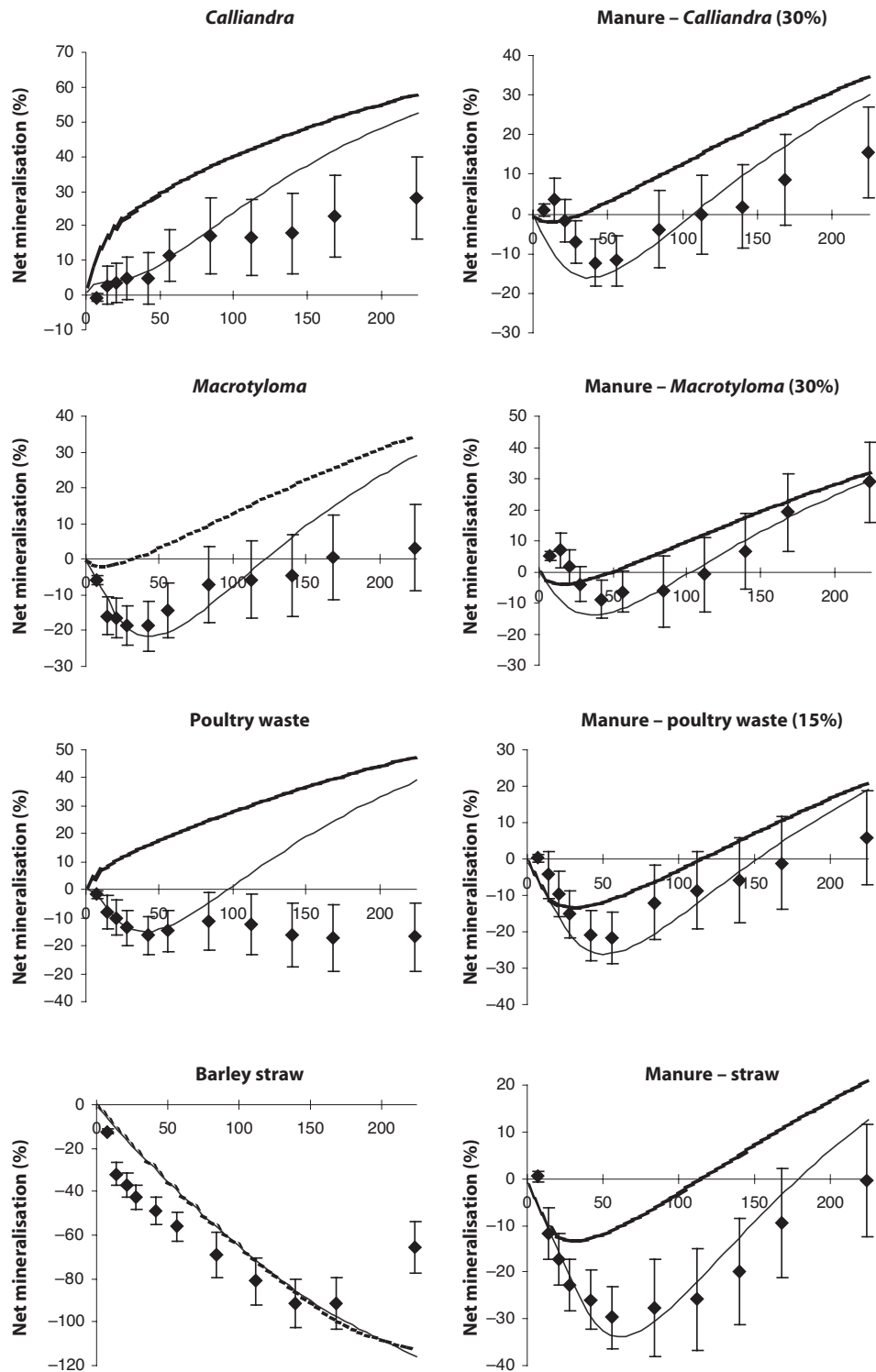
**Table 1.** Composition of organic materials (feeds and faecal samples) used for simulating the mineralisation study of Delve et al. (2001). Overall C:N ratio was measured; FPOOL1 based on measured C and N as water-soluble components; proportion of C in FPOOL3 based on measured ADL. C:N of FPOOL2 and 3 selected, subject to constraint that must be consistent with overall C:N, to give reasonable fit between simulated N mineralisation and measured data.

Sample	Overall C:N	Proportion of carbon in FPOOLS (%)			C:N of FPOOLS		
		Pool 1	Pool 2	Pool 3	Pool 1	Pool 2	Pool 3
<i>Calliandra</i>	13	12	74	14	9	44	3
<i>Macrotyloma</i>	22	16	74	10	17	67	4
Poultry waste	17	5	88.5	6.5	4.5	202	1.5
Barley straw <sup>a</sup>	86	6	84.5	9.5	24	103	103
<i>Calliandra</i> – manure (30%) <sup>b</sup>	22	4	74	22	16	40	9
<i>Macrotyloma</i> – manure (30%)	23	5.5	73.5	21	14	36	11
Poultry waste – manure (15%)	27	4.5	82	13.5	12	41	10
Barley straw – manure	27	9	71.5	19.5	20	66	9

<sup>a</sup> Simulated N mineralisation was not sensitive to partitioning of N between pools 2 and 3.

<sup>b</sup> Value in parentheses denotes proportion of supplement in diet.





**Figure 6.** Net nitrogen mineralisation from feeds and faecal materials (data of Delve et al. 2001). Experimental data shown as symbols with bars representing  $\pm$  standard errors. The heavy broken line is for the model where all organic material is assumed to decompose with the same C:N ratio; the continuous line is for the model with different C:N ratio in each FPOOL. Parameters used to specify the different sources (proportion of C and C:N in the three FPOOLS) are set out in Table 1.

The simulation for the barley straw (C:N 86) predicts that immobilisation continues for at least 200 days. Because all mineral N initially present in the soil becomes immobilised in this treatment, the simulated immobilisation is determined by the rate of mineralisation of the control treatment and is not sensitive to how N is partitioned between FPOOLs 2 and 3 in the decomposing substrate.

## Discussion

Models are capable of capturing the gross effect of C:N ratio on mineralisation/immobilisation from plant residues (as illustrated in Figure 2). However, they are not able to represent the more complex pattern of mineralisation/immobilisation that has been reported from laboratory incubation studies of N release from manures with low C:N (e.g. Figure 1). To capture these patterns of N release, it is necessary to conceptualise the organic input as comprising discrete fractions that differ not only in their rates of decomposition but also in their chemical (i.e. C and N) composition.

The mineralisation data of Delve et al. (2001) (shown in Figure 6) and chemical composition of their materials (Table 1) indicate that the measured water-soluble component had a smaller C:N than the bulk materials. To simulate the observed mineralisation data it was necessary to assume that the materials had higher C:N in FPOOL2 than in FPOOL3.

What is rather simplistically called ‘manure’ is usually a complex mixture of faeces, urine, bedding material, feed refusals and soil! To add to the complexity, it may have undergone further composting and weathering with loss of some components. Thus, it is perhaps naïve to expect that the methods used to characterise the quality factors that determine N mineralisation from plant residues might also be applicable to manures, or that models which simulate N mineralisation from plant residues might also simulate N release from manures.

By simulation of hypothetical materials, we have shown that such a model can be parameterised to simulate the general pattern of N mineralisation that is observed for various organic sources. Nonetheless, it remains a challenge to know how appropriate parameters should be selected for a given source and/or how to derive the parameter values from other information that may be available as analytical data for supposed ‘quality factors’. Here we have used data

for C and N in the water-soluble components to specify FPOOL1, and the measured ADL to specify the C in FPOOL3. To obtain the goodness of fit shown in Figure 6 for the manures required C:N in FPOOL2 in the range 36–66, with corresponding C:N in FPOOL3 of 9–11 (Table 1).

For the feed materials (*Calliandra*, *Macrotyloma*, poultry waste), the predictions were not as good as those for the manure samples. To obtain a reasonable fit in the early stages of the mineralisation, a high C:N in FPOOL2 is required, but this results in very low values of C:N for FPOOL3 and over-prediction as the incubation period progresses beyond 100 days.

## Acknowledgments

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## 4.2

# Evaluation of APSIM to Simulate Maize Response to Manure Inputs in Wet and Dry Regions of Zimbabwe

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### *Abstract*

This study evaluated the ability of APSIM to predict the response of maize to manure inputs as observed in on-farm experiments in Murewa (higher rainfall) and Tsholotsho (lower rainfall) communal areas of Zimbabwe. Three experiments were used in the study. The first experiment studied the initial and residual effects of pit and heap-stored manure on maize grain yields. The 3-year experiment was conducted on a granitic sand in Murewa, with a single application of manure in the first cropping season. APSIM failed to simulate the contrasting initial and residual yield trends observed for pitted and heaped manure. However, chemical characterisation of heaped and pitted manure was contrary to observed behaviour, and the residual effects of the manures may have been masked by the application of inorganic N. The second experiment, also in Murewa, examined combinations of manure with high N concentration and N fertiliser. The model successfully predicted maize grain yield response to the combinations and manure alone, but greatly over-predicted the yield for fertiliser alone. The third experiment examined maize biomass yield response to heap- and pit-stored manure in the drier Tsholotsho region, across several farms on sandy and clay soils. The model successfully predicted mean biomass yield trends for the sandy and clay soils, and higher yields on the clay than the sand. Simulation of the effects of increasing amounts of pit and heap manure (from 0 to 15 t ha<sup>-1</sup>) was largely in agreement with the observed responses. Results of this study demonstrate the need for improved experimentation and measurements of manure quality in order to better understand crop response to applications of pit and heaped manure. This will provide, in turn, a sounder basis for further testing of the model's ability to predict the effectiveness of poor-quality manures.

Manure is used as the main source of nutrients for crop production in most communal areas of Zimbabwe (Mugwira and Mukurumbira 1984; Mugwira and Murwira 1997). This is more so in high rainfall

areas, where crop response is more certain, than in drier areas, where manure resources are often under-utilised (Ahmed et al. 1997). However, manure from communal grazing areas is nearly always of low quality (N < 1%) (Tanner and Mugwira 1984) and its low N content in particular is attributed to poor feed quality and losses during handling and storage (Probert et al. 1995).

Nzuma and Murwira (2000a) conducted a study to reduce N losses from manure through improved handling and storage practices. They compared the use of manure from the conventional heap-storage systems to pit-stored manure. The pit storage

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systems reduced N losses, as was indicated by high total N and ammonium N concentrations in the pitted manure compared with heap-stored manure (Nzuma and Murwira 2000b). When applied to maize in a high-rainfall region, the pit-stored manure gave higher grain yields than heap-stored manure (Murwira 2003). The efficacy of high-quality manures has been further evaluated in field experiments that combined manure and inorganic N application and varied soil type and rates of application in semi-arid regions of Zimbabwe (Murwira et al. 2001).

Biophysical simulation models such as APSIM (McCown et al. 1996; Keating et al. 2003) and CERES–Maize (Jones and Kiniry 1986) have been used to predict crop response to inputs of inorganic N under African conditions. For example, Shamudzarira and Robertson (2002) used APSIM to simulate responses of maize to N fertiliser, and compared the output with observed data from a long-term experiment conducted at Makoholi Research Station in central Zimbabwe. Their results showed that the model predicted grain yield responses to a range of N rates (0, 20, 40, 80 kg N ha<sup>-1</sup>) within one standard error of the observed in nearly all seasons. Importantly, the model was able to simulate the very low biomass and zero grain yield observed in the 1991–92 drought season (simulated biomass = 500 kg ha<sup>-1</sup>, observed = 580 kg ha<sup>-1</sup>). Such low yield levels are characteristic to most African farming systems, particularly in the semi-arid regions. With the addition of the APSIM–Manure module (Probert and Dimes 2004), APSIM acquired the capability to predict nutrient availability following the addition of organic as well as inorganic sources of N in smallholder farming systems. While this capability has been shown to assist in exploring various management options under African conditions (Carberry et al. 2002), there has been no evaluation of APSIM to simulate observed crop response to manure applications in the field.

In the study reported here, a series of manure experiments conducted in wet and dry regions of Zimbabwe was used to evaluate APSIM for simulating maize response to applications of manure with varying N content and availability. The intention was to better understand where APSIM–Manure could be usefully applied and to identify possible areas for improvement in the model.

## Materials and Methods

Three experiments were used to evaluate APSIM's performance to predict maize response following applications of different quality manures. The first experiment studied the initial and residual effects of pit- and heap-stored manure on maize yield in a high rainfall region. It was conducted on a coarse grained, shallow granitic sand soil in Murewa, Zimbabwe.

Manure was taken from open kraals in July 1997 and stored as follows:

- Heap – straw: manure stored in uncovered heap without straw
- Heap + straw: manure plus added maize stover stored in uncovered heap
- Pit – straw: manure stored in a covered pit without straw
- Pit + straw: manure plus added maize stover stored in a covered pit

Manure from the different storage systems was removed in October 1997 and incorporated into field plots on an equal total N basis (60 kg N ha<sup>-1</sup>) before sowing the first maize crop. Residual effects of the manure applications were evaluated in cropping seasons 1998–99 and 1999–2000. Basal P fertiliser was applied to all the treatments, including a control plot that had no manure. N fertiliser was applied to all plots that received manure, but not to the control, in two applications (20 + 20 kg N ha<sup>-1</sup> as ammonium nitrate, in all three cropping seasons. Medium duration maize (SC501) was grown as the test crop. There were three replications for treatment plots.

For the second experiment, manure from a commercial feedlot (%N = 2.7, %C = 19.2) was used to determine the effects of organic–mineral fertiliser combinations on maize yields in Murewa in 1997–98. Manure and ammonium nitrate (AN) were applied at a total N rate of 100 kg N ha<sup>-1</sup>. All the manure was applied at planting, while fertiliser N was applied as split dressings at 4 and 8 weeks after crop emergence. The following combinations were tested:

1. Control (no N applied)
2. 100% AN : 0% manure
3. 75% AN : 25% manure
4. 50% AN : 50% manure
5. 25% AN : 75% manure
6. 0% AN : 100% manure

The third set of experiments was carried out in a semi-arid environment near Tsholotsho, Zimbabwe,

during the 2000–2001 cropping season. Farmer-managed manure (pit-stored and heaped-manure) was applied on clay (7 farms) and sandy (6 farms) soils at the rate of 3 t ha<sup>-1</sup>, with three replicates at each farm. The effects of rate of manure application (0, 3, 6, 9, 12 and 15 t ha<sup>-1</sup>) were also studied on one farm (sandy soil) with three replications. A short season maize variety (SC401) was used in Tsholotsho.

## Simulations

To simulate experiments 1 and 2, daily temperature and radiation data from a nearby weather station (in Natural Region II which receives an annual rainfall of 800–1000mm; Vincent and Thomas 1961) were used in conjunction with daily rainfall measured at the site. Soil parameters for describing N and organic C content of soils were measured, while the soil water balance was estimated based on knowledge of the soil (N. Nhamo, unpublished data). Plant available water capacity (PAWC) to rooting depth (90 cm) was 73 mm, and percentage C in the surface layer was 0.7. For experiment 1, the amount of manure added to the soil varied between treatments according to the N contents (Table 1) to apply 60 kg N ha<sup>-1</sup>. Initial soil water for simulations was assumed to be close to the lower limit (LL) of plant available water capacity and soil mineral N was set to approximately 10 kg N ha<sup>-1</sup>. Experiment 1 was simulated without any re-sets for soil water and N in the residual seasons.

For Tsholotsho experiments, temperature and radiation data from a station representative of Natural Region IV was used in conjunction with rainfall data measured at the site. The soil descriptions used for simulating these experiments were:

clay soil	1.05 m deep, PAWC of 100 mm and 1.4% C in the surface layer:
sandy soil	1.0 m deep, PAWC of 57 mm and 0.4% C.

Initial mineral N for each soil (i.e. a sand and a clay) was chosen so that the simulated biomass yields for the control treatment was similar to the average of measured farmer yields on each soil type. The chemical data available for the manures from Tsholotsho farms (6 heap and 3 pit) show little difference in C and N content of heaped and pit-stored manure (data not shown); this contrasts with manures at Murewa (Table 1). Hence, the manure treatments in Tsholotsho were simulated using the same % C (10%) and only a small difference in N content (heaped 0.6% and pit-stored 0.75%).

For this study, the partitioning of manure carbon into the three pools comprising fresh organic matter (Probert and Dimes 2004) was in the ratio 0.3:0.3:0.4 for the pit-stored manure and 0.01:0.59:0.4 for heaped manure. These values imply that there is material in the pit-stored manure that decomposes and releases N more rapidly than the heaped manure.

## Results

### Manure storage experiment at Murewa

#### *Manure characterisation*

Table 1 shows the chemical characterisation for manures used in Experiment 1 at Murewa. Pit-stored manure had higher carbon, total N and cation concentrations and lower ash content than heaped manure. Despite its higher N concentration, the pit-stored manure had a higher C:N ratio, though all manures had C:N ratios considered conducive to net mineralisation of N (i.e. < 20). Addition of straw during storage had smaller effects on composition than the effect of method of storage.

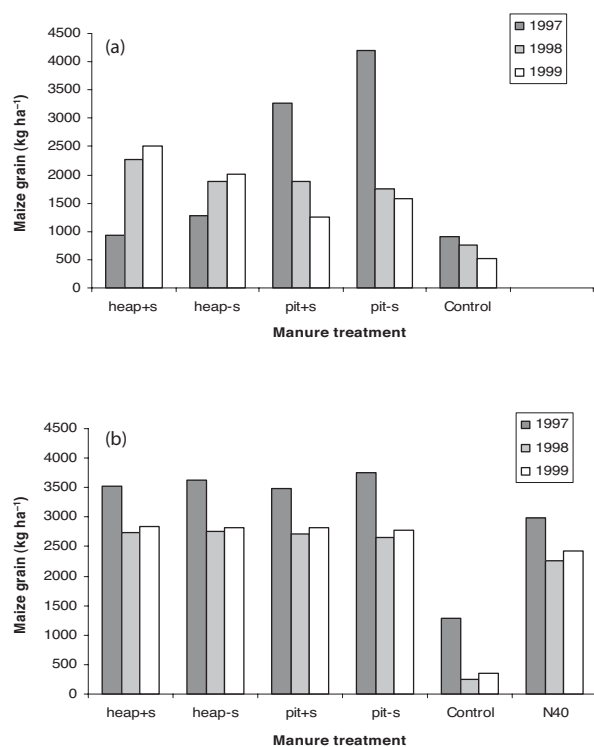
#### *Initial and residual maize responses*

Rainfall in each of the three cropping seasons exceeded 1000 mm. In the first cropping season, pit-stored manure gave much higher grain yields than the control or heaped manure treatments (Figure 1a). In subsequent seasons, maize yields for this treat-

**Table 1.** Characterisation of manures from manure storage experiments in Murewa.

Treatment	C %	N %	P %	K %	Ca %	Mg %	Ash %	C:N ratio
Heap – straw	9.0	0.88	0.20	0.25	0.21	0.53	80.9	10.2
Heap + straw	11.9	0.96	0.13	0.26	0.11	0.21	76.5	12.3
Pit – straw	28.2	1.84	0.25	0.84	0.25	0.70	40.7	15.3
Pit + straw	30.0	1.54	0.28	0.76	0.26	0.57	55.6	19.5

ment declined. In contrast, heaped manure had low yields in the first season, and an increasing yield trend for the second and third seasons, to the extent that yields exceeded those for the pit treatment in the residual seasons. Cumulative yield for the three seasons was higher for pitted manure ( $7 \text{ t ha}^{-1}$ ) than for heaped ( $5.4 \text{ t ha}^{-1}$ ), and both were greater than for the control treatment, which produced  $2.2 \text{ t ha}^{-1}$  for the 3 years.



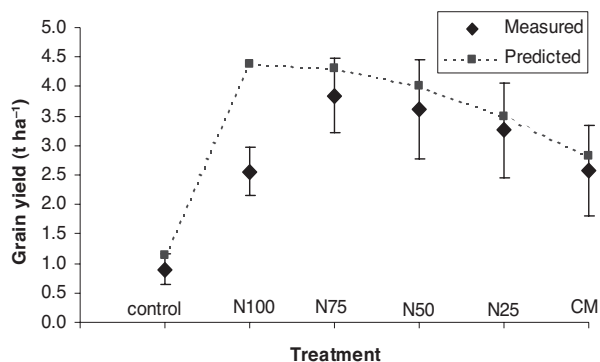
**Figure 1.** Initial and residual effects of heap- and pit-stored manure, with (+s) and without (–s) straw additions on maize grain yields at Musegedi farm in Murewa, Zimbabwe. a) Observed field responses; b) simulated responses.

The simulated yields for the control treatment that received no inputs of N were small in all three years and agreed reasonably well with the observed data (Figure 1b). However, the simulated responses to heaped and pitted manures were almost identical. Clearly, the model failed to simulate the contrasting release patterns observed for the pit-stored and heaped manure in the field. To explore the discrepancy, we tested the prediction for a treatment that received  $40 \text{ kg N ha}^{-1}$  as fertiliser but no manure (included in Figure 1b); it was predicted to yield higher than any of the observed manure treatments except pit-stored manure

in the first season. The model predicted that the yields with both manure and fertiliser would be slightly higher than for fertiliser alone.

### Manure–fertiliser N combinations at Murewa

Grain yield response to various combinations of manure and fertiliser applying a total  $100 \text{ kg N ha}^{-1}$  to maize at Murewa are shown in Figure 2. Combinations gave higher maize yields than sole fertiliser or sole manure. The 100% manure and 100% fertiliser treatments gave almost identical maize yields, and these were more than double the yield of the control treatment that received no inputs of N.



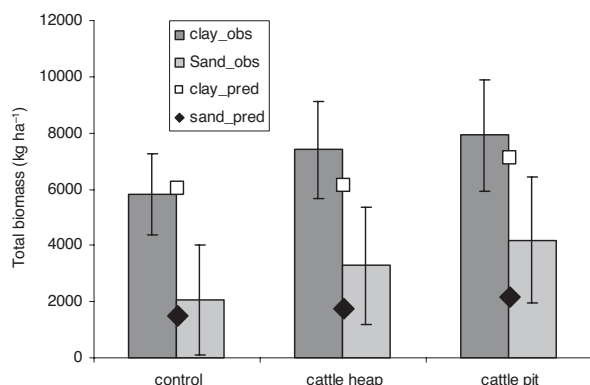
**Figure 2.** Measured and predicted effects of  $100 \text{ kg N ha}^{-1}$  applied as combinations of manure and fertiliser N on maize grain yield at Murewa in the 1997–1998 cropping season. (Control = no N inputs, N100 =  $100 \text{ kg N ha}^{-1}$  applied as fertiliser, CM =  $100 \text{ kg N ha}^{-1}$  applied as manure). Error bars denote standard deviations of measured means.

The model predictions agreed closely with the observed yields for the control and in response to the manure and fertiliser inputs, except for the 100% fertiliser treatment, for which there was a large over-prediction. The trend for yields to increase as the proportion of the N applied as fertiliser increased shows that the high-quality manure used in this experiment was a relatively less effective source of N than the fertiliser.

The reason for the poor prediction of the 100% fertiliser treatment is not known. One explanation could be that the manure inputs supplied some other limiting resource such as another nutrient (e.g. Ca, Mg, S or Zn) or had a liming effect. Such benefits of manure are not considered in the model.

## Manure experiments at Tsholotsho

As a consequence of low rainfall, larger differences in maize growth were observed between soil type than between pit-stored and heap-stored manure in the Tsholotsho experiments. On both the clay and sandy soils, maize biomass was higher with manure inputs relative to the control, with pit-stored manure having the highest biomass yields overall, but these differences were although not statistically significant (Figure 3).



**Figure 3.** Observed and predicted maize response to heaped and pit-stored manure on clay (mean of 7 farms) and sandy (mean of 6 farms) soils near Tsholotsho in cropping season 2000–2001. Error bars denote standard deviations of measured means.

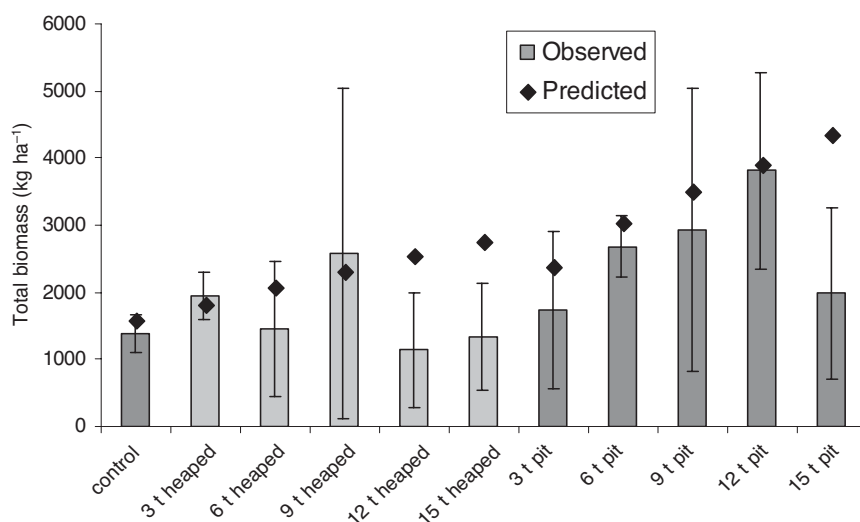
The model successfully predicted maize biomass yields within one standard deviation of the measured yields for the sandy and clay soils (Figure 3). The model also predicted a trend in maize biomass yields for the two soils, with the control treatment having the lowest maize yields and the pit manure treatment the highest.

For the experiment testing rates of manure on a sandy soil, highly variable maize responses were observed in the field (Figure 4). The model could predict the main trends, with maize yield increasing with increasing rates of application, and pit-stored manure having a higher yield trend than the heaped-manure. However, in this experiment, it should be noted that manure was applied on an equal mass basis, rather than equal N. Hence, differences in maize response between the two manure sources are exaggerated by the respective amounts of N added.

## Discussion

The simulations did not always agree with the observed data. Unfortunately, reasons for the lack of conformity are not straightforward. Here we discuss matters that emerged in the testing of the model.

At the wetter location, the observed yields showed a larger response in the first season to the pit-stored manure than to heaped manure (Figure 1). While the pit-stored manure had higher N concentration, this should have been accounted for in the experimental



**Figure 4.** Observed and predicted effects of application rate (t ha<sup>-1</sup>) of heaped and pitted manure on maize yields in Tsholotsho, in 2000–2001 cropping season. Error bars denote standard deviations of measured means.



design in that the manures were compared on an equal N basis. The expectation is that manure quality depends primarily on its C:N ratio and it is such concepts that are built into the model. In terms of C:N ratio, the pit-stored manures had higher values than the heap-stored manure so it would be expected to be a poorer source of N to the first crop. The model accurately predicted the low yields for the control treatment. The fertiliser N that was applied along with the manure treatments effectively masked any differences in the predicted yields for these treatments. It is unclear why the measured yields from the heaped manure should be so low. In the year of application there wasn't enough carbon added (680 kg C ha<sup>-1</sup>) in the applied manure to immobilise the 40 kg N added as fertiliser. In the residual years, there is even less reason to expect the manure treatments to reduce the effect of the fertiliser input.

The simulations of the treatments of experiment 2 involving higher quality manure from a commercial feedlot were satisfactory, except for the treatment where fertiliser was the sole source of N. This treatment was seriously over-predicted. Above it was suggested that manure might have provided some benefit that is not considered by the model. Alternatively, one needs to invoke some mechanism that would result in reduced response to the 100% fertiliser treatment, though how this could be without similarly affecting the 75% fertiliser treatment is somewhat implausible.

The responses measured in experiment 3, particularly to the heap-stored manures, were small and variable (not statistically significant) (Figures 3 and 4). Thus, they are not well suited to providing insights into shortcomings of the model.

The attempts to model these experiments have highlighted several difficulties. The most obvious is that, where there is poor understanding of the measured responses, there can be little basis for judgment on the performance of the model. There is clearly scope for improving the design of experiments to test efficacy of manures (e.g. by not confounding the effects of manure and fertiliser); there is need to identify other possible benefits of manures besides N supply to crops; testing the performance of models would be aided if fuller information were available on initial soil conditions (soil water, mineral N) and it was possible to compare components of crop growth other than grain yield (e.g. total biomass and N uptake).

The results from experiment 1 show our inability to link the analyses of manures that are customarily made (e.g. Table 1) with their observed behaviour in the field. As a result of this study, new experimentation has begun in which the mass balances of C and N will be monitored during storage of manures in the dry (P. Masikate, unpublished data) and wet regions (P. Chivenge, unpublished data).

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## 4.3

# A Capability in APSIM to Model Phosphorus Responses in Crops

M.E. Probert\*

### *Abstract*

Crop simulation models can be used to evaluate climatic risk and alternative management options, including the use of nitrogen fertilisers. However, they have not met the needs of researchers for low-input systems in tropical regions where organic inputs rather than fertilisers are often the only nutrient management option, and other nutrients besides nitrogen (particular phosphorus) frequently constrain crop growth.

This paper describes progress towards developing a capability to simulate response to P within the APSIM (Agricultural Production Systems Simulator) framework, and initial attempts to parameterise such a model to simulate the growth of maize crops grown in semi-arid eastern Kenya. The creation of this capability requires: (1) a new module (APSIM SoilP) that simulates the dynamics of P in soil and is able to account for effectiveness of alternative fertiliser management, e.g. water-soluble versus rock phosphate sources, and placement effects; (2) a link to the modules simulating the dynamics of carbon and nitrogen in soil organic matter, crop residues, etc. in order that the P present in such materials can be accounted for; (3) modification to crop modules to represent the P uptake process, estimation of the P stress in the crop, and consequent restrictions to the plant growth processes of photosynthesis, leaf expansion, phenology and grain filling.

To a large extent, the behaviour of P in the plant and in soil organic matter is modelled in a similar manner to nitrogen. However, that this can lead to a situation where predicted mineralisation of P from crop residues is contrary to experimental observations. It is suggested that the reason lies in the fact that C:P ratios are not common across the sub-fractions of organic matter, with a high proportion of the P being present in the water-soluble components.

The development and application of crop simulation models has focused on water and nitrogen as the main constraints to crop growth (Probert and Keating 2000). Such models have been useful for evaluating alternative management strategies and the effects of climatic conditions. However, their use assumes that other factors (e.g. nutrients other than N, pests, disease) are not limiting. In the case of nutrients, for high-input systems where fertiliser is used to correct nutrient deficiencies the assumption is acceptable. But in low-input systems, as occur in many tropical farming systems,

the assumption is untenable, and these models fail to meet the needs of researchers and extension workers (Palm et al. 1997).

Phosphorus is a limiting nutrient that frequently affects crop growth thereby reducing the usefulness of models. One situation where models have been less than adequate concerns use of scarce manure supplies, which are often the only input of nutrients to the cropping system, and can be a source of both N and P (McCown et al. 1992). It was in response to this particular need that efforts began towards developing a capability within APSIM (McCown et al. 1996; Keating et al. 2003; web site <[www.apsim.info](http://www.apsim.info)>) to simulate growth of crops that were constrained due to P deficiency.

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In order for this to be achieved, a new APSIM module (SoilP) was needed, to describe the dynamics of P in soil; modifications were needed to existing modules to describe the mineralisation of P from manures and other organic inputs; and modifications were needed in the various crop models to describe the P uptake process, together with the extent of P stress in the plant, and its effects on crop growth. This paper sets out how this has been achieved to develop a 'P-aware' APSIM maize module. We use 'P-aware' to distinguish a crop module that has the necessary enhancements to be constrained under low P conditions.

The experimental data set used to derive parameters for the model had been collected during an earlier ACIAR project, from experiments carried out in the Kenyan semi-arid tropics and described by Probert and Okalebo (1992). The testing of the model under a wider range of soils and climate is the subject of other papers in these proceedings (e.g. Kinyangi et al. 2004; Micheni et al. 2004).

## Modelling Phosphorus in Cropping Systems

Phosphorus uptake by plants involves diffusion of phosphate to roots, and is increased by the presence of mycorrhizae. Models of diffusion to plant roots (e.g. Claassen and Barber 1976; Nye and Tinker 1977) show that root density is a controlling factor in P uptake. But models of the diffusion process are at a greater level of detail (in both time and space) than what is found in most crop models. Crop models typically assume that water and nitrogen are homogeneous throughout each soil layer with a dimension of centimetres, in marked contrast with the diffusion models where concentration gradients exist around individual roots with dimension of fractions of a millimetre.

More general system models, like EPIC (Jones et al. 1984) and CENTURY (Parton et al. 1988), have included P routines, but the generic crop routines in these models have limited ability to address crop management issues requiring accurate simulation of crop growth in response to weather, genotype, soil and management practices. They have not been widely used to explore management strategies involving P. It has been reported that the P routines in CENTURY were not able to describe the dynamics of P in tropical soils (Gijssman et al. 1996).

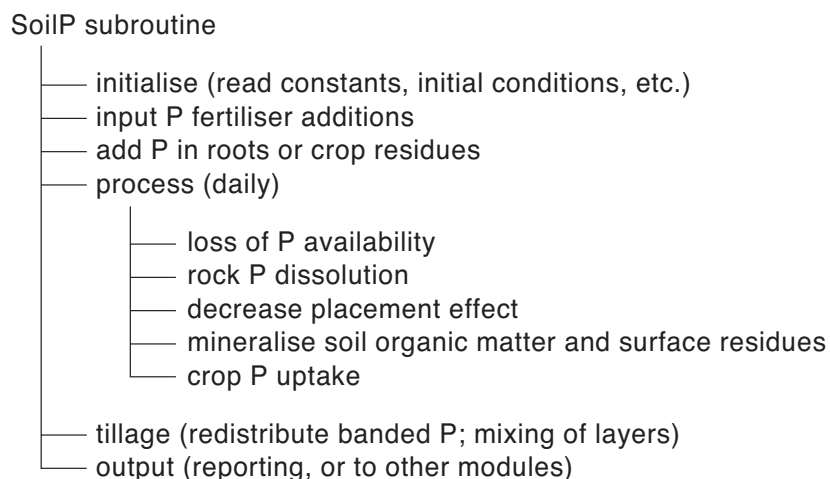
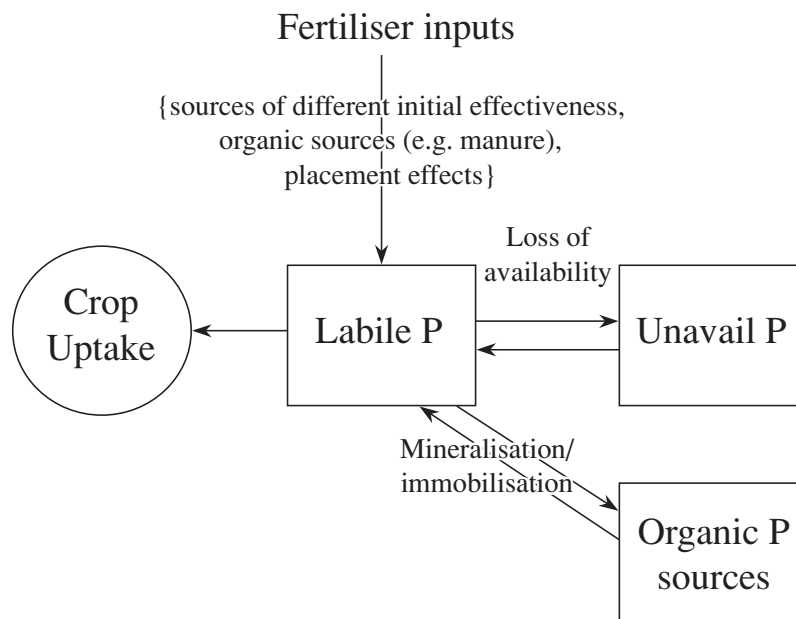
Management of soil P (especially in high-input agricultural systems) has focused on issues like whether to apply fertiliser, at what rate, evaluating placement and residual effects, and comparing relative effectiveness of water-soluble versus insoluble sources. Because P is immobile in soil (at least over the time scale of an annual crop) interactions with climate are of little importance. Unlike the management of N, there has been no need for a detailed crop model to evaluate alternative strategies for management of P. Models operating with a time-step of a growing season and an empirical relationship between yield and soil P status are adequate to gain insights into crop responsiveness to alternative fertiliser P sources and their residual effects (Probert 1985).

However, if there is a need for crop models to simulate response to manures and other organic sources in low-input systems, it is important that they respond to both N and P.

Crop models tend to perform best when there is a similar degree of detail for the various components of the overall model. At the time ACIAR project LW2/1999/003 commenced, it had not been demonstrated that this could be achieved for simulating a P constraint. It is noteworthy that the notion of including a P constraint into crop models has also been an activity for modellers using the DSSAT software. Their model has been published by Daroub et al. (2003).

### The APSIM SoilP module

The central concept of the SoilP module is that it is possible to describe the availability of P in soil in terms of a labile P pool. Figure 1 illustrates the processes that are considered to affect the amount of labile P in soil. These are: inputs (fertilisers, manures etc.); crop uptake; transformation between available and organic forms of P; and transformation between available and unavailable forms of P. The model of this system (see the subroutine structure in Figure 1b) is really a statement of the P balance between the different forms of P present. Thus, the labile P in a given soil layer has units of  $\text{kg ha}^{-1}$  and responds quantitatively to inputs and removal. It cannot therefore be directly equated with any particular soil P test, though we shall return to the topic of how there is need to specify such a model in terms of soil P tests.



**Figure 1.** The APSIM SoilP module. The upper part of the figure shows in diagrammatic form the processes that are considered in the module. The lower part shows the simplified subroutine structure of the model where some actions are event based (e.g. initialisation, add fertiliser, tillage) whereas the ‘process’ activities occur on a daily time step.

### *Fertiliser inputs*

SoilP has been designed to accommodate different forms of P fertiliser and also placement effects in fertiliser application. This is achieved by specifying fertiliser as either immediately available (e.g. water-soluble forms such as mono-ammonium phosphate) or as a non-water soluble source (e.g. rock phosphate) which needs to break down before P becomes

available, or some combination of the two. In the case of addition of an available form, if it is broadcast and mixed into soil its P content is immediately added to the soil labile P; but if it is banded, its P is accounted for separately so that it can be assigned a higher value than the rest of the labile P in terms of supplying P to a crop. Similarly, a rock phosphate source is accounted for separately and releases its P to the

labile P pool at a rate that is specified for a particular simulation run. To date, no effort has been made to make the rate of release of P from non-water soluble sources dependent on the source or soil properties.

#### *Loss of availability*

It is assumed that the transformations between labile P and unavailable P are first-order processes that are dependent on temperature. The relative rates of the forward and reverse processes (Jones et al. 1984) determine the magnitude of the unavailable pool relative to the labile P at steady-state conditions; it has been assumed that at steady state the unavailable pool is typically 10 times the labile pool. No attempt has been made to rationalise the sum of the soil P pools to measured total soil P.

#### *Soil organic P*

The APSIM SoilN module accounts for C and N in the various soil organic matter pools; the APSIM Residue module does likewise for the surface residues (see Probert and Dimes 2004). SoilP assumes that these pools also contain P. Decomposition of any pool (controlled by the SoilN or Residue modules) results in release of C, N and P in proportion to the composition of the pool. SoilP assumes that the C:P ratios of the soil BIOM and HUM pools are invariant (as is the case for the corresponding C:N ratios), but the C:P ratio of the surface residues and FOM can vary depending on the materials being added to the system. Decomposition of soil organic matter can thus result in mineralisation or immobilisation of P depending on the C:P ratios of the pools decomposing and being synthesised.

#### *Crop uptake of P*

SoilP calculates a potential daily supply of P from all soil layers. This involves (1) estimation of the effective P in a soil layer (the sum of labile P and placed P, with a premium being assigned to the latter); (2) conversion to a notional concentration in solution based on the P sorption characteristics of the soil; (3) summation across the soil profile weighted according to the presence of roots, soil water status of the layer, and layer thickness; and (4) application of a P uptake factor that can be crop or cultivar dependent. The P uptake factor, as used here, has similarities with the root absorbing power of Nye and Tinker (1977) in that it is the proportionality between P uptake and concentration in solution. Actual uptake is then the minimum of the potential supply and the demand calculated by the crop module. P uptake is apportioned between labile and placed P in the dif-

ferent layers in the proportion to which they contribute to the potential supply.

The notion of assigning a premium to placed P is analogous to what has been referred to as substitution, whereby one unit of placed P might be considered to substitute for, say, two units of soil P. The justification for relating P uptake to a notional concentration in solution follows from Probert and Moody (1998) who showed how P uptake can be related to a measure of P quantity combined with an index of P buffer capacity.

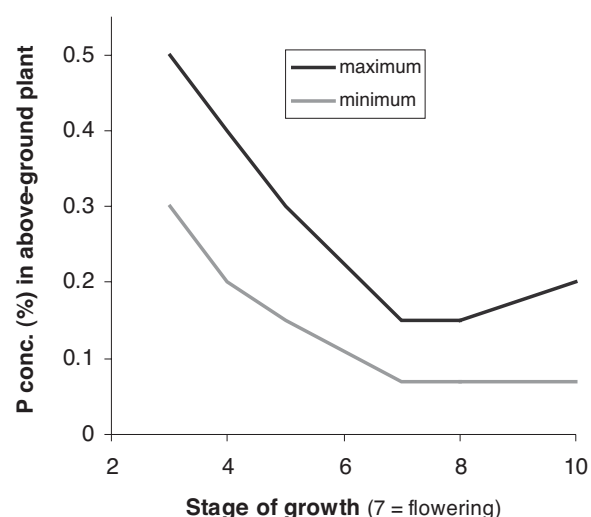
### **Simulating crop growth and development under P limiting conditions**

The routines introduced into the maize module to restrict growth under P limiting conditions are similar to the corresponding N routines. The relative P concentration in the plant (or plant parts) is calculated with reference to defined optimal and minimal concentrations. This is then used to calculate P stress factors for photosynthesis, leaf expansion, phenology and grain filling, which are combined (law of minimum) with corresponding stress factors for water and nitrogen to modify crop growth.

Initial efforts to demonstrate that such a model might be feasible used P concentrations in the whole above-ground plant (see Figure 2) for calculating the P status of the plant. While this could work for a single crop, it is not compatible with simulating a sequence of crops where P in roots and residues must be considered. Accordingly, later efforts have endeavoured to partition P between the various plant components (leaf, stem, flower, grain, root) of the growing crop in a way similar to that in which N is modelled in APSIM crop modules. There is a dearth of information from which the appropriate critical P concentrations can be derived; current values are based on measurements on the short-duration cultivar Katumani Composite B (Probert and Okalebo, unpublished data) together with the published data of Jones (1983).

There are also few data on how P affects plant growth. Compared with the effects of nitrogen there seems to be a lack of information on leaf expansion, and only passing references to the fact that P deficiency delays flowering in maize (Probert and Okalebo 1992) and in sorghum (Sahrawat et al. 1995). Accordingly, the model currently assumes the dominant effect of P is expressed through a reduction in photosynthesis.

The plant demand for P is calculated from (a) the P requirement for today's growth (at the optimal P concentration), and (b) the overall P deficit of the crop, being the amount of P required to raise the whole of the plant mass to its optimal P concentration. Provided the soil supply (see above) is adequate, the model allows part (a) to be met. Further, in order that a plant can 'recover' from a P-deficient condition, the uptake is allowed to exceed the requirement for today's growth by a factor (a value of 1.5 is currently used (Jones et al. 1984)), thereby reducing the overall deficit. Because the predicted P supply from soil is strongly dependent on soil moisture, this approach to estimating uptake prevents the plant from rapidly meeting its P needs following a rainfall event.



**Figure 2.** The P concentrations in maize used to define the crops P status. The minimum P concentrations are derived from the experimental data of Probert and Okalebo (1992); the maximum concentration from Jones (1983).

### Parameterising the SoilP module

An example of a parameter file to initialise the APSIM SoilP module is shown in Table 1. In most circumstances it is envisaged that **banded\_p** and **rock\_p** would be zero in all layers (i.e. one would normally initialise the model before applying fertilisers); similarly in most unfertilised conditions it can be assumed that the labile P is in steady state with unavailable P (the default assumption if no values are provided for **unavailable\_p**). Information is needed for the C:P ratio of roots and residues and also the rate

at which P will be released from **rock\_p** (expressed on an annual basis).

The difficult business of specifying the soil with respect to its P status comes down to initialising the labile P pool and the soil's P sorption characteristics. For the latter the 'standard P requirement' is used, as defined by Beckwith (1965) and widely used by others (e.g. Fox and Kamprath 1970). It corresponds with the P sorbed at a final concentration of  $0.2 \text{ mg L}^{-1}$ . It has the advantage that it provides a scale for P sorption that is generally understood.

In most circumstances, it will be necessary to 'drive' the model using soil P test data to initialise the labile P pool. No effort has been made to include algorithms in the model code to specify how this should be done. Rather it is left to the discretion of the user. In experiences to date, we have used bicarbonate or resin extractable P. On low P sorbing soils it might be expected that these fractions will approximate the labile P, though more generally as P sorption increases it would be expected that the soil tests will extract a decreasing proportion of the soil's labile P.

### Predictive performance

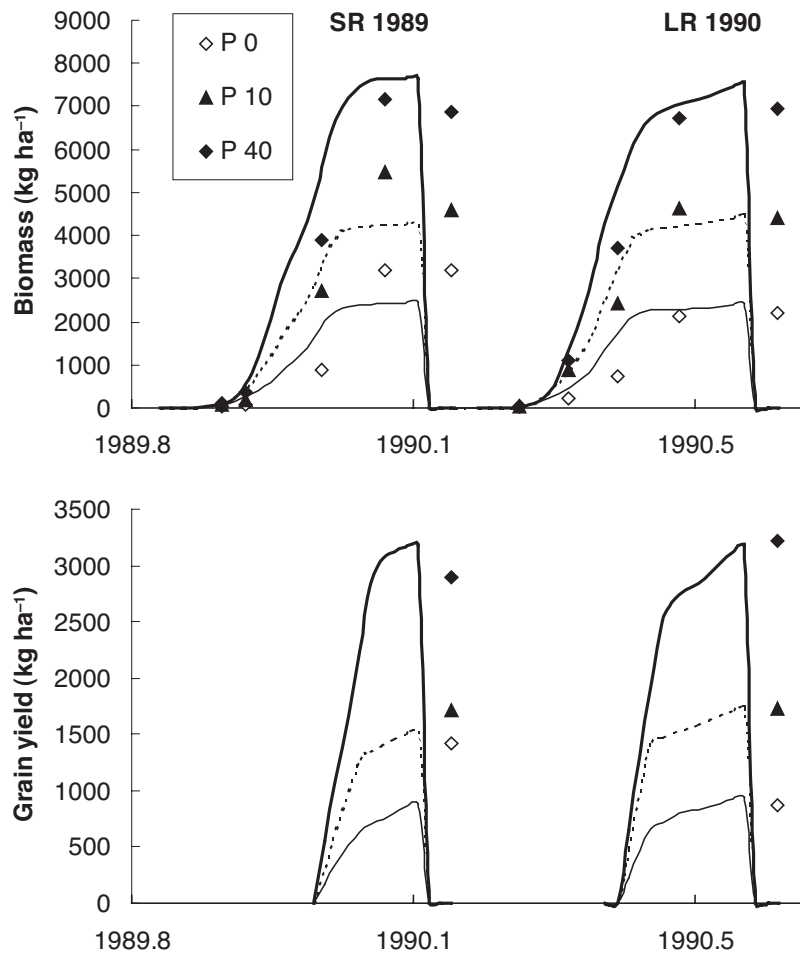
The data set that has been used to test the assumptions that underlie the P capability developed within the APSIM framework was collected on an Alfisol with low P sorption characteristics at Mutua Farm, near Katumani in eastern Kenya (Probert and Okalebo 1992). Bicarbonate extractable P (Olsen) in the surface 0–15 cm soil was  $4 \text{ mg kg}^{-1}$ . Briefly, maize (Katumani Composite B) was grown over two seasons (short rains 1989–1990; long rains 1990) with different inputs of P as single superphosphate and adequate N. Several harvests were made through the duration of the crop, and the plant biomass was separated into its components (leaf, stem, cobs and, at maturity, grain), dried and analysed for P and N.

The output from the model is compared with the measured data in Figure 3. What is shown is not implied to be an independent test of the model. However, it does indicate that the model was able to capture the main features of the measured data in terms of total dry matter and grain yield. Other data (not shown) showed reasonable agreement in leaf area and P concentration in the tissues.

A second experiment examined the effectiveness of different fertiliser sources of P (Figure 4). To demonstrate the potential of the model to simulate

**Table 1.** An example of a SoilP parameter file to initialise an APSIM simulation. The layer structure (number of layers, layer thickness) used in the simulation is defined by the soil water module; the additional input relates only to the P pools.

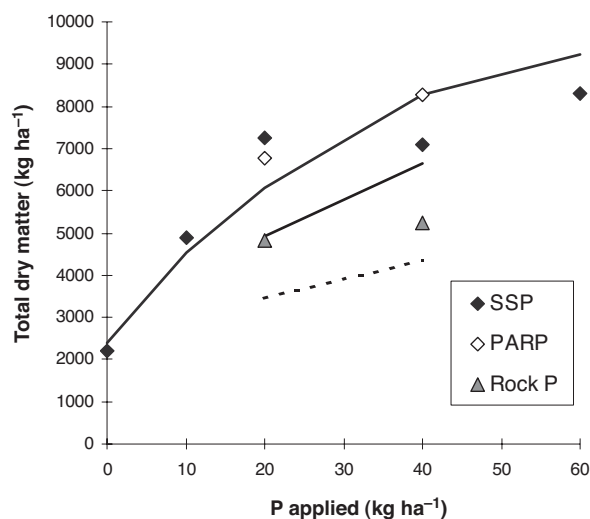
[all.soilp.parameters]					
layer number	1	2	3	4	
labile_p =	5	4	3	3	(mg/kg)
unavailable_p =	50	40	30	30	! optional
banded_p =	0	0	0	0	(kg/ha)
rock_p =	0	0	0	0	(kg/ha)
sorption =	110	150	200	200	! p sorbed at 0.2 mg/L
residue_cp = 250					
root_cp = 200					
rate_dissol_rock_p = 0.40 (L/yr)					



**Figure 3.** Comparison of measured and simulated yields of the maize crops grown at Mutua Farm, near Katumani with different rates of P as superphosphate applied as a band below the seed and 90 kg ha<sup>-1</sup> of N as calcium ammonium nitrate applied as three splits (Probert and Okalebo 1992). The observed data are shown as symbols, the predictions as continuous lines. Note that the crops were harvested several weeks later than physiological maturity as predicted by the model.



response to non-water-soluble sources, it was assumed that the Minjingu rock P had 20% of its P readily available and 80% unavailable; for the partially acidulated product, 60% was assumed available. No attempt was made to optimise values obtain a better fit. The simulated output shows that the model is able to predict a smaller response to P sources that are not immediately available. However, in this experiment the observed response to the partially acidulated product was similar to single superphosphate.



**Figure 4.** Simulation of total DM yield at maturity of maize fertilised with single superphosphate, partially acidulated (50%) rock phosphate, and Minjingu rock phosphate; all treatments received 90 kg ha<sup>-1</sup> of N as calcium ammonium nitrate. The observed data are shown as symbols, the predictions as continuous lines. The rock phosphate sources were only tested at rates of application of 20 and 40 kg P ha<sup>-1</sup>. Experimental data from Probert and Okalebo (1992).

### A comment on modelling the mineralisation of P from organic inputs

It is generally recognised that the mineralisation of N from organic sources depends largely on the C:N ratio of the substrate. This can be expressed succinctly (Whitmore and Handayanto 1997):

$$N_{\text{mineralised}} = C_{\text{decomposed}} [1/C:N_{\text{substrate}} - E/C:N_{\text{SOM}}]$$

where C:N<sub>SOM</sub> is the C:N ratio of the soil organic matter being synthesised; E is sometimes referred to

as the assimilation coefficient, which equates with the fraction of the decomposing carbon that is retained as soil organic matter and in APSIM SoilN is normally set at 0.4. If all the retained carbon is synthesised into the more labile soil carbon pool with a C:N ratio of 8, the C:N ratio of the substrate that determines whether net mineralisation or immobilisation occurs is 20. The essence of this relationship is the basis of the decomposition/mineralisation process in the APSIM SoilN module.

An assumption that the same principle would apply to the mineralisation of organic P leads to a relationship between the P mineralised and the C:P ratios of substrate and the soil organic matter being synthesised:

$$P_{\text{mineralised}} = C_{\text{decomposed}} [1/C:P_{\text{substrate}} - E/C:P_{\text{SOM}}]$$

From this equation, the P concentration determining net mineralisation/immobilisation can be calculated for different assumed C:P ratio of the soil organic matter (Table 2).

**Table 2.** Predicted phosphorus content of plant residues (expressed as C:P ratio and P concentration in dry matter) that would determine whether initial mineralisation or immobilisation of P occurs for different assumed values of the C:P ratio of the soil organic matter being formed.

C:P of organic matter	C:P of residues	P concentration (%) <sup>a</sup>
20	50	0.80
40	100	0.40
67	167	0.24
100	250	0.16
200	500	0.08

<sup>a</sup> Assuming 40% carbon in plant dry matter

Palm et al. (1999) suggest a critical P concentration of 0.24% below which immobilisation of P would occur, while Nguluu et al. (1996) reported that mineralisation of N from plant residues was reduced (presumably because the decomposition rate was limited by P) when P concentration in tissues dropped below 0.16%.

On the other hand, the C:P ratio of soil microbial biomass is generally in the range 10 to 35 (quoted by He et al. (1997)). For a Nitisol from Western Kenya, Nziguheba (2001) measured small changes in microbial C:P due to P inputs and through time, with an

overall average of 27. He et al. (1997) reported much larger variation in a soil under grassland, due to time of sampling and nutrient inputs (range 9–276), but it seems implausible that living organisms could vary so widely. For comparison, the C:N ratio of microbial biomass is higher for fungi (~12) than for bacteria (~8), but otherwise does not seem to vary much across diverse ecosystems.

Thus, there would seem to be some discrepancy between the mineralisation of P from plant residues and the soil microbial C:P ratio. At typical biomass C:P values, no crop residue with P concentration <0.4% would be expected to mineralise P. Why this does not happen can probably be explained by the fact that sub-fractions of the substrate have different C:P ratios (compare Probert et al. (2004) who suggest a similar explanation to account for the N mineralisation pattern from some manures). In the case of crop residues, the C:P ratio of the soluble fraction is much lower than that of the total dry matter. Nziguheba (2001, Table 1.2.1) reports soluble C:soluble P ranging from 12–50 for six organic inputs used as green manure, whereas total C:P was in the range 140–250. For most materials, at least 50% of total P was soluble. Similarly, Nguluu et al. (1996) reported approximately 75% of total P to be water extractable, even for materials that were grown under P limiting conditions.

In many situations where the model will be applied, the mineralisation of organic P is likely to be unimportant. But, clearly, any efforts to simulate the effectiveness as P sources of biomass transfer systems (as studied by Nziguheba (2001)) would need to be able to specify inputs of organic material that have sub-fractions with different C:P ratios.

## Discussion

The development of a capability to model crop response to limited P supply requires code to describe the behaviour of P in both the soil and the plant. The approach adopted to create this capability in APSIM has similarities and conceptual differences from how the problem has been tackled in DSSAT (Daroub et al. 2003).

The most obvious differences are in how the understanding of the behaviour of soil P is represented. Daroub et al. (2003) seek to specify numerous soil inorganic and organic P pools in terms of measured soil fractions. The philosophy in the APSIM

approach has been that the organic P pools are identical to the C and N pools found elsewhere in the model. Thus, there will always be a linkage between mineralisation/immobilisation of N and P and decomposition of soil organic matter. Also, the conceptual labile P pool in the APSIM SoilP module has not been directly linked to any soil P test. In this manner we avoid the difficulty that labile P, as it is defined in the model, responds quantitatively to inputs and removal of P, whereas this is not the case with soil tests. Nevertheless, this is to admit that it is not yet clear how such a model can be initialised and/or validated against measured soil test data. It remains an open question as to what are the ‘pros and cons’ of the two approaches.

Here we have shown that the P-aware maize model can be specified to produce output that matches observations from a single site on an Alfisol. In particular, the desire has been to produce a tool that will perform sensibly with regards to issues like soluble versus non-water-soluble sources, placement effects, and soils with different P sorption characteristics. The challenges that are still to be faced are to show that the model with the same parameterisation is able to perform satisfactorily for different soils and environments, and ultimately can be parameterised for other crops. Other papers in these proceedings test this hypothesis on a wider range of soils.

The SoilP module has been developed with the aim that it will also respond sensibly to inputs of P in organic sources including manures, but validation against suitable data sets has not yet been undertaken. An omission from the model is that it does not explicitly deal with the effects of mycorrhizae on P nutrition of crops. However, it is expected that this will not be a limitation in the low-input farming systems where the model is likely to be used.

## Acknowledgment

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## 4.4

# Testing the APSIM Model with Data from a Phosphorus and Nitrogen Replenishment Experiment on an Oxisol in Western Kenya

J. Kinyangi,\* R.J. Delve<sup>†</sup> and M.E. Probert<sup>§</sup>

### *Abstract*

An experiment was conducted on an Oxisol near Maseno in western Kenya, to compare the growth of maize crops to inputs of two phosphorus sources. Commercial triple superphosphate (TSP) and Minjingu phosphate rock were applied either at a once-only rate of 250 kg P ha<sup>-1</sup> or as five annual inputs of 50 kg P ha<sup>-1</sup>. The experiment was carried out over 10 cropping seasons between 1996 and 2000. An additional factor studied was the source of N, either as urea or tithonia biomass-N to supply 60 kg N ha<sup>-1</sup>. Both N and P sources were applied only to the crops grown in the long rain season. The APSIM model has been tested against this data set. The effects of P treatments were large in the long rain season, but in the short rain season the inadequate supply of N greatly reduced growth and P effects. The yields of the maize crops were predicted well ( $r^2 = 0.88$ ) with respect to both the P treatments (as TSP) and the N inputs (as urea). The predicted water, N and P stresses were informative in understanding the contrasting pattern of response observed in the two seasons. The simulation of this long-term experiment shows that the APSIM SoilP module is robust, in as much as it extends the testing of the model to a very different environment where there were both N and P stresses affecting plant growth, and on a very different soil type to where the concepts in the APSIM phosphorus routines were originally developed and tested.

Crop production on many soils in western Kenya is limited by both nitrogen (N) and phosphorus (P). The concept of recapitalisation of soil P has focused attention on the use of rock phosphate materials rather than commercial forms of processed fertilisers, and the feasibility of raising soil P through large, one-time application rather than a gradual increase with smaller, but regular inputs (Buresh et

al. 1997). Such strategies have been evaluated in long-term experiments in western Kenya.

Probert (2004) describes how a capability to simulate P limited maize crops has been developed within the APSIM modelling framework. The data used to derive the parameter set defining the P status of maize through its growth cycle were from experiments at Katumani in the semi-arid region of eastern Kenya, on soils with low P sorption. There is a need to test the applicability of the model under a much wider range of environments and on different soil types.

In this paper, we describe the testing of the APSIM P routines using an experiment that provides suitable data for testing some aspects of the model. The annual rainfall and soil type, especially with regards to its phosphorus sorption properties, are

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extreme contrasts to those on which the model was first developed.

## The Experiment

### Site description

A field experiment was conducted at Olwenyi, Ondele and Julius farms near Maseno in western Kenya (0°06' N, 34°34' E, 1420 m above sea level). The annual rainfall in the region is typically 1800–2000 mm, with bimodal distribution and two growing seasons; the long rain season between March and July (LR) and the short rain season between September and January (SR).

The soil type is a very fine isohyperthermic Kandudalfic Eutradox (USDA 1992). It has few chemical or physical barriers to rooting in the top 4 m (Mekonen et al. 1997). Air-dried soil (0–15 cm) had a pH of 5.2 (1:2.5 soil:water suspension); organic carbon 18 g kg<sup>-1</sup>; exchangeable acidity (1 M KCl) 1.0 cmol<sub>c</sub> kg<sup>-1</sup>, calcium 3.5 cmol<sub>c</sub> kg<sup>-1</sup>, magnesium 1.3 cmol<sub>c</sub> kg<sup>-1</sup>, potassium 0.12 cmol<sub>c</sub> kg<sup>-1</sup>; bicarbonate–EDTA extractable phosphorus 1.7 mg kg<sup>-1</sup>. Clay, silt and sand contents were 35%, 20% and 45%, respectively. P sorption is very high; based on sorption isotherms 250 mg P kg<sup>-1</sup> of soil was required to raise soil solution P to 0.2 mg L<sup>-1</sup> for 0–15 cm soil.

### Treatments

The experiment began in 1996. It was designed as a balanced factorial combination comparing a one-time application versus repeated annual additions of P, with two P sources (triple superphosphate (TSP) and Minjingu rock phosphate from Arusha, northern Tanzania) plus a control treatment that did not receive any P, and two nitrogen sources (urea and tithonia biomass to supply 60 kg N ha<sup>-1</sup>). The annual P application was 50 kg ha<sup>-1</sup> applied in March–April before the LR crop, while the one-time application rate was 250 kg ha<sup>-1</sup> applied before the 1996 LR crop only. The P sources were broadcast and incorporated into the soil before planting. After 10 seasons, the total P applied was the same for the one-time and annual applications.

The N inputs as urea or tithonia biomass (3.3% N) were applied to only the LR crops. Urea was split-applied, one-third at sowing and two-thirds at 5 weeks after sowing. The tithonia was chopped and

incorporated into soil before planting maize in the LR season.

### Management

Sole maize crop was planted at 0.75 × 0.25 m spacing using medium to short duration hybrid varieties. The LR crops were sown in March–April, the SR crops in August–September. During maize harvest, all stover was removed from the plots. Between crops, soil was ploughed to 15 cm depth.

Potassium deficiency was observed to seriously affect the yield of the first crop. In March 1997, all plots were split to accommodate an additional factor testing the effect of 1) no addition of K fertiliser, and 2) annual application of 60 kg K ha<sup>-1</sup> as KCl. In this paper, we consider only data from plots that received K, and yields are assumed to be unaffected by K deficiency.

The soil (0–15 cm) was sampled in 1996, 1997 and 2000 at the time of sowing the LR crop after all organic and inorganic fertiliser materials had been applied and incorporated into the soil. Samples were air-dried, sieved through 2 mm, and fractionated for soil P using a method that employs a series of increasingly aggressive extractants to remove labile inorganic and organic P (P<sub>i</sub> and P<sub>o</sub>) followed by more stable P<sub>i</sub> and P<sub>o</sub> forms. The method is modified from the procedure of Tiessen and Moir (1993), which in turn is based on the fractionation procedure of Hedley et al. (1982).

### Simulations

The model was specified to simulate the experimental treatments involving TSP and urea. We used the genetic coefficients for the maize hybrid HB 511 for all seasons, these being available from other studies. For most crops, the predicted maturity of the crop agreed reasonably with the date of harvest. An exception was the LR crop in 2000 (sown 7–8 April), which the model predicted to be mature on 10 September, later than the sowing date (29–30 August) for the next SR crop. This was accommodated by delaying the sowing of the SR crop until 12 September.

The simulation runs were initialised on 15 March 1996, corresponding to the start of the experiment, with the soil properties set out in Table 1. A continuous simulation was run for the 10 seasons. The soil's plant available water capacity to the rooting

depth of 1.8 m was 155 mm. The soil organic carbon in the surface soil layer was the measured value. The soil labile P in the surface layer was based on the sum of resin and bicarbonate-P measured in the sequential fractionation of soil P. Both organic carbon and soil P were assumed to decrease with depth, while P sorption was assumed to be higher in the subsoil layers.

## Results and Discussion

### Observed maize yields

The overall effects of the treatments on the total above-ground dry matter (DM) yield for maize are summarised in Table 2. Maize grain yields showed responses that were similar to the total DM yields and these data are not presented.

There is a very large response to P in the LR seasons, but only small differences between the two P sources or the frequency of application of the P fertiliser. This is consistent with Minjingu rock phosphate being recognised as an effective source of P, especially on an acidic soil.

The yields of the SR crops were much lower than for the LR. The stresses predicted in the simulations indicate that this is predominantly a nitrogen effect,

because there were no N inputs to the SR crops (see Figure 3).

The apparent effects of the two N sources are complex. For the LR crops, the main effect of N source was not statistically significant ( $p > 0.05$ ). The application of tithonia-N resulted in higher average DM yields, but this observation is due almost entirely to the 1996 LR crop. In the first year of the experiment, before the K treatments had commenced, the tithonia biomass (containing 56 kg ha<sup>-1</sup> of K) largely overcame the K limitation that occurred when urea was the N source. The annual input of tithonia biomass also contained 6 kg ha<sup>-1</sup> of P and this contributes to some of the difference between the two N sources in the absence of any P fertiliser. The SR crops, grown without additional inputs, show a residual effect from the tithonia-N compared with urea-N, maize DM yields being approximately 1 t ha<sup>-1</sup> higher where P was applied ( $p < 0.01$ ).

### Comparison of observed versus predicted yields

Figure 1 compares the observed effects of the three P treatments with the output from the simulation, showing the response to P in each of the cropping

**Table 1.** Soil properties used for specifying APSIM simulation of the Maseno experiment.

Layer	1	2	3	4	5	6	7
<i>SoilWat parameters<sup>a</sup></i>							
Layer thickness (mm)	150	150	300	300	300	300	300
BD (g cm <sup>-3</sup> )	1.10	1.22	1.31	1.23	1.19	1.15	1.21
SAT	0.50	0.49	0.46	0.48	0.50	0.50	0.49
DUL	0.35	0.38	0.40	0.37	0.36	0.35	0.37
SWCON	0.7	0.7	0.7	0.7	0.7	0.7	0.7
<i>Maize parameter</i>							
LLmaize	0.22	0.24	0.28	0.30	0.30	0.29	0.30
<i>SoilN parameters</i>							
organic C (%)	1.8	1.0	0.72	0.57	0.45	0.35	0.30
finert <sup>b</sup>	0.35	0.7	0.8	0.9	0.95	0.99	0.99
fbiom	0.02	0.015	0.01	0.01	0.01	0.01	0.01
<i>SoilP parameters</i>							
labile P (mg kg <sup>-1</sup> )	8.5	5	2	2	2	2	2
P sorption (mg kg <sup>-1</sup> ) <sup>c</sup>	260	400	400	400	400	400	400

<sup>a</sup> The soil water balance is described in terms of the volumetric water content at saturation (SAT), drained upper limit (DUL), and lower limit of extraction by the crop (LL); BD is soil bulk density; SWCON is the proportion of water in excess of DUL that drains in 1 day.

<sup>b</sup> finert is the proportion of soil carbon assumed not to decompose; fbiom is the proportion of decomposable soil carbon in the more labile soil organic matter pool.

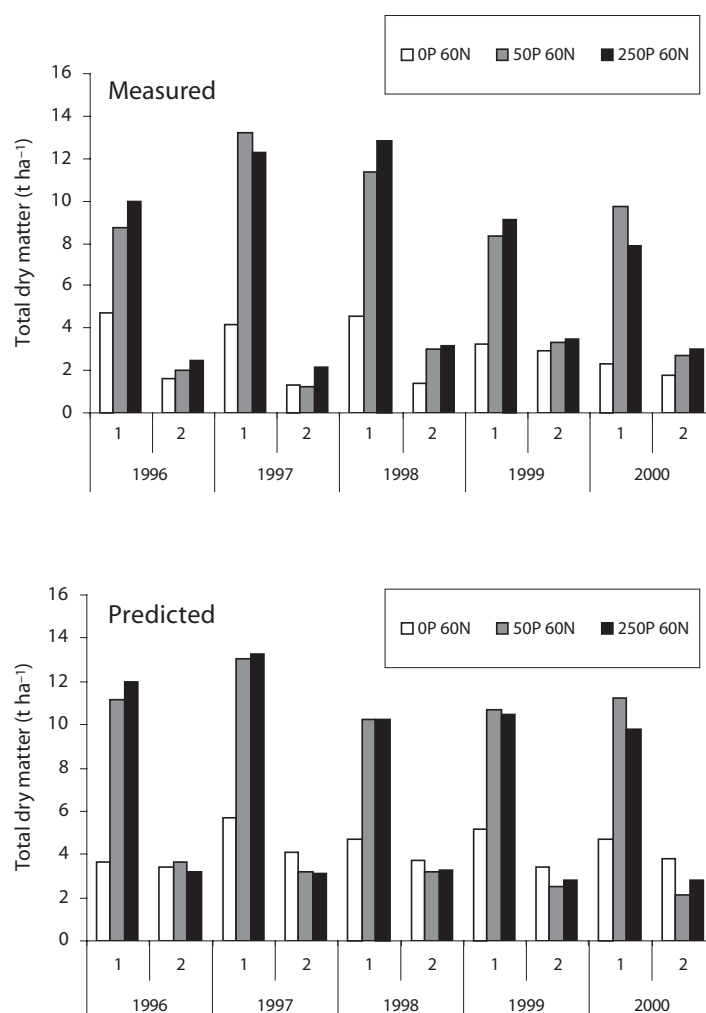
<sup>c</sup> P sorbed at 0.2 mg L<sup>-1</sup> in solution.

**Table 2.** Effect of P treatments on maize biomass yields ( $\text{t ha}^{-1}$ ) at Maseno for the two sources of nitrogen. Data averaged across the 5 years 1996–2000.

Phosphorus treatment	Long rain crops		Short rain crops	
	Urea	Tithonia	Urea	Tithonia
No added P	3.3	5.8	1.6	2.2
Annual addition ( $50 \text{ kg ha}^{-1}$ ) as TSP	9.6	10.3	2.2	3.1
Annual addition ( $50 \text{ kg ha}^{-1}$ ) as MPR	8.8	10.3	2.2	3.2
One time addition ( $250 \text{ kg ha}^{-1}$ ) as TSP	9.5	10.6	2.5	3.5
One time addition ( $250 \text{ kg ha}^{-1}$ ) as MPR	9.1	9.9	2.5	3.3

Analysis of variance:			
P treatment	$p < 0.001$		$p > 0.05$
N source	$p > 0.05$		$p < 0.01$
P treatment $\times$ N source	$p > 0.05$		$p > 0.05$



**Figure 1.** A comparison of the measured (upper pane) and simulated (lower pane) dry matter yields of maize through 10 seasons for the treatments receiving  $60 \text{ kg ha}^{-1}$  of N as urea and different inputs of P as TSP: none,  $50 \text{ kg ha}^{-1}$  annually, or  $250 \text{ kg ha}^{-1}$  as a single application before the 1996 crop. Note that for the measured data, the yields for the first crop in 1996 are for the treatments that received tithonia-biomass as the N source. For the later crops, the N source was urea, and potassium was also applied after 1997.

seasons. In Figure 2 the data are plotted in the more conventional ‘observed versus predicted’ manner.

The most marked feature of the pattern exhibited in Figure 1 is the difference in DM yields between the two seasons. This is captured well by the model. In the second (SR) season when no additional P and, more importantly, no N was applied, yields were very low (2–3 t ha<sup>-1</sup>) and were little affected by P treatments. In the LR, the DM yields without P addition were around 4 t ha<sup>-1</sup> increasing to ~10 t ha<sup>-1</sup> where P was applied. There was reasonable agreement between the observed and fitted yields ( $r^2 = 0.88$ ) with little indication of bias (Figure 2). However, the model provides no ability to discriminate between the treatments for the SR crops.

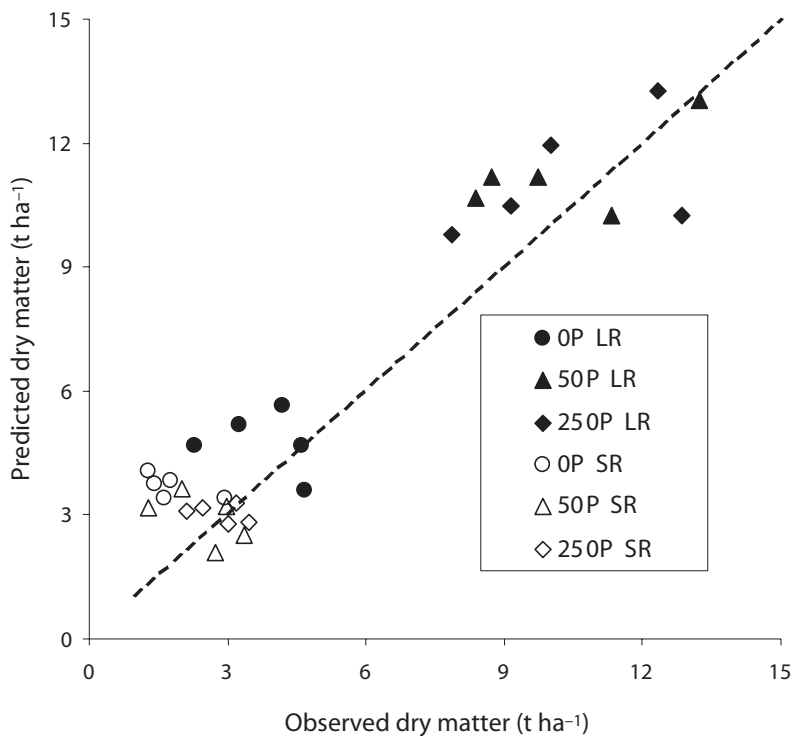
Where the P effects are not obscured because of limiting N, both the observed and predicted data show that, in the early years of the experiment, there was not much difference between the 50 and 250 kg ha<sup>-1</sup> rates, though with a tendency for the measured yields to respond beyond the 50 kg ha<sup>-1</sup> rate in 1996 and 1998 (Figure 1); but by the fifth year there is some suggestion that the annual application of 50 kg ha<sup>-1</sup> is giving larger yield than the single input of 250 kg ha<sup>-1</sup>.

## Insights provided by the model

### Stresses on crop growth

In this experiment, there is little indication of year-to-year variation in crop growth, but it is evident that there are great differences between the two seasons and due to the treatments. The output from the model is helpful in understanding the cause of these effects.

In Figure 3 we show the predicted stresses on crop growth due to water, phosphorus and nitrogen. The experimental site enjoys high rainfall and the model predicts that, through the 10 crops, water stress was never limiting. For the no-P treatment, the simulation shows that P stress always dominates N stress, though for the SR crops after 1997 there are signs that N is also suboptimal. However, when P has been applied, the situation is reversed and N stress dominates. Particularly in the SR crops, N stress commences early and growth is severely restricted. Thus, the inference from the simulations is that the experiment was carried out under less than optimal N. Treatments with higher N inputs might well have accentuated the differences between the P treatments, especially in the SR crops.



**Figure 2.** Plot of observed versus simulated maize dry matter yields in relation to the 1:1 line. The root-mean-square deviation between observed and predicted yields is 1.58 t ha<sup>-1</sup>.



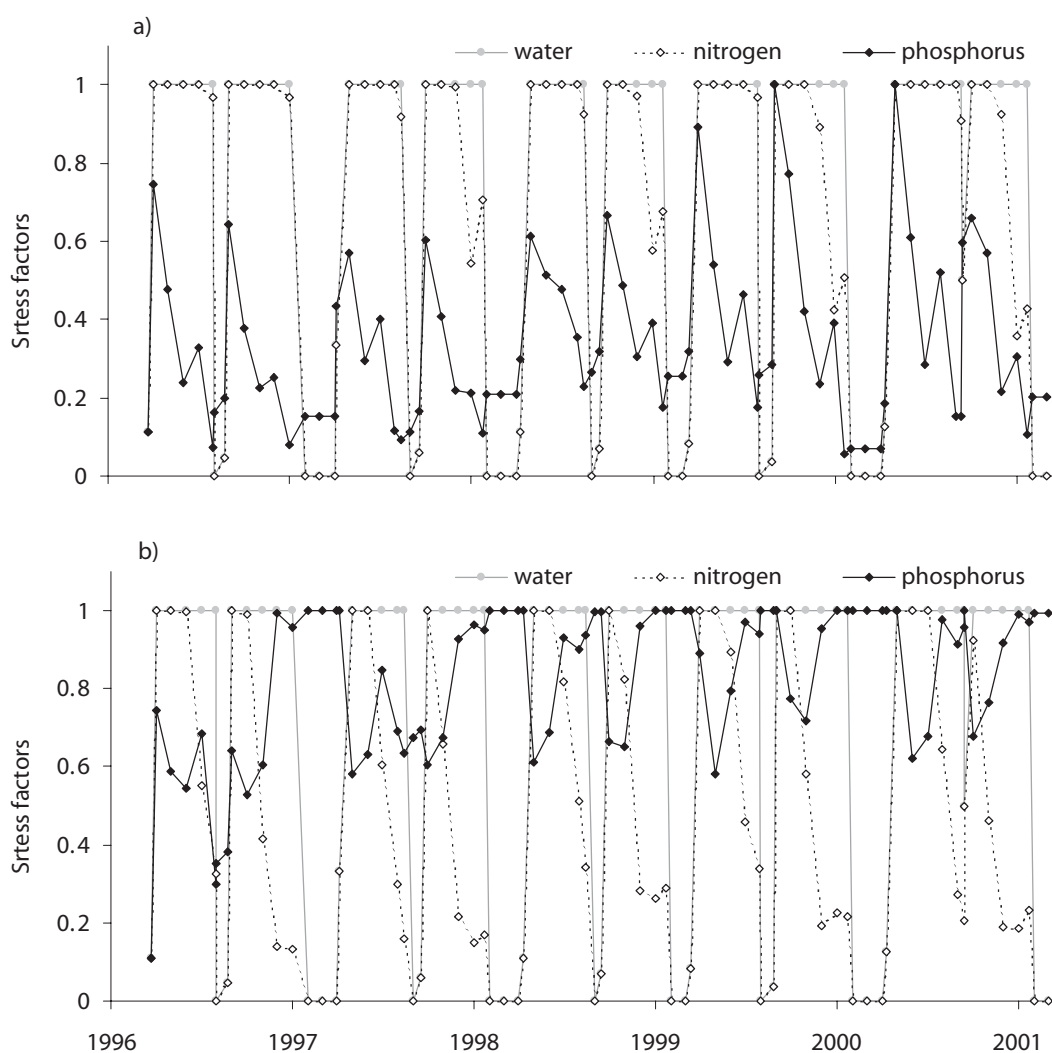
Figure 4 illustrates some aspects of the simulated water balance at the site. Over 25% of the rainfall is predicted to end up as drainage. Not much attention should be paid to the run-off values, because we deliberately parameterised the model to keep run-off low, based on the assertion that little run-off occurs on these soils. The large drainage reinforces that this is a very wet location where maize crops are not likely to be limited by water stress.

Another effect of the large drainage term is that it will effectively leach nitrate-N from the rooting zone. The lack of treatment effects in the second season is perhaps surprising, particularly where P-deficient crops have not fully exploited all of the applied N.

However, such behaviour is understandable in light of the predicted water balance. Table 2 shows that there is a greater residual effect from tithonia-biomass than from urea. The inference to be drawn from the water balance is that this occurs because more of the tithonia-N is present in organic form and so is protected against leaching, and will become available when it is re-mineralised in the second season.

#### Soil P

The simulated changes in labile P in the topsoil layer are shown in Figure 5. Only small changes are predicted to occur in the treatment without P addition; the small increase in labile P is due to minerali-

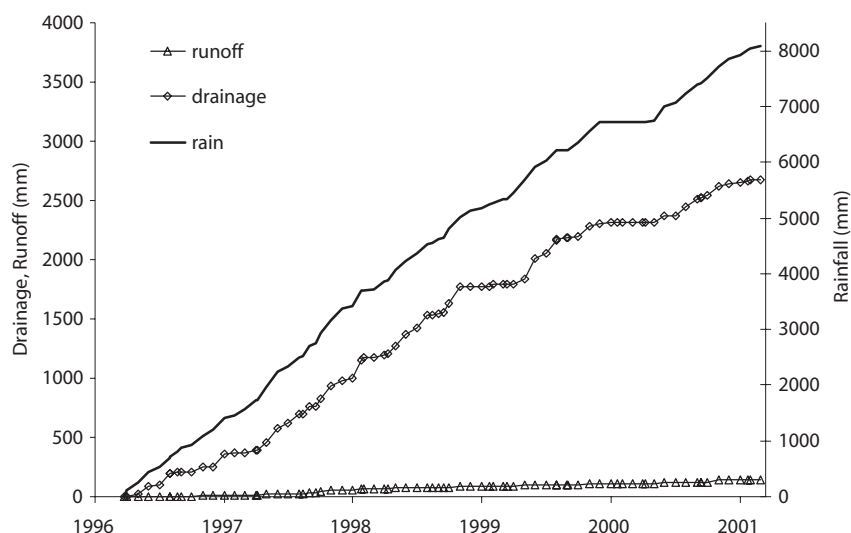


**Figure 3.** Illustration of the predicted stresses (1 – no stress, 0 – extreme stress) on the maize crops. The upper pane is for the treatment without applied P, the lower pane for the treatment with 50 kg ha<sup>-1</sup> of P applied annually. Nitrogen as urea (60 kg ha<sup>-1</sup>) was applied to only the LR crops.

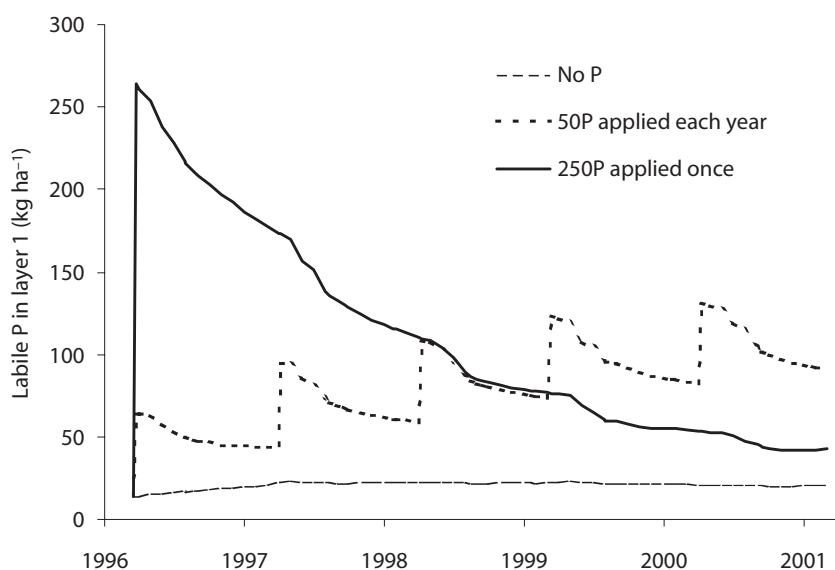
sation of soil organic matter, which is predicted to decline during the course of the experiment. It is to be noted that all above-ground crop residues were removed from the plots. The inputs of P fertiliser in 1996 result in the increase in soil P being five times larger for the one-time application. However, the processes presumed to be occurring in soil, notably the loss of availability with time, result in declining

labile P, so that by the end of the experiment the five annual applications results in higher labile P than for the one-time application. As mentioned above, some evidence to support this behaviour is found in the crop DM data.

Resin-P and bicarbonate extractable-P are generally considered to be the ‘available’ forms of P in soil. The measured data for the surface soil layer are



**Figure 4.** Cumulative rainfall and predicted drainage and run-off for the nil P treatment through the 10 seasons of the experiment. Note that rainfall is plotted on the right hand axis with a different scale to that used for drainage and run-off.



**Figure 5.** Simulated changes in labile P in the 0–15 cm layer of soil through the 10 crops for treatments that received different P treatment as specified in the legend.

**Table 3.** Measured soil P for the treatments receiving triple superphosphate (units: mg P kg<sup>-1</sup> soil). Resin- and bicarbonate extractable-P (inorganic) were determined successively on the same aliquot of soil. Values reported are averaged across the two N treatments.

Phosphorus treatment	Resin-P			Bicarb-P			Resin + Bicarb-P		
	1996	1997	2000	1996	1997	2000	1996	1997	2000
No added P	4	3	1	5	7	6	9	10	7
Annual addition (50 kg ha <sup>-1</sup> )	16	7	5	12	13	18	27	21	23
One time addition (250 kg ha <sup>-1</sup> )	28	8	4	19	22	19	47	30	23

summarised in Table 3. Conformity with the pattern of the model output is not good for either resin or bicarbonate P. However, when the two fractions are summed there is some semblance of agreement: the nil treatment changed little through time; a clear decline for the one-time application of P was measured; the pattern suggests that the soil P for the annual application will eventually exceed that for the one-time application, though it does appear that this treatment reached a plateau rather than exhibiting a regular increase as shown in the model output.

Other fractions of soil P that were measured are difficult to interpret and are not reported here. The organic-P fraction of the bicarbonate extract was unaffected by treatment or time of sampling; it averaged 26 mg P kg<sup>-1</sup> soil. Thus, for the treatment without P addition, a high proportion (~80%) of the bicarbonate extractable P was present as organic-P.

## Conclusions

The Maseno experiment was carried out in a very different environment and on a very different soil to those on which the concepts in the APSIM phosphorus routines were originally developed and tested. Notably, this is a location with high rainfall where the model predicted that water stress did not affect crop growth, and the soil, an Oxisol, has high P-sorption characteristics. The parameter set used to simulate the behaviour of P in the soil and the P concentrations and uptake by maize was that based on crops grown on a low P-sorbing soil in a semi-arid environment. The model performed creditably in predicting the growth of maize crops for the different P treatments. A second aspect of this data set was that the N inputs (applied to only the LR crops) resulted in very different crop growth between the two seasons. The predicted water, P and N stresses were informative in helping to understand the reasons for the differences

in response to the N and P inputs in the two seasons. This is the first instance where the P version of the maize model has been tested under conditions where N stress was also a factor. Output from the model suggests that simulation of crop growth with two potential limiting nutrients was sensible.

Elsewhere Olsen P data have been used for initialising the labile P of the model. Here a fractionation procedure was used for the soil P data, and labile P has been equated to the sum of the resin and bicarbonate-P fractions. The soil P data were obtained for samples taken soon after the application of the fertilisers. There was poor agreement between the predicted changes in labile P and the soil P data.

## Acknowledgments

The experiment was conducted by Bashir Jama and Roland Buresh of ICRAF, Nairobi. Obadiah Kyunguti and John Mailu are thanked for the management of the field trials.

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## 4.5

# Testing the APSIM Model with Experimental Data from the Long-term Manure Experiment at Machang'a (Embu), Kenya

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### *Abstract*

A 27 season, long-term study (1989–2002) was conducted at Machang'a, near Embu in the semi-arid lands of eastern Kenya, to assess the effect of manure application on soil nutrient status and crop productivity. The experimental treatments comprised a control (no inputs); 5 and 10 t ha<sup>-1</sup> rates of high quality manure (26% C; 2.0% N; 0.48% P) from a single source and applied annually in October; residual manure treatments where manure application ceased from 1993; and a NP fertiliser treatment on previously unfertilised plots from 1993. The data from this experiment have been used to test the performance of the Agricultural Production Systems Simulator (APSIM) in predicting the crop dry matter yield, extractable soil phosphorus and soil organic carbon on a P-deficient soil. The experiment was simulated using the APSIM P-aware maize module, even though maize was not the test crop before the November 1999 season. Agreement between model predictions and measured data was generally satisfactory for all three of the variables tested.

The APSIM modelling framework described elsewhere in these proceedings now has a capability to simulate the dynamics of phosphorus in addition to nitrogen, and the effects of both nutrients on crop growth (Probert 2004). In order to validate that the model predictions are credible, there is a need to compare the model outputs against measured data. Unfortunately, few studies have been carried out in the tropics that provide suitable data sets for such purposes.

In this paper, we describe an experiment that does provide suitable data for testing the model, and to allow comparison of the observed data with model predictions.

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## The Experiment

### Field site

The experimental site was at Machang'a, Mbeere District (0°47'S, 37°40'E; 1060 m above sea level), approximately 200 km northeast of Nairobi. The soil is a chromic Cambisol containing 56% sand, 13% silt and 31% clay, with pH (in water) 6.55 (Warren et al. 1997). These soils are deficient in nitrogen and phosphorus (Siderius and Muchena 1977; Warren et al. 1997). The site was cleared from native bush at the end of 1988 and cropping began in March 1989. There are two cropping seasons, which we identify by the month of peak rainfall; these are the 'November season' from October–January (in Kenya commonly referred to as the 'short rains') and the 'April season' from March–June (the 'long rains').

## Experimental design and treatments

The original design (Gibberd 1995) was a complete factorial of three cropping systems by three manure treatments (0, 5 and 10 t ha<sup>-1</sup>), with the manure applied annually in October. In February 1993, all plots were sampled and it was found that the different crop rotations had not caused any significant effects on soil organic C, total N, extractable P or exchangeable cations (Warren et al. 1997). Subsequently, the rotation treatments were discontinued and new treatments introduced to study residual effects of manure and the effect of fertiliser applied to every crop (Table 1). Manure and fertiliser were broadcast and incorporated during cultivation before sowing (cultivation depth 0.15 m).

The manure was acquired from a single source (Goats and Sheep Project at Marimanti, Tharaka District) where flock management remained the same throughout the experiment. Average composition of the manure (dry matter basis) was 25.6% C, 2.04% N, 0.48% P (C:N = 12.7).

## Crops and management

Before 1993, the cropping systems comprised rotations of sole legume and cereal crops and legume/cereal intercrops. The crops alternated between (i) sorghum (*Sorghum bicolor*) and cowpea (*Vigna unguiculata*), and (ii) pearl millet (*Pennisetum typhoides*) and green gram (*Vigna radiata*). After the experimental design was changed in 1993, the cropping system became sorghum/cowpea intercrop for the November season and millet/green gram intercrop for the April season, which closely follows local farming practice. Starting with the November 1999 season, all plots were cropped to maize (*Zea mays*, var. Katumani composite B) in both seasons. Sowing of all

crops was done at the start of the rains. Other agronomic practices were carried out at appropriate times using hand tools for cultivation and weeding. All plant materials except the grains were returned to the respective plots at the end of every season. The above-ground biomass was cut at ground level, residues chopped into small portions and incorporated into the soil during land preparation for the succeeding cropping seasons. Crop biophysical, soil nutrient characterisation and meteorological data were collected.

## Soil sampling and analysis

Regular sampling of the soil (0–20 cm) began in 1993. Sampling was done either in February or September, before cultivation and incorporation of residues and manure. Soil was subsampled, air-dried, ground < 2 mm sieve and analysed for: extractable P (Olsen method; 0.5 M NaHCO<sub>3</sub>, adjusted to pH 8.5); organic C by heating for 2 hours at 130–135° C with H<sub>2</sub>SO<sub>4</sub> / H<sub>3</sub>PO<sub>4</sub> / K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub> mixture (Anderson and Ingram 1993).

## Simulations

The maize module is currently the only crop module available in APSIM that is ‘P-aware’, meaning that it has the necessary routines to constrain crop growth under P-limiting conditions (Probert 2004). We have therefore simulated the whole experimental period assuming that sole maize was planted every season (sowing dates 14 October and 18 March; 4 plants m<sup>-2</sup>). Manure was applied and incorporated on 2 October each year and fertiliser applied at sowing. Cultivations before sowing incorporated all residues from the previous crop.

**Table 1.** Soil fertility treatments used in the long-term experiment at Machang’a.

Treatment	1989–1992	1993–2001
Control	None	None
A1	5 t ha <sup>-1</sup> y <sup>-1</sup> manure <sup>a</sup>	5 t ha <sup>-1</sup> y <sup>-1</sup> manure
A2	10 t ha <sup>-1</sup> y <sup>-1</sup> manure	10 t ha <sup>-1</sup> y <sup>-1</sup> manure
B1	5 t ha <sup>-1</sup> y <sup>-1</sup> manure	None
B2	10 t ha <sup>-1</sup> y <sup>-1</sup> manure	None
F	None	NPK fertiliser (51, 12, 30 kg ha <sup>-1</sup> ) every season <sup>b</sup>

<sup>a</sup> Manure applied annually in October.

<sup>b</sup> From November 1993; these rates provide same annual inputs of N and P as the 5 t ha<sup>-1</sup> manure treatment.

The simulations for each treatment were carried out as a single run, with all treatments initialised with identical inputs on 1 October 1989. Soil carbon in the surface 0–20 cm layer was based on the measured data in 1993, with an assumption that it declined in deeper layers (soil C deeper than 0.4 m was assumed not to mineralise). Soil labile P was initialised using the measured Olsen P data from the control treatment in 1993 and a factor of 2.5 to convert Olsen P (mg kg<sup>-1</sup>) to labile P (see below for discussion of the relationship between labile P as conceptualised in the model and soil P test values).

The soil profile had been sampled to determine bulk density and gravimetric soil water when dry (to estimate crop lower limit, LL) and also when wet (to estimate drained upper limit, DUL). However, using these values in the simulation tended to over-predict crop yields. The DUL values were obtained following two weeks of wet weather with 40 mm rainfall on the day before sampling. It is surmised this may have over-estimated the soil's plant available water capacity (PAWC). For the simulations shown below, smaller values of DUL have been assumed,

with the rooting depth set to 0.8 m, resulting in PAWC of 92 mm. The soil parameters used for the simulation are set out in Table 2.

## Results and Discussion

The mean annual rainfall during the experiment was 796 mm, while seasonal rainfall ranged from 100 to 1030 mm (Figure 1).

### Crop yields

In presenting the crop data, emphasis is placed on the total above-ground DM yields since this procedure offers the best chance of minimising any effects of the actual crops grown, and whether grown as sole crops or intercrops. The measured and simulated yields are shown in Figure 2.

In most seasons, observed crop growth responded strongly to inputs of manure, though there were several seasons when yields were very poor for all treatments (April 1992, 1999, 2000; November 1998). There was little difference in yields between the 5 t ha<sup>-1</sup> and 10 t ha<sup>-1</sup> rates of manure.

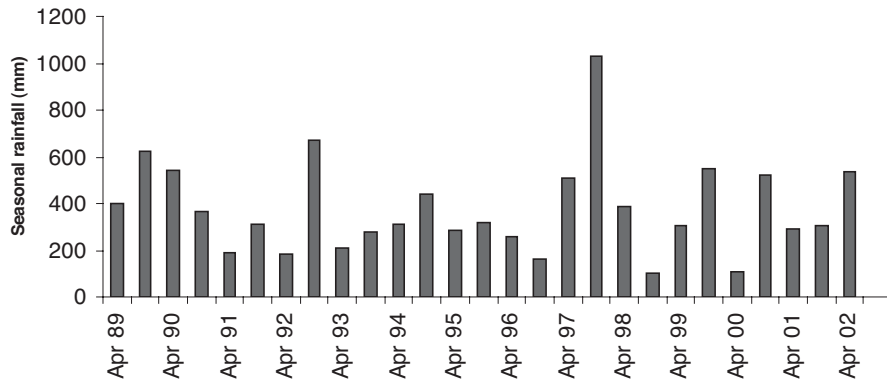
**Table 2.** Soil properties used for initialisation of the simulation of the Machang's experiment.

Layer no.	1	2	3	4	5	6
<b>SoilWat parameters<sup>a</sup></b>						
Layer thickness (mm)	200	200	200	200	200	200
Bulk density (g cm <sup>-3</sup> )	1.28	1.27	1.31	1.31	1.31	1.31
SAT	0.42	0.42	0.43	0.43	0.43	0.43
DUL	0.25	0.27	0.27	0.27	0.26	0.26
LL15	0.13	0.14	0.15	0.16	0.16	0.16
<b>Maize parameter</b>						
LLmaize	0.13	0.14	0.15	0.18		
<b>SoilN parameters</b>						
organic C (%)	0.59	0.50	0.40	0.38	0.36	0.36
finert <sup>b</sup>	0.50	0.90	0.99	0.99	0.99	0.99
fbiom	0.02	0.015	0.01	0.01	0.01	0.01
nitrate-N (mg kg <sup>-1</sup> )	1.25	0.75	0.5	0.5	0.5	0.5
ammonium-N (mg kg <sup>-1</sup> )	0.8	0.35	0.2	0.2	0.2	0.2
<b>SoilP parameters</b>						
labile P (mg kg <sup>-1</sup> )	2.5	2.5	1.0	0.8	0.5	0.5
P sorption (mg kg <sup>-1</sup> ) <sup>c</sup>	94	200	200	200	200	200

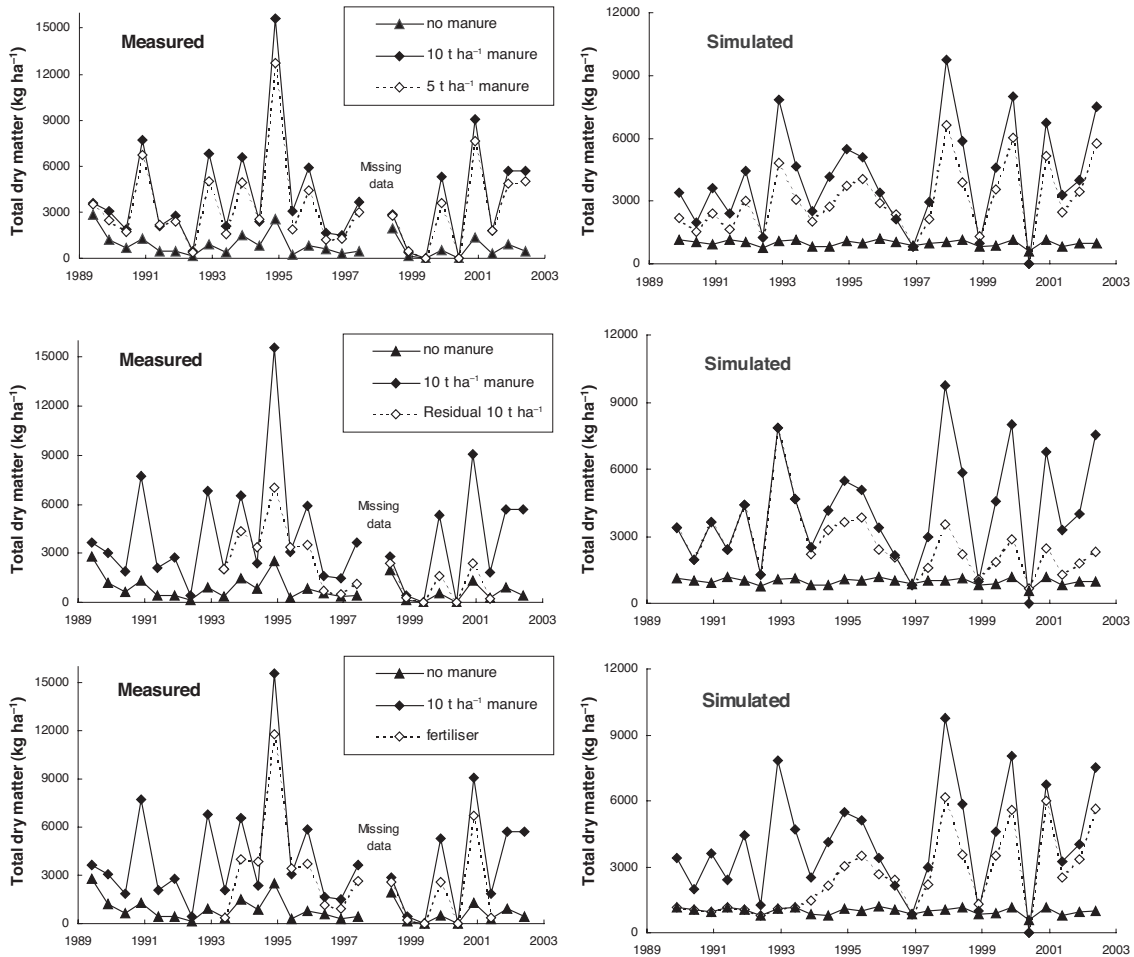
<sup>a</sup> The soil water balance is described in terms of the volumetric water content at saturation (SAT), drained upper limit (DUL), and lower limit of extraction by the crop (LL); BD is soil bulk density; SWCON is the proportion of water in excess of DUL that drains in 1 day.

<sup>b</sup> finert is the proportion of soil carbon assumed not to decompose; fbiom is the proportion of decomposable soil carbon in the more labile soil organic matter pool.

<sup>c</sup> P sorbed at 0.2 mg L<sup>-1</sup> in solution.



**Figure 1.** Total rainfall for the ‘April’ (March–June) and ‘November’ (October–January) seasons at the site during the experiment.



**Figure 2.** A comparison of the measured and predicted dry matter yields during the experiment. The measured data are in the left-hand panes, the corresponding simulated results in the right-hand panes. The top panes show the treatments that received 0, 5 or 10 t ha<sup>-1</sup> of manure; beneath are shown the effects of the 10 t ha<sup>-1</sup> residual treatment (application ceased from 1993) and the NP fertiliser treatment (began 1993) with the 0 and 10 t ha<sup>-1</sup> of manure treatments repeated for scaling purposes.



After manure application ceased from 1993, the residual effect from manure declined and yields were only marginally better than the control in the later years of the experiment. Fertiliser application commencing from the November 1993 season increased yields to levels similar to those of the manure treatments.

This overall pattern in the observed yield data was captured reasonably well by the model. In particular, there was conformity in terms of: (i) the yields for the no-manure treatment were typically 1–2 t ha<sup>-1</sup> though, in contrast to the observed data, the simulated yields exhibited much less season-to-season variation and were never close to zero; (ii) yields with manure were 3–8 t ha<sup>-1</sup> with only small differences between the 5 and 10 t ha<sup>-1</sup> rates of manure; (iii) the declining effect from the residual manure treatment; (iv) the response to the fertiliser treatment; (v) crop failures in April 1992, 2000 and November 1996, 1998 seasons when yield for treatments with nutrient input was similar to the no-manure treatment. The largest discrepancy is for the November 1994 season when observed yields of sorghum for all treatments were unaccountably high. The model output permits examination of the stresses (water, N or P) that were limiting to growth.

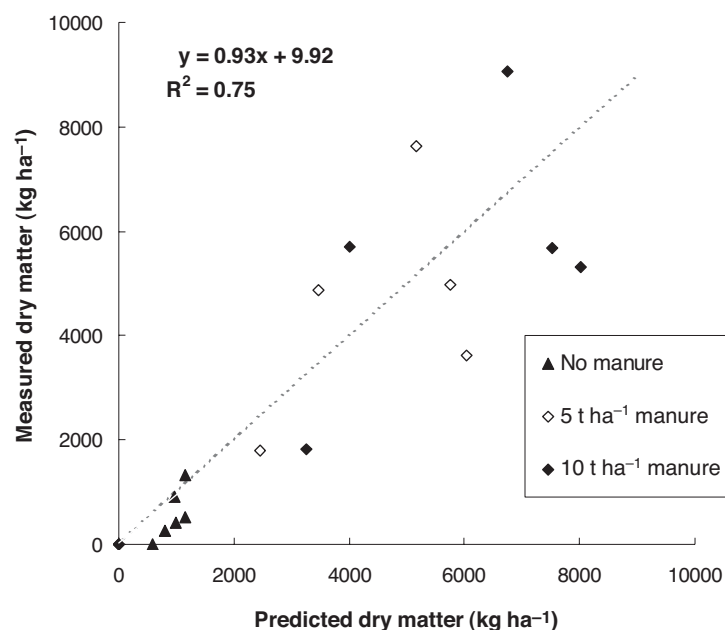
For the control treatment, the dominant nutrient stress in all seasons was predicted to be due to P (data not shown).

The agreement between measured and predicted DM yields displayed in Figure 2 is despite the fact that the maize model is being used for the simulation when other crops were grown. From the November 1999 season this was no longer the case, with maize being grown. Figure 3 summarises the results for these crops. The correlation between observed and predicted yield is high and without any obvious bias.

#### Soil P

The frequent sampling and analysis for extractable P provides an opportunity to test another component of the model, namely the predicted changes in labile P through time and in response to inputs of P as fertiliser or manure. Conceptually, labile P as defined in the model does not equate directly to any soil P test (Probert 2004). However, it might be expected that, on a given soil, labile P would be proportional to some suitable soil test, so that the soil test values become the means of initialising the model and of testing the sensibleness of the output.

The simulated labile P (expressed as kg ha<sup>-1</sup>) is compared with the measured Olsen P (mg kg<sup>-1</sup>) in



**Figure 3.** Comparison of measured and predicted dry matter yields of maize for seasons from November 1999. The dashed line is the 1:1 relationship. The fitted linear regression equation and correlation coefficient are given in the figure.

Figure 4. In these graphs, note that the proportionality between the two variates is the same for all of the treatments. For the control treatment, there is little change in P status during the experiment. The trends in the Olsen P data are well matched by the model for the 10 t ha<sup>-1</sup> manure treatment and the fertiliser treatment (though with much greater variability in the Olsen P data for the manure input). For the 5 t ha<sup>-1</sup> manure treatment the model over-predicts the Olsen P data, while for the residual treatment the measured Olsen P data decline more rapidly than the simulated labile P.

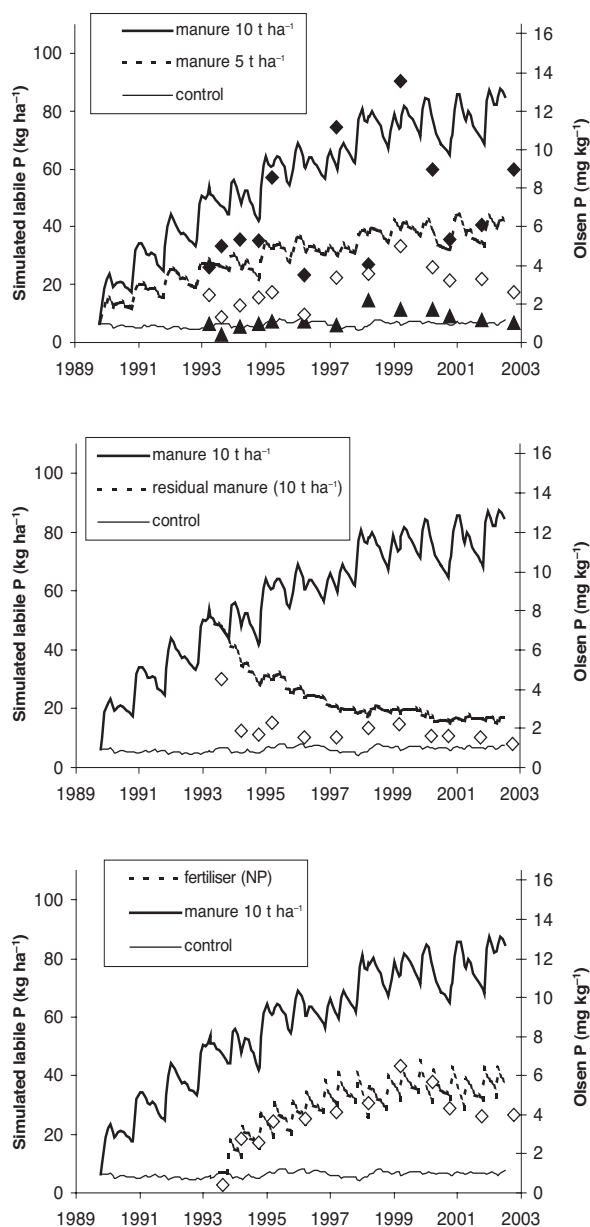
As presented in Figure 4, the factor between labile P and Olsen P, when adjusted for units, is approximately 2.5, which is the justification for how the labile P pool was initialised for the simulations.

### Soil carbon

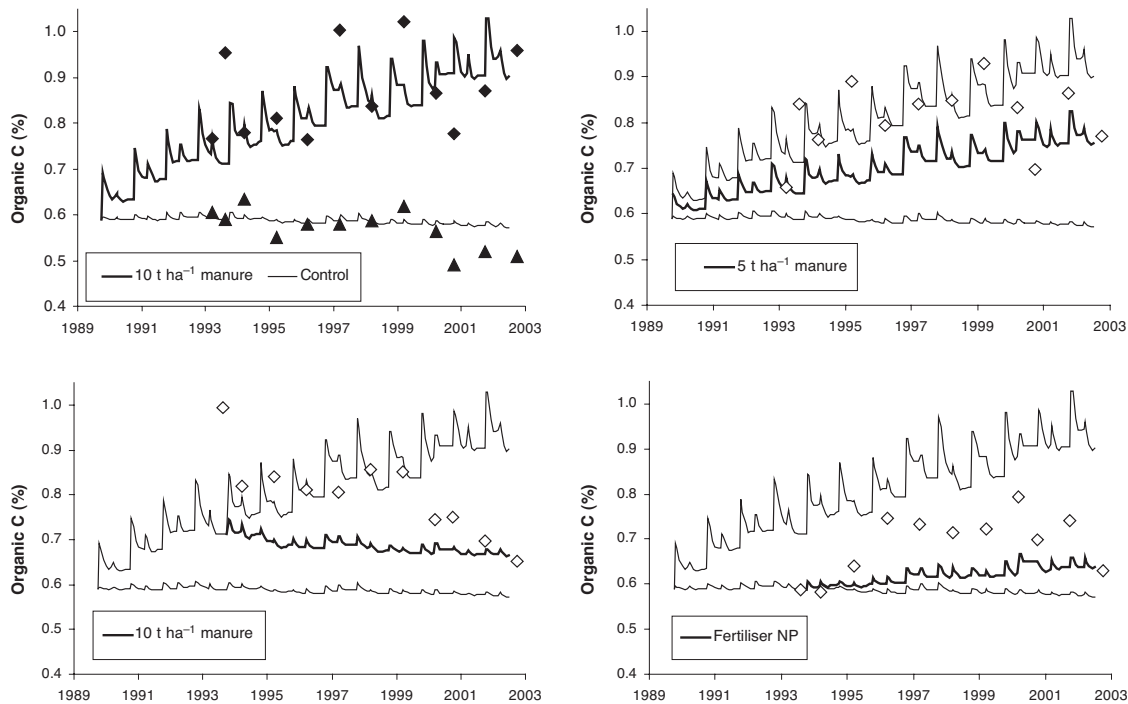
The simulated and measured soil organic C data are displayed in Figure 5. The agreement looks particularly good for the two treatments that differ most in soil C, and the model simulated well the difference that evolved between the control and 10 t ha<sup>-1</sup> manure treatment. For the other treatments the agreement is less impressive, though the direction of the trends is well captured by the model. The measured difference in soil C between the 5 and 10 t ha<sup>-1</sup> manure treatments was less than predicted. Also, the measured decline in soil C after manure application ceased was less rapid than predicted by the model, though there was close agreement at the end of the experimental period in 2002. For the fertiliser treatment, the model agreed with the measured data in that soil C increased compared with the control, but the increase was under-predicted. The change in soil C in the fertiliser treatment must occur as a result of greater crop growth and thus higher returns of crop residues and roots, since there are no direct inputs of C associated with this treatment.

## Conclusions

The Machang'a experiment is a long-term experiment, on a P and N-responsive site. The experiment has studied the response of crop growth to inputs of nutrients as manure and fertiliser. Furthermore, it has documented the changes in the soil organic C and Olsen P as well as crop yields. The results of the experiment therefore provide a valuable data set against which several aspects of the APSIM model can be tested.



**Figure 4.** Comparison of simulated labile P (lines) in the surface 0–20 cm layer with the measured Olsen P data (symbols). Note that the two variates are plotted on different scales, but the proportionality between them is identical in the three panes. The top pane shows the 0 (▲), 5 (◇) and 10 (◆) t ha<sup>-1</sup> of manure treatments; the lower panes show the residual 10 t ha<sup>-1</sup> of manure treatment and the NP fertiliser treatments with the simulations for 0 and 10 t ha<sup>-1</sup> of manure treatments repeated for scaling purposes.



**Figure 5.** Comparison of simulated soil organic C (lines) in the surface 0–20 cm layer with the measured data (symbols). The top-left-hand pane shows the 0 and 10 t ha<sup>-1</sup> of manure treatments; in the other panes the simulated results for these treatments are repeated (for scaling purposes) together with the simulations and measured data for the 5 t ha<sup>-1</sup> of manure treatment, the residual 10 t ha<sup>-1</sup> of manure treatment, and the NP fertiliser treatment.

The manure source used in the experiment was from a single source throughout the experiment, and was of high quality and therefore may be expected to be a good source of N and P.

The model performance was tested in terms of:

1. *Dry matter yields.* To model the experiment, it was necessary to use the APSIM maize module as a surrogate for other crops that were grown in the early years of the experiment. In recognition of this, we have focused only on the dry matter production. It would be inappropriate to dwell on discrepancies between the observed and predicted yields; rather the focus should be on the ability of the model to capture the trends. The model captured reasonably well the patterns and trends due to treatments and seasons. For the most recent seasons, when maize was the test crop, there was close agreement between observed and predicted yields.

An issue that arises in the interpretation of the output of the model is whether P or water stress is the factor determining growth. For the seasons where there was no difference in yield between the different treatments, it seems probable that water was the lim-

iting factor. This is supported by the low rainfall in these seasons, as shown in Figure 1. However, in the model, P uptake is very dependent on soil water content, so that in these dry seasons the model predicts that P uptake is impaired and P stress becomes important for crop growth. Further testing of the model to explore this matter would require experimental data for a range of P treatments.

2. *Soil P.* The pattern of labile P simulated in the model was very similar to that of Olsen P. On this soil type, the proportionality between Olsen P and labile P (as simulated) was found to be approximately 2.5.

3. *Organic carbon.* The model predicted well the difference between the treatments with and without manure. Other aspects of the simulated soil C, such as the difference between the 5 and 10 t ha<sup>-1</sup> manure treatment, the decline of soil C in the residual manure treatment, and the magnitude of the increase in soil C when fertiliser was applied, were not so well predicted.

The conformity between simulated and measured data for the crop biomass and soil properties is

encouraging. A fuller test of the model's capability to simulate grain yields under P-limiting conditions requires P-aware versions of APSIM modules for the different crops.

## **Acknowledgments**

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## 4.6

# Evaluation of APSIM to Simulate Plant Growth Response to Applications of Organic and Inorganic N and P on an Alfisol and Vertisol in India

J.P. Dimes\* and S. Revanuru†

### *Abstract*

Field experiments in India examined the response of sorghum and pigeonpea to inputs of low and high quality manures on N and P-responsive alfisol and vertisol soils. A special feature of the work was that inorganic fertiliser treatments were included to help quantify the cereal and legume responses to the N and P content of the manure. This paper provides a brief overview of the Indian experiments and results, and reports on the performance of APSIM to simulate aspects of the observed legume and cereal crop responses to N and P inputs, and the residual legume benefits to a following cereal. For this preliminary evaluation, the model performed poorly in simulating the observed P response of the cereal (sorghum) at low N levels. However, further modifications to input parameters for the P model, especially in relation to P supply and uptake for deeper soil layers, may improve the fit between observed and predicted results. In contrast, APSIM performed well in predicting the growth of pigeonpea well supplied with P, and the residual N benefits to a following cereal crop, including the response to additional inputs of N fertiliser.

Manures can contain appreciable amounts of P as well as N. In some instances, P is an additional, and sometimes greater, constraint to crop growth than N in low-input farming systems. With the generally low N content of manures found in smallholder farming systems (Motavalli and Anders 1991; Probert et al. 1995; Mugwira and Murwira 1997), questions arise as to whether a farmer would get a higher return from application of manure to a legume crop instead of a cereal, and to what degree is the residual N benefit of the legume to the following cereal crop enhanced by the legume responding to the applied manure?

Experimentation in India has examined these two questions for the case of low and high-quality manures applied to sorghum and pigeonpea crops grown on alfisol and vertisol soils (Revanuru 2002). A special feature of this work is that inorganic fertiliser treatments were included to help quantify the cereal and legume responses to the N and P content of the manure. Another is that monitoring of the experiments was quite extensive and many of the input parameters for simulation were known, especially for the soil and manure characterisation.

The data set was thought ideal for evaluating the performance of APSIM and its new modules, SoilP and Manure, to simulate the complex of climate, soil and plant interactions and effects on crop growth and yield. A complication, however, is that currently only the APSIM Maize module is able to respond to low soil P conditions to simulate P stress on plant growth (Probert 2004). Nevertheless, it was felt that

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the simulated total biomass response of APSIM Maize could be used as a surrogate for the observed sorghum responses. Within APSIM, the maize and sorghum models are based on a common crop template and share the same routines for interacting with the soil water and nutrient (N and P) modules to supply growth demand.

This paper provides a brief overview of the Indian experiments and results, and reports on the performance of APSIM to simulate aspects of the observed legume and cereal crop responses to N and P inputs, and the residual legume benefits to a following cereal crop.

## Materials and Methods

### Field experiments

Experiments were conducted at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh, in southern India (17.5°N, 78.3°E, 545 m above sea level) during the kharif (rainy) and rabi (dry) seasons of 1998. The experiments were conducted on two soils: an alfisol (Udic Rhodustalf) and a vertisol (Typic Pellustert).

### Manure

Manure used in the experiments was collected from the bullock shed on the ICRISAT farm and from a local supplier in a nearby village. Manure was applied (11 June) to treatment plots on a fresh weight basis (10 t ha<sup>-1</sup>). Dry weights and chemical characteristics of the manures applied are shown in Table 1. For the purpose of this paper, the two manures are referred to as high quality (HQM – narrow C:N, high P, from bullock shed) and low quality (LQM – wide C:N, low P, from village supplier).

## Experimental design and treatments

Experiments investigated sorghum (*Sorghum bicolor*) and pigeonpea (*Cajanus cajan*) response to inputs of manure and fertiliser N and P on the two soils. For each crop, a split-plot design was implemented with soil type as main plots and nutrient treatments as sub-plots. For sorghum, there were six nutrient treatments: control, LQM, HQM, single superphosphate fertiliser at 20 kg P ha<sup>-1</sup> (P20), ammonium nitrate fertiliser at 80 kg N ha<sup>-1</sup> (N80), and N and P fertiliser at 80 kg N and 20 kg P ha<sup>-1</sup> (N×P) with six replicates. For pigeonpea there were four treatments: control, LQM, HQM and P20 with three replicates.

### Management

Fallow pastures that preceded the experiments were incorporated in early May 1998. Extra-short duration pigeonpea, cultivar ICPL 88039, was planted (alfisol – 20 June, vertisol – 23 June) on 60 cm ridge spacing. Sorghum hybrid, CSH 9, was planted (alfisol – 20 June, vertisol – 23 June, both re-sown on 29 June) on similar ridges. Pigeonpea and sorghum plots were treated with pre-emergence herbicides and hand weeded twice during the season. During excessively wet conditions, pigeonpea plots were drenched to combat blight. Application of P fertiliser was banded at sowing, whereas application of N fertiliser was split; 40 kg N ha<sup>-1</sup> banded at sowing and 20 kg N ha<sup>-1</sup> side-banded at 30 and 60 days after sowing. Three irrigations were applied to help crop emergence and establishment.

Following harvest of grain and removal of stalks, kharif pigeonpea plots were planted with a medium duration sorghum variety, Maldandi-35-1 (9 November, both soils). The treatment plots were further subdivided into three sub-plots to accommodate three N levels (0, 40 and 80 kg N ha<sup>-1</sup>) applied

**Table 1.** Nutrient content and application rates of manures applied to pigeonpea and sorghum at the start of the 1998 kharif season, at ICRISAT, Patancheru, India.

Manure type	%C	%N	%P	C:N	Dry weight applied (kg ha <sup>-1</sup> )	N applied kg ha <sup>-1</sup>	P applied kg ha <sup>-1</sup>	C applied kg ha <sup>-1</sup>
LQM <sup>a</sup>	25.3	0.7	0.3	35.0	2350	16.9	11.6	848.4
HQM	16.3	0.8	0.6	22.0	2870	21.7	17.3	469.1

<sup>a</sup> LQM, low quality manure; HQM, high quality manure.

to the following sorghum crop. Application of N fertiliser was split; 40 kg N ha<sup>-1</sup> side-banded at 14 and 37 days after sowing. The rabi sorghum was irrigated throughout the crop cycle.

## Measurements and analysis

Soil and manure samples were analysed for per cent organic carbon (OC) (Walkley and Black 1934), total N (Keeney and Nelson 1982), total P (Tandon et al. 1962), mineral N (Keeney and Nelson 1982) and extractable P (Olsen and Sommers 1982). Soils layers were sampled to 90 cm for the alfisol and 150 cm for the vertisol. Gravimetric water content of soil layers was monitored regularly throughout the kharif and rabi crop cycle for each experiment. Total plant biomass was harvested at maturity. Meteorological data were collected at the ICRISAT weather station. Treatment differences were analysed using ANOVA for a split-plot design.

## Simulations

### Soil descriptions

Soil parameters and initial conditions used to simulate experiments on the two soils are set out in Tables 2 and 3. Analysis of the gravimetric moisture determinations taken throughout the kharif and rabi crops provided estimates for the crop lower limit and the drained upper limit water contents in layers for each soil. Concentrations of OC, and NO<sub>3</sub>-N and the amounts of soil water were measured. Bulk density and NH<sub>4</sub>-N values were estimated. P sorption characteristics for surface layers were known (Sahrawat and Warren 1989), data for the other layers were estimates. Finert values (stable SOM not contributing to mineral N supply) have been set using %OC in the bottom layer as a guide and based on experience in setting this parameter (Probert et al. 1998b).

High atmospheric N contributions to the crop–soil budget have been reported for the Patancheru environment (up to 12 kg N ha<sup>-1</sup> year<sup>-1</sup> in rainfall (Murthy et al. 2000)), resulting in unexpectedly high biomass yields on the N impoverished soils. To increase the soil N supply and include the effects of N additions from the atmosphere, labile N (*f\_biom*) in the soil surface layer was adjusted upwards until there was agreement between simulated and measured biomass yield for the control treatments. Simi-

larly, labile P values in Tables 2 and 3 were calibrated for the two soils, to give reasonable prediction of observed yields in the presence of adequate N.

### Kharif sorghum (maize)

Simulation of the kharif experiment began on 11 June 1998, which coincided with application of the manure treatments. The applied manure was fully incorporated into the surface soil layer. A maize planting was simulated on 29 June (the re-sowing date for both soils, see Management above), with plant population set to 10 plants m<sup>-2</sup> (the observed plant stand at harvest, both soils). Crop parameters for maize cultivar Hybrid 614 were found to best approximate the duration of the kharif sorghum crop. Fertiliser applications were made on 21 June (P20 banded and 40N), 21 July (20N) and 3 Sept (20N). Irrigation was applied on 29 June (63 mm), 1 July (63 mm) and 13 July (50 mm). To assess model predictions, simulated maize biomass was compared with the observed total biomass of kharif sorghum.

### Pigeonpea–sorghum (maize) sequence

Pigeonpea–maize sequences for the kharif–rabi seasons were simulated for each soil using the data in Tables 2 and 3, except in this case it was assumed that there was no P constraint. Simulations began on 11 June 11 and an extra short duration pigeonpea was planted on 20 June, with a population of 33 plants m<sup>-2</sup>. After grain harvest, removal of pigeonpea stover was simulated on 4 November. Maize cultivar Hybrid 511 was planted on 9 November with a population of 13.8 plants m<sup>-2</sup> for the alfisol, and 14.7 for the vertisol. Three N fertiliser treatments for the rabi maize were simulated; 0, 40 and 80 kg N ha<sup>-1</sup>, with fertiliser applied as per the experimental details described above for rabi sorghum. A total of 260 mm of irrigation was applied for the simulated rabi crop. To assess model predictions for pigeonpea, simulated biomass is compared to observed biomass from the P20 treatment (i.e. adequate P conditions). To assess simulation of maize response in the rabi following pigeonpea, simulated biomass is compared to observed biomass for rabi sorghum following pigeonpea receiving 20 kg P ha<sup>-1</sup> in the kharif season.

**Table 2.** Soil properties and initial conditions for simulation of the alfisol experiments at ICRISAT, Patancheru, India. C:N ratio for all layers was 8.6.

Layer no.	1	2	3	4	5
<b>SoilWat parameters<sup>a</sup></b>					
Layer thickness (mm)	150	150	300	300	300
Bulk density (g cm <sup>-3</sup> )	1.50	1.45	1.40	1.40	1.40
SAT	0.36	0.40	0.42	0.42	0.42
DUL	0.21	0.21	0.23	0.23	0.24
LL15	0.09	0.09	0.11	0.14	0.18
Soil water	0.09	0.09	0.11	0.14	0.18
<b>SoilN parameters</b>					
Organic C (%)	0.57	0.42	0.31	0.24	0.18
Finert <sup>b</sup>	0.35	0.47	0.52	0.62	0.74
Fbiom	0.04	0.020	0.015	0.01	0.01
Nitrate-N (mg kg <sup>-1</sup> )	1.60	1.40	1.80	1.30	1.00
Ammonium-N (mg kg <sup>-1</sup> )	0.50	0.10	0.10	0.10	0.10
<b>SoilP parameters</b>					
Labile P (mg kg <sup>-1</sup> )	10	10	10	10	10
P sorption (mg kg <sup>-1</sup> ) <sup>c</sup>	30	60	100	150	200

<sup>a</sup> The soil water balance is described in terms of the volumetric water content at saturation (SAT), drained upper limit (DUL), and lower limit of extraction by the crop (LL).

<sup>b</sup> Finert is the proportion of soil carbon assumed not to decompose; Fbiom is the proportion of decomposable soil carbon in the more labile soil organic matter pool.

<sup>c</sup> P sorbed at 0.2 mg L<sup>-1</sup> in solution.

**Table 3.** Soil properties and initial conditions for simulation of the vertisol experiments at ICRISAT, Patancheru, India. C:N ratio for all layers was set at 12.

Layer no.	1	2	3	4	5	6
<b>SoilWat parameters<sup>a</sup></b>						
Layer thickness (mm)	150	150	300	300	300	300
Bulk density (g cm <sup>-3</sup> )	1.00	1.10	1.20	1.20	1.20	1.20
SAT	0.55	0.54	0.50	0.50	0.50	0.50
DUL	0.37	0.37	0.42	0.42	0.46	0.46
LL15	0.17	0.23	0.29	0.32	0.37	0.41
Soil water	0.12	0.27	0.34	0.38	0.41	0.41
<b>SoilN parameters</b>						
Organic C (%)	0.57	0.47	0.43	0.37	0.19	0.17
Finert <sup>b</sup>	0.31	0.37	0.50	0.62	0.74	0.83
Fbiom	0.04	0.02	0.015	0.01	0.01	0.04
Nitrate-N (mg kg <sup>-1</sup> )	3.00	2.00	1.50	1.30	1.00	1.00
Ammonium-N (mg kg <sup>-1</sup> )	0.50	0.10	0.10	0.10	0.10	0.10
<b>SoilP parameters</b>						
Labile P (mg kg <sup>-1</sup> )	6.0	5.0	4.0	3.0	2.0	1.0
P sorption (mg kg <sup>-1</sup> ) <sup>c</sup>	50	100	100	100	100	100

<sup>a</sup> The soil water balance is described in terms of the volumetric water content at saturation (SAT), drained upper limit (DUL), and lower limit of extraction by the crop (LL).

<sup>b</sup> Finert is the proportion of soil carbon assumed not to decompose; Fbiom is the proportion of decomposable soil carbon in the more labile soil organic matter pool.

<sup>c</sup> sorbed at 0.2 mg L<sup>-1</sup> in solution.



## Results

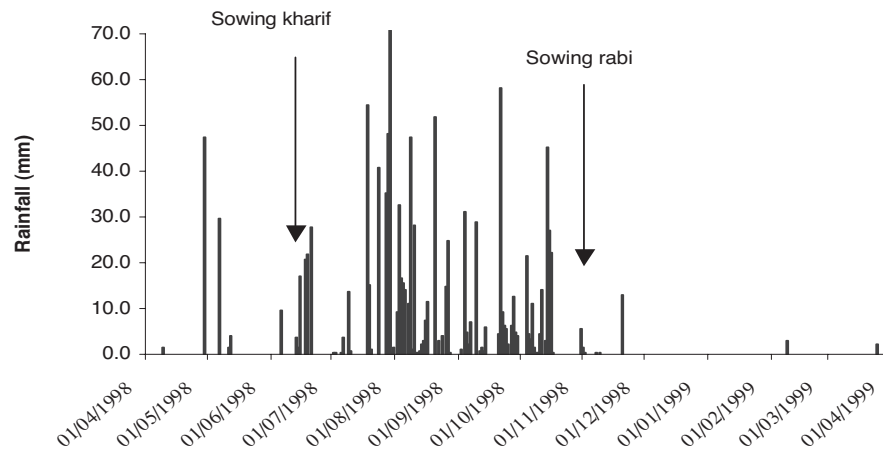
In-crop rainfall (980 mm) for the kharif (Figure 1) exceeded the long-term annual rainfall (899 mm) and waterlogging was observed in both soils for pigeonpea plots. There was little rainfall during the rabi crops, which were grown under irrigation.

### Sorghum experiments

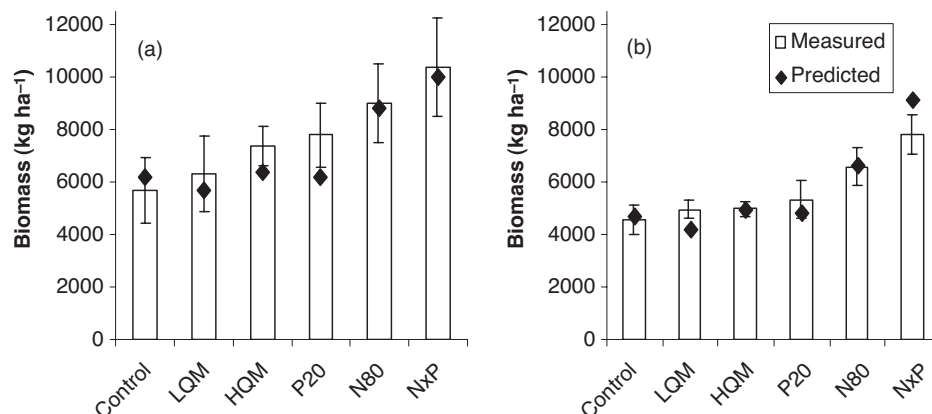
The simulated and observed biomass responses of kharif sorghum crops on alfisol and vertisol soils are shown in Figure 2. Observed biomass responses on the alfisol were significantly ( $p < 0.05$ ) greater than those on the vertisol. For the alfisol, biomass yields for the manure and fertiliser treatments are signifi-

cantly ( $p < 0.05$ ) higher than the control. In contrast, only the fertiliser treatments provided statistically significant responses on the vertisol. Results for both soils show a stronger response to N fertiliser (N80) than to P fertiliser ( $p < 0.05$ ) and an increased N response ( $p < 0.05$ ) in the presence of P (N  $\times$  P treatment).

The simulated trends in Figure 2 are less responsive, with almost no change in predicted yields for the application of manures or inorganic P on either soil. In fact, simulated biomass yields with addition of LQM are lower than that simulated for the control on each soil, indicating that the model simulated net immobilisation and a reduced N supply for crop growth with the addition of the LQM. Simulated



**Figure 1.** Rainfall during the kharif and rabi seasons in 1998 at Patancheru, India. Sowing of kharif and rabi crops shown by arrows.



**Figure 2.** Measured (sorghum, bar) and simulated (maize, symbols) total crop biomass for kharif crops on (a) alfisol and (b) vertisol in response to low (LQM) and high (HQM) quality manure, fertiliser P (P20), fertiliser N (N80) and fertiliser N and P (N  $\times$  P). Error bars are standard deviations of treatment means.

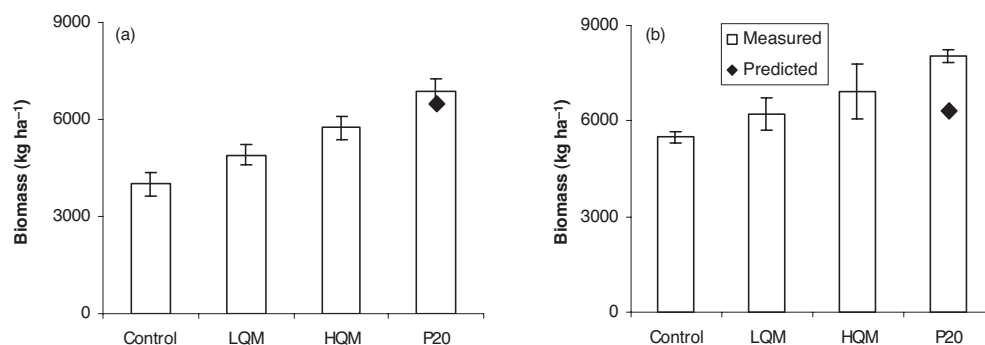
responses to application of fertiliser N on both soils and N+P for the alfisol are close to the observed responses, but there is a large over-prediction for the N+P treatment on the vertisol. What the model was able to simulate reasonably well were the differences in biomass yields between soils.

### Pigeonpea–Sorghum

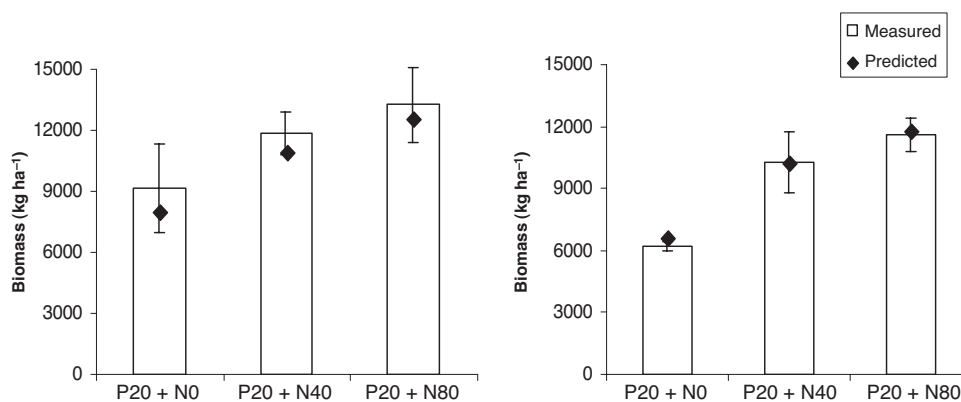
Observed responses of pigeonpea to manures and fertiliser P in the kharif are shown in Figure 3. In the case of pigeonpea, biomass yields are significantly higher ( $p < 0.05$ ) for the vertisol than for the alfisol. There are significant ( $p < 0.05$ ) increases in biomass response of pigeonpea to the three nutrient treatments (LQM, HQM and P20) compared with the control, and between the nutrient treatments, indicating that pigeonpea responded to the different

levels of P input (12, 17 and 20 kg P ha<sup>-1</sup>) and its availability.

As APSIM–Pigeonpea is not ‘P-aware’, simulated biomass can be compared only for the situation where P nutrition can be assumed adequate, in this case the P20 treatment. In Figure 3, simulated biomass of pigeonpea for the alfisol compares well with observed yield, but for the vertisol, the simulated yield is actually less than that for the alfisol, and substantially less than the observed. The Pigeonpea model used here (APSIM Version 1.61) has routines to simulate waterlogging stress on plant growth, and over-prediction of this stress seems to be responsible for simulation of the lower yield on the vertisol. For the vertisol, 87% of crop days are simulated to have profile water contents indicative of saturation, whereas for the alfisol it is less than 50% of days.



**Figure 3.** Measured (bar) and simulated (◆) total crop biomass for pigeonpea crops on (a) alfisol and (b) vertisol in response to low (LQM) and high (HQM) quality manure and fertiliser P (P20). Error bars are standard deviations of treatment means.



**Figure 4.** Measured (sorghum, bar) and simulated (maize, ◆) total crop biomass for rabi crops on (a) alfisol and (b) vertisol following kharif pigeonpea (fertilised with 20 kg P ha<sup>-1</sup>). Rabi crops received zero (P20+N0), 40 (P20+N40) and 80 (P20+N80) kg N ha<sup>-1</sup>. Error bars are standard deviations of treatment means.

The pigeonpea–maize sequence provides an assessment of how well the systems model is able to simulate the combined effects of organic and inorganic N supply. Figure 4 shows the observed and predicted biomass yield of the rabi cereal crops planted following pigeonpea (fertilised with P20) and receiving three rates of N fertiliser. From the observed responses to fertiliser N, it is clear that the preceding pigeonpea was unable to supply all of the rabi crop N requirements on either soil.

The model was able to predict very closely the observed biomass responses for the respective soils along with the response to N fertiliser inputs on each soil (Figure 4). It should be noted that, for both the simulated and observed rabi crops, all above-ground biomass from the preceding pigeonpea was removed, and the carryover of N from the kharif legume is via the pigeonpea root system and detached leaf material. Hence, results in Figure 4 suggest that the system model is able to simulate these residual organic N benefits, and interaction with inorganic N, with a high degree of accuracy.

## Discussion

The measured yield responses for the legume and cereal crops in these experiments clearly indicate P and N responsive soils. However, the results of simulation of the observed P responses and interaction with N supply in the kharif cereal crop were disappointing, showing no sensitivity to inputs of organic or inorganic P at low N levels (i.e. LQM, HQM and P20 treatments). Application of APSIM to simulate the Indian data is one of the earliest attempts at using the new P capabilities on an independent data set. Results achieved here undoubtedly reflect a measure of inexperience with parameterising this new model.

Probert (2004) has suggested that the difficulty in parameterising the model is largely associated with specifying the P status in terms of P sorption and labile P in each soil layer. Further exploratory modifications to input parameters are no doubt warranted, especially in terms of the proportionality factor between measured Olsen P and labile P (Micheni et al. 2004) and how this may need to vary between soils, and perhaps with soil depth. Another parameter that may warrant attention is the P uptake factor that Probert (2004) suggests is crop and cultivar dependent. In this analysis, the *p\_supply\_factor* was set to 3.

However, the main concern with the model is the insensitivity of plant response to P inputs at the low N levels. Part of this problem is perhaps attributable to the calibration process used for labile P. For the kharif crop responses used in this study, moisture stress, at least due to deficits, can be discounted. Hence, the results suggest further testing of the model is required for conditions where both N and P are limiting plant growth. The ideal data set would have crop growth response to each element quantified in the presence of adequate levels of the other, in addition to limiting levels of both. This would help eliminate some of the calibration problems encountered in this current study.

The APSIM–Pigeonpea model (Robertson et al. 2001) is also relatively untested against observed growth responses in the field. While the P effects on pigeonpea growth in these experiments cannot be considered at this time, simulation of the P20 treatment for the two soils provided some useful insights. Clearly, the waterlogging stress routines in Pigeonpea and the soil drainage parameters for the vertisol warrants closer consideration. The close agreement between observed and predicted biomass at zero N for the rabi cereal crop (Figure 4) suggests that the model captures very well the key components contributing to enhanced soil N supply following a legume, in this case simulation of leaf senescence and detachment and residual root biomass of the pigeonpea.

In the past, APSIM has been shown to perform well in simulating mineral N supply following organic inputs (Probert et al. 1998b) and crop response to inorganic and organic N, including legume–cereal rotations (Probert et al. 1998a; Shamuazarira et al. 2000). Simulation of the pigeonpea–maize sequence in this study has extended evaluation to a tropical legume species and for two of the important soil types in semi-arid agricultural systems. The study has also highlighted the need to extend the P stress routines to other cereal and legume crops commonly grown by smallholder farmers in the tropics.

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## 4.7

# Soil Phosphorus Dynamics, Acquisition and Cycling in Crop–Pasture–Fallow Systems in Low Fertility Tropical Soils: a Review from Latin America

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A. Oberson¶ and B.R. Singh\*\*

### *Abstract*

Knowledge of the phosphorus (P) dynamics in the soil–plant system, and especially of the short- and long-term fate of P fertiliser in relation to different management practices, is essential for the sustainable management of tropical agroecosystems. A series of field trials was conducted in the tropical savannas and Andean hillsides in Colombia to follow the dynamics of P under different management systems. In tropical savannas in the Llanos of Colombia, in cereal–legume rotations (maize–soybean or rice–cowpea) and ley pasture systems, measurements of soil P fractions indicated that applied P moves preferentially into labile inorganic P pools, and then only slowly via biomass production and microbes into organic P pools under both introduced pastures and crop rotations. Field studies conducted to quantify the residual effectiveness of P fertiliser inputs in crop rotations in terms of both crop growth response and labile P pool sizes, indicated that soluble P applications to oxisols of Colombia remain available for periods that are much longer than expected for ‘high P-fixing’ soils, such as the oxisols of Brazilian Cerrados. In Andean hillsides of Colombia, the impact of short-term planted fallows to restore soil fertility in N and P-deficient soils by enhancing nutrient recycling through the provision of organic matter, was investigated. Results indicated that the fractionation of soil organic matter and soil P could be more effective for detecting the impact of planted fallows on improving soil fertility than the conventional soil analysis methods. Litterbag field studies contributed to characterisation of the rate of decomposition and nutrient release from green manures and organic materials that could serve as biofertilisers. The data sets from these field and greenhouse studies are valuable for further testing and validation of APSIM.

Phosphorus (P) deficiency is a widespread nutrient constraint to crop production on tropical and subtropical soils and it affects an area estimated at over  $2 \times 10^9$  hectares (Fairhurst et al. 1999). However, for most resource-poor farmers in developing countries, correcting soil P deficiency with large applications of

P fertiliser is not a viable option. Furthermore, the inexpensive rock phosphate reserves remaining in the world could be depleted in as little as 60–80 years (Runge-Metzger 1995). Therefore, sustainable P management in agriculture requires additional information on the mechanisms in plants that enhance P

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acquisition in order to make plants more efficient at acquiring P, development of P efficient germplasm, and advanced crop management schemes that increase soil P availability (Rao et al. 1999a; Vance 2001).

Knowledge of the P dynamics in the soil–plant system, and especially of the short and long-term fate of P fertiliser in relation to different management practices, is essential for the sustainable management of tropical agro-ecosystems. Sequential chemical extraction procedures have been and still are widely used to divide extractable soil P into different inorganic and organic fractions (Hedley et al. 1982). The underlying assumption in these approaches is that readily available soil P is removed first with mild extractants, while less available or plant-unavailable P can be extracted only with stronger acids and alkali.

Several studies have related these different P fractions in tropical soils to plant growth (Crews 1996; Friesen et al. 1997; Guo and Yost 1998; Oberson et al. 1999, 2001; Phiri et al. 2001a, b; Lehmann et al. 2001; Bühler et al. 2002). The results obtained in these studies suggest that, in tropical soils, the amounts of P in the different pools measured by sequential P extraction procedures, and the fluxes of P between pools, are controlled both by physico-chemical factors such as sorption and desorption and by biological reactions such as immobilisation and mineralisation. However, the importance of these processes for different land-use systems, such as monocropping, pasture or intercropping, remains largely unknown.

CIAT researchers, in collaboration with their partners, conducted a series of field trials in the tropical savannas and Andean hillsides in Colombia. The main objectives of these studies were: (i) to quantify the soil and plant processes associated with changes in primary biomass productivity in typical systems and ‘best bet’ options to develop indicators of soil quality and degradation; (ii) to quantify and understand nutrient dynamics in systems to improve cycling and minimise losses; and (iii) to quantify factors that influence and determine the rates of processes to calibrate, modify, or develop simulation models for overcoming site specificity and testing alternative scenarios. We describe here the progress in quantifying soil P dynamics, acquisition and cycling under different management systems in tropical savannas and hillsides agro-ecosystems.

## **Tropical Savannas Agroecosystem — Llanos of Colombia**

The neotropical savannas occupy 243 million hectares in South America and are one of the most rapidly expanding agricultural frontiers in the world (Thomas and Ayarza 1999), with oxisols predominating. Intensification of agricultural production in this ecosystem requires acid soil (aluminium) tolerant crop germplasm, soil fertility improvement and management of highly vulnerable physical properties (Amézquita 1998). Grain legumes, green manures, intercrops and leys are possible system components that could increase the stability of systems involving annual crops (Karlen et al. 1994). Soil P dynamics, acquisition and cycling were quantified in crop rotations and ley pasture systems (Friesen et al. 1997). Comparison of rooting patterns of crop and forage components indicated that introduced legume-based pastures are more deep-rooted than crops, and acquire considerable amounts of P despite a lower level of available P in the surface soil. Greenhouse studies indicated that forage legumes are more efficient in acquiring P per unit root length (Rao et al. 1997). Comparative studies of a forage grass (*Brachiaria dictyoneura* CIAT 6133) and a legume (*Arachis pintoii* CIAT 17434) demonstrated that the legume could acquire P from relatively less-available P forms from oxisols of Colombia (Rao et al. 1999b). Field studies on root distribution of maize showed that most of the roots are in top 20 cm of soil depth. These differences in rooting strategies have important implications for P acquisition efficiency in relation to available soil P in different crop and pasture systems (Table 1). Application of higher amounts of lime did not improve subsoil-rooting ability of maize but contributed to greater nutrient acquisition. This knowledge is useful to match the plant components to overcome edaphic constraints and to model plant responses to P supply in soil.

Observed differences in crop–forage residue decomposition and P release rates suggest that managing the interaction of these residues with soil could reduce P fixation. Measurements of soil P fractions indicated that applied P moves preferentially into labile inorganic P pools, and then only slowly via biomass production and microbes into organic P pools under both introduced pastures and crop rotations (Friesen et al. 1997). In cultivated soils, much higher P fertiliser doses significantly increase available inorganic P contents with lesser impact on

organic P pool sizes. Agricultural land-use systems replacing native savanna on oxisols affect the partitioning of P among inorganic and organic P fractions (Table 2). The amount and turnover of P that is held in the soil microbial biomass is increased when native savanna is replaced by improved pasture while it was lowered when soils are cultivated and cropped continuously (Oberson et al. 2001). Based on these studies alternative strategies for cropping low P oxisols, involving strategic application of lower amounts of P fertiliser to crops and planting of grass–legume pastures, would promote P cycling and efficient use of P inputs.

Legume-based pastures (16 years old) maintained higher organic and available P levels than the grass alone or native pastures (Oberson et al. 2001). Greater turnover of roots and above-ground litter in legume-based pastures could provide for steadier organic inputs and therefore higher P cycling and availability. Failure of P to enter organic P pools is thought to indicate a degrading system due to low level of P cycling. If that is true, work done so far in the Llanos of Colombia indicates that legume-based pastures could be considered as important land-use options to stimulate P cycling, reduce P fixation and minimise soil degradation in tropical savannas.

Field studies were conducted to quantify the residual effectiveness of P fertiliser inputs in cereal–grain legume rotations (maize–soybean or rice–cowpea) in terms of both crop growth response and labile P pool sizes in an oxisol in the Llanos of Colombia (CIAT 1996; D. K. Friesen, unpublished data). The results showed that soluble P applications to oxisols of Colombia remain available for periods that are much longer than expected for ‘high P-fixing’ soils, such as the oxisols of Brazilian Cer-

rados. For determining the available P in low-P supplying oxisol, we compared an acid ammonium oxalate extraction method with Bray-II extraction, resin and bicarbonate extraction, and extraction with iron-impregnated paper strips (Guo and Yost 1998; CIAT 2001). This comparative study of P extraction methods indicated that use of either oxalate-P or resin-P + bicarbonate-P pools of Hedley sequential fractionation scheme are better suited to determine soil P availability in oxisols that receive strategic applications of lower amounts of fertiliser P.

Crop simulation models are increasingly used to estimate crop yields as affected by nutrients and water inputs as well as management practices and climatic conditions. A group of models, CERES for cereal simulation growth and CROPGRO for legume simulation, has been used successfully around the world for various purposes. A computer model for the simulation of P in soil and plant relations has been developed and added to the two above crop simulation models to enhance their capabilities, especially in tropical areas where P deficiencies are common. We tested these models using data on maize, soybeans and upland rice grown under acidic tropical conditions in the Colombian savannas (CIAT 2000; S. Daroub, unpublished data). The sensitivity analysis done on the model showed that it is responsive to different rates of P fertiliser applications as well as to initial conditions of labile P. Several growth parameters responded to P additions. Some of the growth parameters from the model that do not seem to be affected by P fertilisation are: flowering and maturity dates, panicle number and leaf number. This early work lead to the inclusion of P routines in DSSAT (Daroub et al. 2003).

**Table 1.** Differences among crop and pasture systems in accessible phosphorus (P) recovery in relation to available soil P (0–20 cm soil depth).

System	Bray-II available P (mg kg <sup>-1</sup> )	Total root length (km m <sup>-2</sup> )	Specific root length (m g <sup>-1</sup> )	Total P uptake (kg ha <sup>-1</sup> )	Accessible P recovery <sup>a</sup> (%)
Native savanna pasture	1.6	5.8	122	4	74
Introduced grass/legumes pasture <sup>b</sup>	3.5	7.2	75	14	94
Maize monoculture <sup>c</sup>	19.8	4.8	106	18	24

<sup>a</sup> Total P uptake per unit available P in rhizosphere soil (assuming an effective rhizosphere diameter of 5 mm).

<sup>b</sup> *Brachiaria humidicola* CIAT 679/*Stylosanthes capitata* CIAT 10280 + *Centrosema acutifolium* CIAT 5277 + *Arachis pintoi* CIAT 17434.

<sup>c</sup> *Zea mays* cv. Sikuani

**Table 2.** Distribution of phosphorus (P) in various fractions in fertilised land-use systems (continuous rice, grass–legume pasture) 5 years after establishment on native savanna as assessed from sequential extraction. Relative changes (% increase) describe the percentage of total P increase in fertilised systems over native savanna that was found in a given fraction (for formula see footnote †). Adapted from Oberson et al. (2001).

Treatment	Resin		NaHCO <sub>3</sub>		NaOH		HCl		Resid		Sum	
	P <sub>i</sub>	P <sub>i</sub>	P <sub>o</sub>	P <sub>i</sub>	P <sub>o</sub>	P <sub>i</sub>	P <sub>o</sub>	P <sub>t</sub>	P <sub>t‡</sub>	P <sub>i</sub> §	P <sub>o</sub> ¶	
<i>Savanna</i>												
Mean (mg kg <sup>-1</sup> )	2.6a	3.9a	11.3a	27.4a	45.3	35.6a	23.9	60.6	212a	69a	81.9	
<i>Grass–legume</i>												
Mean (mg kg <sup>-1</sup> )	4.8b	6.7b	14.6b	45.5b	51.0	46.5b	30.3	62.2	263b	103b	97.8	
% increase	4.3	5.4	6.5	35.5	11.3	21.4	12.6	3.2	101	66.6	31.1	
<i>Continuous rice</i>												
Mean (mg kg <sup>-1</sup> )	14.3c	20.2c	17.1b	111.0c	42.7	54.3b	36.2	65.6	363c	200c	98.0	
% increase	7.7	10.7	3.8	55.0	-1.7	12.3	8.1	3.3	100	85.8	10.6	
F-test	***	***	**	***	ns	*	ns	ns	***	***	ns	

Means of four field replicates samples per treatment. Means within a column followed by the same letter are not significantly different ( $p = 0.05$ ) by Tukey's multiple range test. F-test: \*\*\* $p < 0.001$ , \*\* $p = 0.001-0.01$ , \* $p = 0.01-0.05$ , ns = not significant.

† Increase (%) = (size of fraction in fertilised treatment – size of fraction in SAV) / (Sum P<sub>t</sub> fertilised treatment – Sum P<sub>t</sub> SAV) \* 100

‡ Sum P<sub>t</sub> = Resin P<sub>i</sub> + NaHCO<sub>3</sub> P<sub>i</sub> + NaOH P<sub>i</sub> + HCl P<sub>i</sub> + Resid P<sub>i</sub> = Sum P<sub>i</sub> + Sum P<sub>o</sub>

§ Sum P<sub>i</sub> = Resin P<sub>i</sub> + NaHCO<sub>3</sub> P<sub>i</sub> + NaOH P<sub>i</sub> + HCl P<sub>i</sub>

¶ Sum P<sub>o</sub> = NaHCO<sub>3</sub> P<sub>o</sub> + NaOH P<sub>o</sub> + HCl P<sub>o</sub>



A need identified during this simulation work was for a P rate and fractionation experiment in the Llanos designed specifically for testing P routines in simulation modelling. This four-year experiment, established in 2001, is a balanced P experiment, with a one-off addition of 80 and 160 kg P ha<sup>-1</sup>, compared with annual applications of 5, 10, 20 and 40 kg P ha<sup>-1</sup>. Crop yields from a maize–bean rotation and soil P fractionation will be used to further test the SoilP routine in APSIM and P routines in other simulation models. This work is ongoing and simulation modelling using APSIM will continue during 2004–2005.

The main lessons learned from the work in tropical savannas can be summarised as follows: 1) P from fertilisers and P released from organic residues flows preferentially into labile inorganic pools, but much more slowly into more stable pools; 2) P flows rapidly through, and does not accumulate in, organic pools in the short-term; and 3) crop and forage cultivars differ in their ability to acquire and utilise P, and these differences can be exploited to improve P input use efficiency in crop–livestock systems of the tropics.

### Andean Hillsides Agroecosystem – Cauca, Colombia

Hillsides of tropical America cover about 96 million hectares (Jones 1993) and have important roles as reserves of biodiversity and source of water for

areas downslope (Whitmore 1997). Agriculture in this region is often characterised by farming systems under which soils are degrading through erosion and loss of nutrients (Amézquita et al. 1998). Maintenance of the natural resource base in the hillsides is thus vital not only to ensure the future livelihood of resource-poor farmers, but also to prevent their migration to urban centres where social problems are already endemic. Agriculture in the Andean hillsides of Colombia is practised on steep slopes, on soils that are acidic, rich in allophane with a very high capacity to fix P, and prone to severe erosion, particularly on farms of the poorest farmers (Ashby 1985; Reining 1992).

Traditional agricultural systems in the Andean hillsides of Colombia are based on slash-and-burn shifting cultivation with 3–5 years of cropping and then abandonment to fallow vegetation because of low crop yields (Knapp et al. 1996). Local farmers recognise soil nutrient depletion and estimate that it takes more than 6 years for complete soil fertility recovery by natural fallows. Planted fallows are an appropriate technological entry point because of their low risk for the farmer, relatively low cost, and potential to generate additional products (i.e. fuelwood) that bring immediate benefit while improving soil fertility (Barrios et al. 2004).

The volcanic-ash soils in Colombian hillsides generally contain high amounts of soil organic matter (SOM) but nutrient cycling through SOM in these

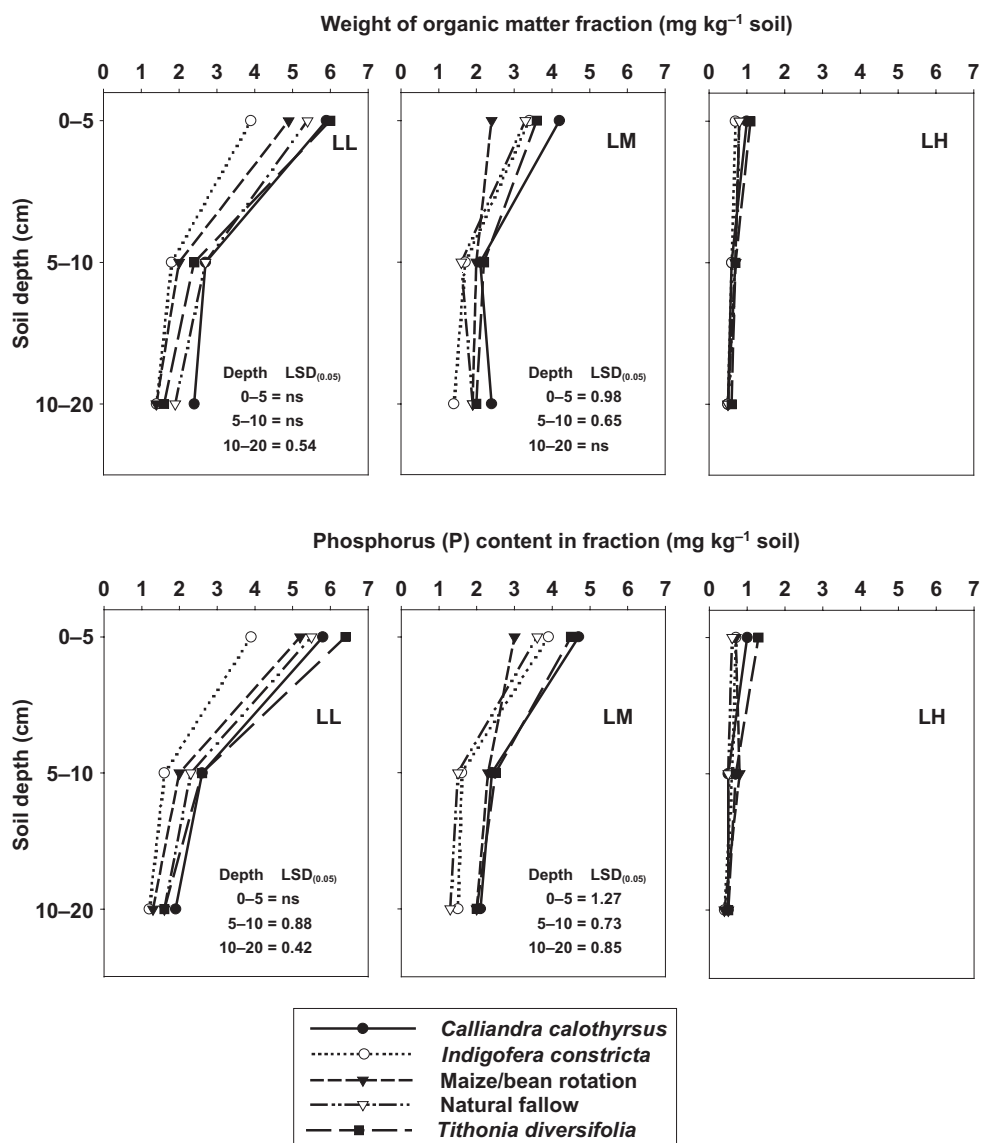
**Table 3.** Decomposition and nutrient release differences among green manures and organic materials. Results are from a 20-week litterbag field study in hillsides of Cauca, Colombia. Adapted from Cobo et al. (2002b).

Plant species <sup>a</sup>	Decomposition rate (kD, d <sup>-1</sup> )	N release rate (kN, d <sup>-1</sup> )	P release rate (kP, d <sup>-1</sup> )	Total N release (kg ha <sup>-1</sup> )	Total P release (kg ha <sup>-1</sup> )
CAN	0.019	0.045	0.033	116	8.0
CRA	0.009	0.026	0.015	90	3.5
IND	0.034	0.061	0.024	130	5.7
MDEE	0.019	0.048	0.044	144	11.4
MPBR	0.022	0.045	0.032	131	8.9
MPIT	0.020	0.039	0.029	110	7.7
MPTL	0.021	0.042	0.030	116	7.9
TTH	0.037	0.044	0.022	124	7.6
INDm	0.015	0.054	0.028	91	4.5
INDs	0.005	0.040	0.063	41	3.5
MPITm	0.017	0.028	0.032	83	6.5
MPITs	0.008	0.011	0.044	28	4.7

<sup>a</sup> CAN = *Canavalia brasiliensis* (leaves); CRA = *Cratylia argentea* (leaves); IND = *Indigofera constricta* (leaves); MDEE = *Mucuna deerengianum* (leaves); MPIT = *Mucuna puriens* var. IITA-Benin (leaves); MPTL = *M. puriens* var. Tanzania (leaves); MPBR = *M. puriens* var. Brunin (leaves); TTH = *Tithonia diversifolia* (leaves); INDm = *I. constricta* (stems + leaves); INDs = *I. constricta* (stems); MPITm = *M. puriens* var. IITA-Benin (stems + leaves); N = nitrogen; P = phosphorus.

soils is limited because most of it is chemically protected, which limits the rate of its decomposition (Phiri et al. 2001b). Short-term planted fallows on these P-fixing soils could restore soil fertility by enhancing nutrient recycling through the provision of organic matter to increase N supply and decrease P fixation (Barrios and Cobo 2004). Field and greenhouse studies were conducted to assess the magnitude and timing of nutrient release and to establish relationships with chemical characteristics (quality) of five green manures and four organic materials as a means of defining selection criteria for use as biofer-

tilisers (Cobo et al. 2002a). Results indicated significant diversity in decomposition and nutrient-release patterns (Table 3) and highlighted the value of screening new farming system components to achieve efficient nutrient cycling and minimal environmental impact. Greenhouse studies on nitrogen mineralisation and crop uptake from surface-applied leaves of green manure species indicated that green manures that decomposed and released N slowly resulted in high N uptake when they were used at pre-sowing in a tropical volcanic-ash soil (Cobo et al. 2002b).



**Figure 1.** Soil profile weight distribution of light (LL), intermediate (LM), and heavy (LH) fractions of soil organic matter and their phosphorus (P) contents as affected by different fallows and the crop rotation system. LSD values are presented only when the differences among treatments are significant Adapted from Phiri et al. (2001b).

Studies on the impact of improved fallows on soil fertility indicated that a *Tithonia diversifolia* slash/mulch system has the greatest potential to improve soil fertility (Barrios et al. 2004; Barrios and Cobo 2004). Nevertheless, such a system may not be suitable for areas with seasonal drought as it is not very tolerant of extended dry periods. The *Calliandra calothyrsus* slash/mulch fallow system proved to be the most resilient as it produced similar amounts of biomass independent of initial level of soil fertility and was thus a candidate for wider testing as a potential source of nutrient additions to the soil and to generate fuelwood for resource-poor rural communities. The slower rates of decomposition in *C. calothyrsus*, compared with *Indigofera constricta* and *T. diversifolia*, indicated that the benefits provided may be longer lasting. The *I. constricta* slash/mulch fallow, on the other hand, was less adapted to low soil fertility and this may limit its potential for extended use.

The *T. diversifolia* slash/mulch fallow showed the greatest potential to improve SOM, nutrient availability, and P cycling, because of its ability to accumulate high amounts of biomass and nutrients (Phiri et al. 2001b; Barrios and Cobo 2004; Barrios et al. 2004). The amount of P in the light (LL) and medium (LM) fractions of SOM was greater with *T. diversifolia* fallow than the other two planted fallows (Figure 1) and it correlated well with the amount of 'readily available' P in the soil (Phiri et al. 2001b). It is suggested that the amount of P in the LL and LM fractions of SOM could serve as sensitive indicators of 'readily available' and 'readily mineralisable' soil-P pools, respectively, in P-fixing volcanic-ash soils. These results also indicated that fractionation of SOM and soil P could be more effective than the conventional soil analysis methods in detecting the impact of planted fallows on improving soil fertility.

The main lessons learned from the work in Andean hillsides can be summarised as follows: 1) the *Tithonia* slash/mulch fallow system appear to be the best option to contribute to the rapid restoration of soil fertility by increasing the plant available P pool in soil; and 2) a *Calliandra* fallow system could improve soil fertility and also provide good quality firewood for cooking for resource-poor farmers.

## The Way Forward

Strategic P inputs are an essential component to increased and sustained agricultural production in

low-P soils. Strategic P applications based on soil P availability, soil P fixation, crop P uptake and reduced crop P requirements could gradually increase the level of available P in the soil. Consequently, the frequency and amounts of P applications required to sustain production will decrease with time. Combined with strategic P inputs, P-efficient germplasm will contribute to agricultural sustainability by: (i) reducing the need to improve soil P status to higher levels to achieve similar productivity, a strategy which is also more demanding regarding maintenance levels of P; and (ii) increasing the efficiency of use of the applied P, which is a non-renewable resource. Moreover, P-efficient crops would bring the economic rates of applied P within reach of smallholder farmers who might otherwise not use fertilisers.

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## 5

# Improved Capabilities in Modelling and Recommendations: Summary

R.J. Delve,\* M.E. Probert† and J.P. Dimes§

The purpose of the project ‘Integrated nutrient management in tropical cropping systems: improved capabilities in modelling and recommendations’ (ACIAR Project no. LWR2/1999/03) was to test and enhance a modelling capability that can be applied to farming systems where both organic and inorganic sources of nutrients are used. In tropical regions, organic materials are often more important for maintenance of soil fertility than fertilisers, yet current fertiliser recommendations and most crop models are unable to take account of the organic inputs and the different qualities of these organic inputs used by farmers.

When the project commenced, simulation modelling had a limited ability to predict the effects on soil processes and crop growth of organic sources that differed in ‘quality’. APSIM was chosen because it had draft modules to describe the release of nutrients (both nitrogen and phosphorus) from manures (Manure module) and the dynamics of P in soil (SoilP module), and it contained routines to limit crop growth under conditions of water, N and P stress. At the start of the project, these modules were largely untested. The project tested, and where necessary improved, the APSIM Manure and SoilP modules, so that they can be applied to the management of soil fertility, especially in low-input systems in the tropics.

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### Developments in Improving APSIM Manure and SoilP Modules

Resource-poor farmers regularly make decisions on the use of scarce nutrient sources in crop–livestock production systems. The decisions made generally reflect farmer experience (of expected returns) and livelihood preferences. However, for resource-poor farmers, ‘experience’ is often limited by the feasibility and capability of the farmer to experiment with alternative management practices. In the case of allocating animal manure for crop production, this decision is usually taken with limited knowledge of the impact of the potential of alternative uses on plant production and soil and water resources. A deeper understanding of the comparative values and usefulness of manures and other locally available resources and sources of P would help fill such knowledge gaps, offering the possibility for increased production and efficiency of mixed crop–livestock systems. While efforts are required to expand our knowledge of the biophysical aspects of alternative uses of organic nutrient sources, similar efforts are also required on the socioeconomic driving forces behind farmers’ decision-making.

### Cross-method analysis of plant quality

N content or C:N ratio are the primary indicators of decomposition and N release across a range of plant materials of different quality. However, other parameters (such as lignin and polyphenolics) are needed to explain the variation observed in N mineralisation studies.

Measurements for assessing plant resource quality include an extensive array of proximate analyses (lignin, acid-detergent fibre (ADF), total soluble

polyphenolics, and a variety of condensed tannins). Decomposition is determined by the combination of these different factors. Indirect methods that can serve as ‘integrative measures’ of resource quality are discussed in Section 3 of these proceedings. These include aerobic decomposition, near infrared reflectometry (NIR) and in vitro dry matter digestibility. Results from these integrative methods correlated well with mineralisation rates estimated in the traditional leaching tube experiment and have the potential to predict this laboratory estimation of resource quality.

From this cross-method analysis, the minimum data set to assess organic resource quality consists of N, lignin, and soluble polyphenol content. This finding is consistent with conclusions from earlier efforts. Considerations of cost and speed also need to be compared where more than one method is available. Aerobic incubations are one of the cheapest but slowest methods, whereas NIR is the fastest. Although NIR instrumentation is expensive to set up, for routine analysis of many samples it could become cost effective. Construction of spectral calibration libraries in centralised laboratory facilities would greatly increase the efficiency of NIRS use for routine organic resource characterisation in laboratories and dramatically reduce the costs of such analyses.

### **Modifying and testing the APSIM Manure module**

Existing laboratory incubation experiments and SWNM network trials in East and southern Africa situated in diverse agro-ecological zones and soil types were used to test the manure module (see Section 4). The field experiments used manures of differing quality and combined organic and inorganic sources of N. These trials provided data on the short and long-term effects on nitrogen availability, soil organic matter and crop production — information that is necessary for testing APSIM and to provide the insights needed for making any modifications to APSIM.

Initially, as in other models of soil organic matter turnover, the model assumed that the soil organic matter pools (BIOM and HUM) have C:N ratios that are unchanging during the decomposition process. Additions of fresh organic matter (FOM) are considered to comprise three pools (FPOOLS): the carbohydrate-like, cellulose-like and lignin-like fractions.

Each FPOOL has its own rate of decomposition, which is modified by factors to allow for effects of soil temperature and soil moisture. Although the three fractions have different rates of decomposition, they did not have different compositions in terms of C and N content. During this project we concluded that, to simulate release of N from diverse sources of manure, the model could match observed short-term release patterns only if the pools had different C:N ratios. This insight came from the results of laboratory studies that showed variable N-release patterns depending on the C:N ratio of the soluble fraction of the manures (Probert et al., these proceedings). The APSIM Manure module has been modified so that the pools can now be specified to have different C:N ratios. This enabled the effects of different qualities of organic resources on N-mineralisation patterns to be simulated in accordance with observed responses, especially during periods immediately following manure application.

### **Modifying and testing APSIM’s phosphorus routines**

The SoilP and modified maize modules that existed when the project commenced explored the feasibility that it might be possible to include P-stress as a limitation to growth in APSIM crop models. During this project, as it became clear that that was indeed feasible, two significant advances were made.

Firstly, the P status of the crop had been considered only on a whole plant basis. This is not consistent with how N is modelled in the APSIM crop modules; in particular, it is far from ideal when a sequence of crops is to be simulated (for example, how to handle P in residues at harvest?). The development was to simulate the partitioning of P to different plant components (leaf, stem, flower, grain, root) throughout the life of the crop. A consequence of this development is that the data requirements for specifying the P dynamics in the crop are much greater, because P concentrations in the various plant components need to be described. A new parameter set (specifying P concentrations and stresses) was created for maize (based on results from an earlier experiment at Katumani — ACIAR Project no. 8326).

The second improvement was in the P-uptake routine. In the prototype, this was directly related to the amount of labile P in a soil layer. Current understanding suggests it ought to be related to the P concentration in solution at the root interface. A new

routine was introduced into the code and ‘tuned’ to the Katumani experiment. Testing against other data sets (particularly that from Maseno on a very different soil with much higher P sorption characteristics, and from Machang’a) showed that the new uptake routine and parameter set was transferable. Having shown that the model could simulate P-deficient maize, the P routines were put into an APSIM crop template so that, in principle, any model using the template can be P-aware, provided the necessary parameter set exists to define P concentration in the plant and the effects of P stress on the plant growth processes.

The initialisation of the APSIM SoilP module requires inputs for labile P and P sorption on a soil layer basis. In this project, labile P has been identified with bicarbonate extractable P (Olsen P), though further testing on a wider range of soils is needed. It is unlikely that there is a 1:1 fit between the conceptual labile P of the model and any soil P test. The measure of ‘P sorption’ used is the amount of P sorbed at  $0.2 \text{ mg L}^{-1}$ .

For model-testing purposes, the only additional crop variables beyond those needed to validate the N and water routines would be P concentrations in plant components and P uptake. The parameter set required to make a crop model ‘P-aware’ comprises values for the maximum, minimum and senesced P concentration in the different plant components through the growth cycle of the crop, together with factors specifying how P stress affects photosynthesis, leaf expansion and phenology.

Unfortunately, during the project, no data set from Latin America, Africa or Asia contained all the required data to thoroughly evaluate the model. Ideally, for testing the ability of the SoilP module to simulate effects of P on crop growth, one would want to look at crop growth (yields, phenology, leaf area, nutrient uptake), soil water and rooting depth, mineral N in soil, soil P test values and, in a long-term experiment, soil organic matter. To address this, ongoing fieldwork in Latin America will be used for further testing of the model.

None of the data sets explicitly addressed the effectiveness of P in organic sources. In the model, mineralisation of P is simulated in a similar manner to N and will be determined by the C:P ratios of the substrate and the soil organic matter being synthesised. Using typical values for C:P in soil microbial biomass of 10–35, leads to the inference that net P mineralisation from an organic source would require

a C:P of less than 100 (i.e. a P concentration of greater than 0.4% in tissue). This does not conform with published data. The cause of the disparity is again thought to lie in the C:P ratio not remaining constant during decomposition. For P, the water-soluble fraction has a much lower C:P ratio than the total C:P. Therefore, in the enhanced SoilP module the release of plant-available P from organic inputs depends on the FPools having different C:P ratios.

### **Testing of APSIM with long-term tropical data sets**

Long-term experiments covering a range of soil types were identified by project collaborators in East and West Africa, Latin America, and Southeast Asia, and were used to test the new APSIM modules for predicting nutrient release and plant growth under field conditions. Results show that the model performed well across a wide range of applications, from simulation of N and P supply to crops where P constraints were more severe than N, to long-term P and C dynamics, and for crop responses to different rates and qualities of manures, responses to inorganic and manure combinations, and residual benefits of manure.

Using the long-term data for the Machang’a experiment, the model was shown to accurately predict crop responses to inputs of manure or fertiliser, while the predicted dynamics of labile P in soil were similar to the measured Olsen P data. Of course, none of these simulations was perfect, and discrepancies between observed and predicted data were reported. Notably for the Maseno data set, where soil P was determined irregularly (and soon after fertiliser application), the agreement between observed and predicted values was poor. In some cases, the lack of fit between model and observed data will arise from limitations in the modelling capability, e.g. there are effects of manures other than N and P that cannot be modelled. In other cases, the discrepancies are due to our poor understanding of the observed responses, which limits our interpretation.

Generally, experiments, especially long-term ones, are not established with model validation or development in mind. This project used existing long-term experiments from East and West Africa, Latin America, and Southeast Asia and, of course, found some shortcomings in the available data. While this did not hamper model development, it has prevented the evaluation of model performance from



being as thorough as one might like. Accordingly, new experimentation was established during this project in Latin America, to overcome these data constraints and for further testing of APSIM.

### **Extension to other crops**

The 'P-aware' maize model was a major breakthrough in our thinking of how to explicitly reflect soil P dynamics and especially P limitations in crop simulations. There is a clear need to apply the new capability to other crops. During this project, fieldwork was initiated to conduct experiments that would permit parameter sets to be assembled. This work was co-funded from other projects. The crops being studied are cowpea and millet (funded by IFDC in West Africa), pigeonpea, groundnut and sorghum (funded by DFID and ICRISAT in India), and canola (funded by CSIRO in Australia).

Many of the soils in Africa and Latin America are P-fixing and/or P deficient, and these projects are now contributing further modelling capability for P dynamics in these farming systems. The SoilP module developed and evaluated within this project has provided the opportunity for these other projects to proceed, and this is a major outcome and one measure of the project's success.

### **Future Activities Needed in Developing APSIM**

The ACIAR-funded project LWR2/1999/03 developed a unique capability in simulation modelling by introducing the ability to have crops respond to P constraints and to model N and P dynamics following addition of manures of different quality. There remains a need to test these routines against a wider suite of data sets, especially for a wider range of cropping systems and soil types.

The external review team made several recommendations about follow-up activities with project partners. In the short and medium terms, these were to:

1. generate a few high-quality contrasting data sets for validation
2. refine and publish the data collection protocols for others to use
3. start working with end users including farmers to utilise model outputs.

A two-year project extension has since been funded by ACIAR to address the first two recommendations and, at the same time, strengthen the skills of current APSIM users in the project. The major components of this extension are as follows:

1. The N and P capabilities of the APSIM Manure and SoilP modules are being further tested against existing data sets in Latin America and Southeast Asia. Field studies established during the project were designed to provide a comprehensive data set for testing of the SoilP module and the P routines in the maize module. These studies are still in progress.
2. As part of the testing activities above, researchers from Latin America and Southeast Asia would be exposed to the use of the APSIM model and how it might be applied in the carrying out of their research activities and in extending, to the farming community, the results of their research. Training in the use of APSIM for the partners would be a component of this activity.
3. The data collection protocols for manure characterisation are being refined and published, so future researchers collect data that are appropriate to Manure module use. Also, the minimum data set protocols for APSIM are being updated.