Modelling The Long-Term Productivity And Soil Fertility Of Maize/Millet Cropping Systems In The Mid-Hills Of Nepal

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EXTENDED ABSTRACT

In Nepal, maize is currently the second most important staple food crop after rice, having doubled in area over the past 30 years to around 800,000 ha. Due to population increases and increased demand for livestock fodder, demand for maize in Nepal is estimated to grow by 6-8% per annum over the next 20 years, representing a nearly four-fold increase over this period. Although the use of artificial fertilisers is increasing, in some cases this has led to the abandonment of traditional methods of soil fertility maintenance, and initial yield increases have not always been maintained. Questions are arising as to the best way to combine organic and inorganic sources of nutrients into integrated nutrient management systems, so that crop yields can be maintained at a satisfactory level without resulting in soil fertility decline. These same questions also have relevance at a global level, as there is increasing interest in agricultural management strategies that can help offset the detrimental effect of anthropomorphic emissions of carbon into the atmosphere, by enhancing sequestration of C into soil organic matter.

Previously experiments investigated the influence of different combinations of inorganic fertilisers and farmyard manure (FYM) on crop yields in maize/millet cropping systems at two contrasting sites in the mid-hills of Nepal, one at Pakhribas in the Eastern Region, and the other at Dordor Gaun in the Western Region. Following standard farmer practice at each site, maize was grown either in relay rotations or sequential rotations with finger millet. Treatments included an unfertilised control (T1), and ones in which 90 kg N ha^{-1} was added either as inorganic fertilizer (T2), or as farmyard manure (FYM) (N content: 1.3%) applied at a rate of 6.9 t DM ha^{-1} (T3). Due to the short time period available for field experimentation, long-term trends in crop yields could not be determined, neither could changes in soil carbon and nitrogen levels be measured.

To address these issues, we opted to use a detailed but robust simulation model to test different scenarios and to develop appropriate recommendations based on knowledge of the likely impact of different types and rates of nutrient inputs. We used the People and Landscape Model (PALM), which simulates resource flows in a rural subsistence community and its environment, and consists of a number of households, the landscape, and livestock, all of which are simulated simultaneously. The landscape is made up of a number of homogeneous land units, or 'fields', each of which consists of a number of soil layers, with each layer containing routines to calculate its water balance and carbon and nitrogen dynamics. In this paper, we describe the parameterisation and validation of PALM based on data from the field experiments at Pakhribas and Dordor Gaun, and its use to investigate the effect of different nutrient management treatments on long-term trends in crop yields and soil carbon and nitrogen dynamics. For this study, the model was set up for one household and two fields. To use the model for investigating the long-term impacts of the various treatments on soil fertility, the WGEN weather generator was used to generate 100 years of daily weather data, the parameters of which were extracted from the existing years of recorded weather data available from Pakhribas and Dordor Gaun.

At both sites, the highest crop yields were obtained in the treatment receiving only inorganic fertiliser at a rate of 90 kg N ha^{-1}. The model predicted declines in soil organic C and N for all three fertiliser and FYM treatments, with the severest rates of loss in the treatment receiving no nutrient inputs at all and the slowest rates of loss in the treatment receiving 6.9 t ha^{-1} of organic manure. At current prices, the use of inorganic fertilisers was by far the most rational option for farmers in terms of net returns, regardless of the site, and despite the associated decline in soil C and N levels. It was estimated that if greater use of organic manure is to be promoted as a way of increasing carbon sequestration in the soil, then farmers in the mid-hills of Nepal will need to be compensated at a rate of at least US$9.90 (t C)$^{-1}$ for the lower crop yields they will obtain.

1. INTRODUCTION

In Nepal, maize is currently the second most important staple food crop after rice, having doubled in area over the past 30 years to around 800,000 ha (Ransom & Rajbhandari, 2000). The greatest areas of maize production are in the mid-hills regions (600-1800 m), where 70% of the total national production is grown, often in relay intercropping systems with millet, soybean, cowpea and potato. Despite the expansion in cultivated area, yields have remained more-or-less unchanged over this period, implying sustainable production, albeit at a low level (e.g. <1.6 t ha^{-1} for maize (Thapa & Rosegrant, 1995)). However, due to population increases and increased demand for livestock fodder, demand for maize in Nepal is estimated to grow by 6-8% per annum over the next 20 years (Ransom & Rajbhandari, 2000), representing a nearly four-fold increase over this period.

Traditionally, cropping systems in Nepal are tightly coupled with livestock production, with crop residues providing fodder, livestock providing manure, and resources for both of these being drawn from the forest (Carson, 1992). However, whether such practices are sustainable in the long-term is unclear, let alone whether a four-fold increase in crop productivity can be achieved. The use of artificial fertilisers, particularly urea, is on the increase, although this has led to the abandonment of traditional methods of soil fertility maintenance in some cases, and, moreover, the initial yield increases have not always been maintained (Sherchan *et al.*, 1999). Thus, questions are arising as to the best way to combine organic and inorganic sources of nutrients into integrated nutrient management systems, so that crop yields can be maintained at a satisfactory level without resulting in soil fertility decline. These same questions also have relevance at a global level, as there is increasing interest in agricultural management strategies that can help offset the detrimental effect of anthropomorphic emissions of C into the atmosphere, by enhancing sequestration of C into soil organic matter.

In recent years, attempts to evaluate the sustainability of agricultural systems in Nepal have been made using nutrient balance approaches to quantify the nutrient fluxes into, within, and out of fields, farms and households (e.g. Brown *et al.*, 1999; Pilbeam *et al.*, 2000), and have concluded marginal sustainability or declines in soil fertility depending on the cropping system considered. However, these studies generally construct nutrient balances on an annual basis, and, therefore, do not, and cannot, consider the dynamic processes and feedbacks involved between soil fertility and crop production. Calculated nutrient deficits (Brown *et al.*, 1999), for example, may be transitory with crop yields falling to a lower equilibrium over several years to reach a new balance of inputs and outputs.

Historically, one approach to examining the level of productivity and sustainability of particular cropping systems has been to establish and maintain field experiments with crops receiving different types and rates of nutrient inputs. Such trials provide the basis for developing robust recommendations for sustainable cropping systems, but they have a number of drawbacks; namely, they are resource intensive, location specific, and deliver relevant results only slowly. An alternative approach, which can address each of these deficiencies, is to use detailed but robust simulation models that accurately reflect the physical, chemical and biological processes that underpin the cropping system. A model that has been effectively and adequately validated may then be used to test different scenarios and to develop appropriate recommendations based on knowledge of the likely impact of different types and rates of nutrient inputs. Matthews (2006) has described the development of the People and Livelihoods model (PALM), which is able to simulate the growth and development of a number of crops, along with soil water, carbon and nitrogen dynamics for a number of fields. This paper describes the validation of the model for maize-based cropping systems in the mid-hills of Nepal, and its use to evaluate the sustainability and productivity of three different crop management strategies applied to a series of maize-millet field trials (Pilbeam *et al.*, 2002).

2. METHODOLOGY

2.1. Experimental data

On-farm field trials were established in 1997 at two contrasting sites in the mid-hills of Nepal, one at Pakhribas (latitude 27°03’ N, longitude 87°17’ E, 1680 m) in the Eastern Region, and the other at Dordor Gaun (latitude 28°10’ N, longitude 84°20’ E, altitude 1100 m) in the Western Region. Selected properties of soil from a 1 m soil profile at Pakhribas (sandy loam) and Dordor Gaun (silt loam) are presented in Pilbeam *et al*. (2004).

Maize (*Zea mays* L. cv. Manakamana-1) was grown either in relay rotations (at Pakhribas) or sequential rotations (at Dordor Gaun) with finger millet (*Eleucine coracana* L. cv. Okhale-1). Maize was generally sown in mid-April and harvested in August/September depending on location and year. At both sites, the maize rows were 75 cm apart with 25 cm between plants in the row (5.3 plants m^{-2}).

At both sites, seven N treatments were imposed, although, for clarity in this paper, results from only the three most contrasting of these are reported. These three were the unfertilised control (T1), and ones in which 90 kg N ha^{-1} was added either as inorganic fertilizer (ammonium diphosphate and urea) (T2), or as farmyard manure (FYM) applied at a rate of 6.9 t DM ha^{-1} (T3). The FYM nitrogen content was measured at 1.3%. For comparison, recommended rates of inorganic N fertiliser and FYM for maize are 120 kg N ha^{-1} and 10 t DM ha^{-1}, respectively (LARC, 1997), although farmers usually apply less than these values depending on location, farmer perception of soil fertility, economic status of farmer, etc. The experimental layout was a randomised complete block design with four replications. Other details of the field trials, including other nutrient additions are given in Pilbeam *et al.* (2002). Both grain yield and total aboveground biomass were determined for both crops at both sites in each of three years beginning in 1997, with the exception of the 1999 data for Dordor Gaun, which were not available.

2.2. The model

PALM (People and Landscape Model, Matthews, 2006) simulates resource flows in a rural subsistence community and its environment, and consists of a number of households, the landscape, and livestock, all of which are simulated simultaneously on a daily time-step. The landscape is made up of a number of homogeneous land units, or 'fields', each of which consists of a number of soil layers, with each layer containing routines to calculate its water balance and carbon and nitrogen dynamics. Organic matter decomposition is simulated by a version of the CENTURY model (Parton *et al.*, 1988), while water and nitrogen dynamics are simulated by versions of the routines in the DSSAT crop models (Tsuji *et al.*, 1998). The soil processes are simulated continuously, and vegetation types (crops, weeds, trees) can come and go in a field depending on its management. Crop growth and development is simulated by a generic model based on the DSSAT crop models, and which can be parameterised for different crops. Decisions made by the households result in activities being performed, which in turn influence the flows of resources within and between farms. The numbers of households, fields and livestock to be simulated are specified by the user – in the current study, the model was set up for one household and two fields only. Corresponding to the experimental data (Pilbeam *et al.*, 2002), four soil layers (0-25, 25-50, 50-75, 75-100 cm) were simulated.

In both of the areas in our study, millet is sown in a nursery, and then transplanted, either into a standing maize crop (mid-July at Pakhribas) or following the harvest of the maize (end of August at Dordor Gaun). The model was modified, therefore, to describe the transfers of crop biomass, C and N involved in transplanting plants from one field to another, as well as competition between the two crops for resources. At both sites, harvesting of the millet is in late November/early November. Due to lack of data for validation, weeds were not simulated.

2.3. Weather data

To use the model for investigating the long-term impacts of the various treatments on soil fertility, the WEATHERMAN facility within the DSSAT crop modeling package was used to generate 100 years of daily weather data. For this, the WGEN weather generator option (Richardson, 1981) in WEATHERMAN was used, the parameters of which were extracted from the existing years of recorded weather data available from Pakhribas and Dordor Gaun.

3. RESULTS

Comparisons of observed and predicted values for the summed above-ground biomass produced by the two crops combined in each year across all fertiliser and FYM treatments in each year are shown in

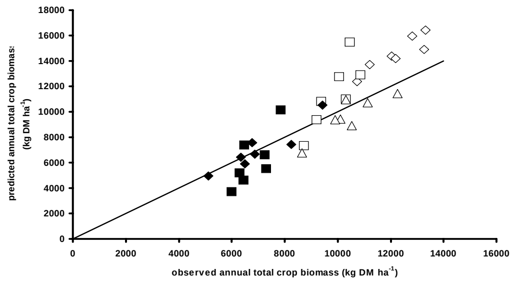


Figure 1, indicating good agreement. Similarly, the model was able to predict very well the total annual N uptake by the two crops combined, and there was also reasonable agreement between simulated and observed nitrate concentrations at the 90 cm level in the soil profile (data not shown).

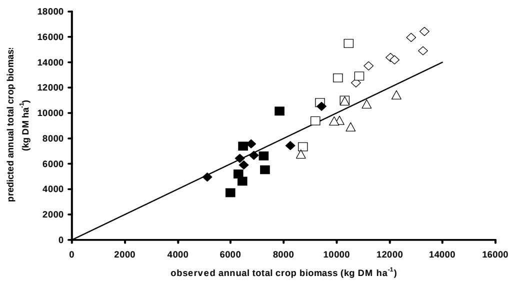
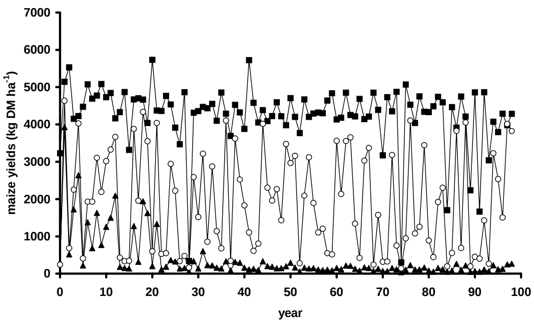


Figure 1: Observed vs. simulated total above-ground biomass for maize and millet combined for each year. Open symbols are for Pakhribas, filled symbols for Dordor Gaun; diamonds: 1997, squares: 1998, triangles: 1999. 1:1 line is shown.

a.



b.

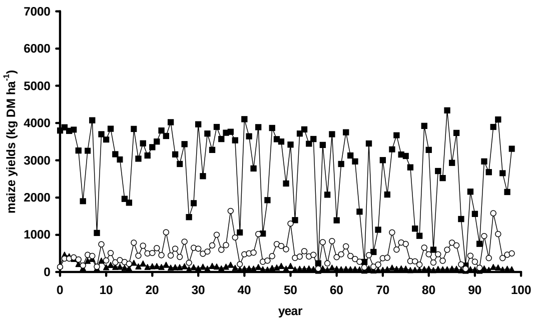


Figure 2: Predicted maize yields (kg DM ha^{-1}) for treatments T1 (filled triangles), T2 (filled squares) and T3 (open circles) at (a) Pakhribas and (b) Dordor Gaun over the 100-year period.

The predicted maize yields for the three treatments over the 100-year period for Pakhribas and Dordor Gaun are shown in Figure 2. Year-to-year variability was caused by variations in temperature, solar radiation, rainfall, and nitrogen availability. At Pakhribas, in the control treatment T1, there was a gradual decline in maize yields over the first 20 years until a new level of about 130 kg DM ha^{-1} was reached, after which they remained stable. By contrast, in the 90 kg N ha^{-1} inorganic fertiliser treatment, T2, maize yields were predicted to remain high at a level of more than 4000 kg DM ha^{-1}, although there was evidence of a very slow decline of about 6.3 kg DM ha^{-1} per year over the period. In the T3 treatment with the full rate of FYM application, maize yields were predicted to be about half those in the T2 treatment at about 1800 kg DM ha^{-1}, and also to be much more variable from one year to the next. At Dordor Gaun, a similar, but not identical, situation was predicted. Overall crop yields were lower, due in part to the lower initial soil fertility, and in part to the shorter crop duration caused by the higher temperatures at that site. In the control treatment T1, maize yields again declined in the first 20 years to around 80 kg DM ha^{-1} thereafter. Again, maize yields in treatment T2 with the full application of inorganic fertiliser gave the highest yields, averaging about 2700 kg DM ha^{-1} throughout, but year-to-year variability was considerably more than at Pakhribas. There was also a gradual decline in yields over the period of 12 kg DM ha^{-1} y^{-1}. Maize yields in treatment T3, with full FYM application, were intermediate at about 500 kg DM ha^{-1}, but also with considerable year-to-year variability.

The predicted changes in soil organic carbon over the 100-year period under each of the three treatments at the two sites are shown in Figure 3. There was a general decline in soil organic carbon in all treatments as a result of continuous cropping. At Pakhribas, the largest decline was in treatment T1, from the starting point of 0.57% down to 0.37%, representing a loss of 29.3 t C ha^{-1} or an average of 293 kg C ha^{-1} y^{-1}. The rate of decline in the other treatments was less, commensurate with the rate and form of C and N application, with the slowest rate of decline being in treatment T3, with a loss of 109 kg C ha^{-1} y^{-1}. In treatment T2, with annual applications of inorganic fertiliser at the rate of 90 kg N ha^{-1}, the rate of decline in SOC was intermediate between these two extremes at an average of 170 kg C ha^{-1} y^{-1}, resulting in a loss of about 17 t C ha^{-1} over the 100 years. The situation predicted for Dordor Gaun was similar. Again, there was a steady decline in SOC levels in the three treatments, with the control treatment T1 declining at an average rate of 254 kg C ha^{-1} y^{-1} and T3 at a rate of 72 kg C ha^{-1} y^{-1}, with T2 intermediate between these two values with a rate of decline of 197 kg C ha^{-1} y^{-1}. In general, the rate of decline was proportional to the amount of organic manure added. Although the data is not shown, levels of soil organic nitrogen followed a similar pattern in each case.

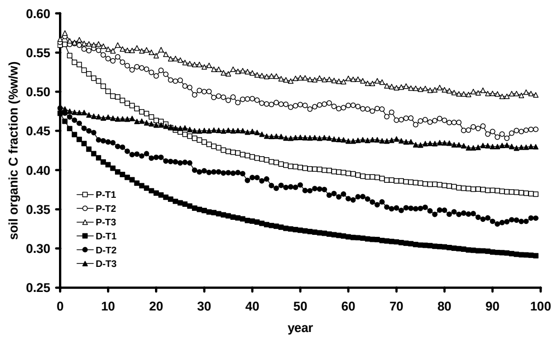


Figure 3: Predicted changes over the 100-year period in soil organic carbon content (%w/w) averaged over 1 m soil depth under each of the three treatments at the two sites.

4. DISCUSSION

All three crop management strategies adopted in the field trials reached near-equilibrium in terms of crop yields, albeit at very different levels of production depending upon site and treatment (Figure 2). Yields of maize were greatest with an annual input of 90 kg N ha^{-1} fertilizer only, sustaining at 3000-4000 kg ha^{-1} y^{-1}. This is counter to the predictions of Sherchan *et al.* (1999) who showed that over an 8-y period yields at Pakhribas were greatest when either FYM alone or in combination with fertilizer were applied, although in accord with Giller *et al.* (1997) who note that whilst animal manures are of major importance in nutrient cycling, they are generally a poor supplier of plant nutrients.

The initial declines in soil C and N predicted in all of the treatments would seem to confirm farmers' own perceptions that the fertility of their soils is declining (Turton *et al.*, 1995; Desbiez *et al.*, 2004). Many farmers feel that the cause of this is increasing reliance on mineral fertilisers at the expense of manure, which is confirmed to some extent by our results, applications of reasonable quantities of manure (i.e. T3) seem to be able to slow the decline in soil C and N levels compared to the use of inorganic fertiliser alone (i.e. T2). However, the general decline in C and N for all treatments at both sites would suggest that the very act of cropping is the major cause of soil fertility decline. The predicted rates of decline in soil N contents varied from -12 to -25 kg N ha-1 y^{-1} at Pakhribas, and from –6 to –23 kg N ha^{-1} y^{-1} at Dordor Gaun, depending on the treatment. For comparison, Brown *et al.* (1999) calculated annual N balances in maize/wheat cropping systems in Eastern Nepal ranging from surpluses of +75 kg N ha^{-1} y^{-1} to deficits of -180 kg N ha^{-1} y^{-1}, with a median value of about -90 kg N ha^{-1} y^{-1}. Our annual rates of N loss are values averaged over the 100-year period of the simulations, but in T1 were as high as -63 kg N ha^{-1} y^{-1} at both sites at the beginning of the simulation, declining after 100 years to a constant value of around -11 kg N ha^{-1} y^{-1}. These rather low values would suggest that the values calculated by Brown *et al.* (1999) may not be at equilibrium, but are still declining over time.

Even though, in biophysical terms, all three treatments were 'sustainable' in the long term, none provided the required four-fold increase in maize production estimated by Ranson & Rajbhandari (2000). It is beyond the scope of this paper to evaluate socio-economic factors in detail, but to give some idea of the implications of each treatment from the farmer's viewpoint, we have applied a simple gross margin analysis to the simulated maize and millet yields, using current (2000) prices in Nepal of fertiliser (urea: Rs10 kg^{-1}; di-ammonium phosphate: Rs21.10 kg^{-1}), FYM (Rs1 kg^{-1}), and maize (Rs23 kg^{-1}) and millet grain (Rs15 kg^{-1}) (Source: MOAC, 2000). Crop residues were ascribed the same value as FYM of Rs1 kg^{-1}. Results are shown in Figure 4. At both sites, the most profitable strategy by far was to apply inorganic fertiliser at 90 kg N ha^{-1}, giving a gross margin averaged over the 100 year period of Rs105,200 yr^{-1} at Pakhribas and Rs68,600 yr^{-1} at Dordor Gaun. The least profitable strategy was T1 at both sites – gross margins averaged over the 100-year period were Rs13,800 y^{-1} for Pakhribas, and Rs6980 y^{-1} for Dordor Gaun, an order of magnitude lower than the corresponding T2 treatments. It is interesting to note in comparing treatments T2 and T3 (i.e. use of inorganic fertiliser alone vs. use of organic manure alone), that the lower net return obtained from the latter could be compensated for by payment to the farmer for the extra carbon sequestered at a rate of about Rs720 (t C)$^{-1}$, or about US\$9.90 (t C)$^{-1}$ at current (2004) exchange rates, which is cheaper than most figures of between US\$12-100 per tonne sequestered C given for carbon credits (e.g. Antle *et al.*, 2001).

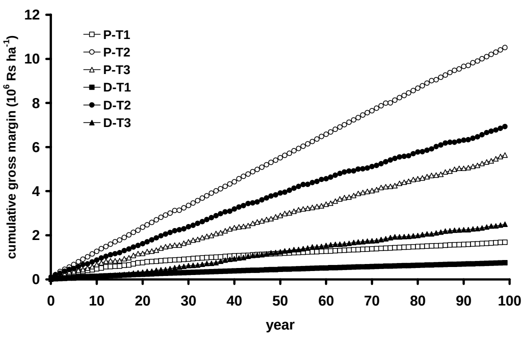


Figure 4: Cumulative gross margins (10^6 rupees ha^{-1}) for the three treatments at the two sites.

Clearly, in the absence of compensation for carbon sequestration, applying inorganic fertiliser where possible seems to be the most profitable strategy, regardless of the site characteristics. Using FYM appears to provide some benefit at cooler sites such as Pakhribas, but almost no benefit at all at warmer sites such as Dordor Gaun. This is qualitatively consistent with a previous analysis (Pilbeam *et al.*, 1999), which showed that margins were generally negative when manure was applied either alone or in combination with fertilizer, but positive with applications of fertilizer only. Similar results have been obtained elsewhere. In Zambia, for example, Matthews *et al*. (1992) found that subsidised inorganic fertilisers as a nutrient source always gave a higher gross margin than alley-cropping, although when subsidies were removed, alley-cropping became more attractive. Similarly, Bruentrup *et al*. (1997) in comparing the long-term economics of using a crop residue mulch to those for the complete removal of crop residue from fields in Niger, found that not only was short-term profitability low from using the crop residues as a mulch, but also with mulching alone, soil degradation could not be prevented. In a study of the economic viability of combined fertiliser, green manure and grain legume techniques, Ali (1999) found that the short-term benefits of green manure were 'negative or trivial' compared with inorganic fertiliser, despite on-farm experiments showing that yields were higher with combined fertiliser and green manure treatments.

5. CONCLUSIONS

The relative merits of using chemical fertilisers and organic manures or both in integrated nutrient management systems have long been debated (see Graves *et al*. (2004) for a review). There is a growing realisation that these debates extend well beyond merely considering only the biophysical characteristics of each. The use of FYM by farmers in the mid-hills, for example, has been declining for a number of years due both to a reduction in labour availability for its collection and transport, and to a decrease in available fodder for feed and bedding as the forest area has declined (Pilbeam *et al.*, 2000), or community projects have restricted access to forest lands (Ransom & Rajbhandari, 2000). This decline has led to an increase in the use of chemical fertilisers which are easier to apply, requiring less effort to transport, and cheaper to purchase because of substantial governmental subsidies. The results from our study would suggest that, in addition to these advantages, chemical fertilisers also give consistently higher crop yields, although this comes at the expense of a more rapid decline in soil C and N levels. The acidifying effect of long-term use of nitrogenous fertilisers also needs to be taken into account, and, indeed, some farmers in Nepal do complain of a deterioration or 'hardening' of their soil and a decline in yields due to the use of such fertilisers, and are becoming reluctant to use them. However, if a return to using more manure rather than inorganic fertiliser is to be promoted to meet commitments to global agreements on climate change, then farmers with a choice of using one or the other will need to be compensated for lower yields they will obtain with using manure only.

Our study has shown that a well-tested simulation model offers the potential to explore the long-term impact of different management scenarios for maize-millet systems. With appropriate re-parameterisation for different crops (such as rice or wheat or legumes), the sustainability of other significant cropping systems in the mid-hills of Nepal can also be evaluated. Moreover, although we have considered only a single household with two fields, the PALM model has the ability to simulate a number of households and fields simultaneously, approximating a virtual community. This opens the way to exploring more realistically the interactions between the socio-economic and biophysical aspects of agricultural production systems, taking into account such factors as labour availability within the community, inequity between households in the resources they have available, and interactions between households.

6. ACKNOWLEDGMENTS

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