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Nutrient use efficiencies and crop responses to N, P and manure applications in Zimbabwean soils: Exploring management strategies across soil fertility gradients

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Abstract

The spatial variability in crop yields commonly observed in smallholder farms of sub-Saharan Africa is often caused by gradients of declining soil fertility with increasing distance from the homestead. This heterogeneity means that recommendations based on regional soil surveys are of limited value. The variability in soil qualities within farms must be considered when designing management strategies, and their feasibility analysed by integrating results at the farm livelihood scale. For this purpose, we have developed the model FARMSIM, a dynamic bio-economic model for analysis and exploration of trade-offs in resource and labour allocation in heterogeneous smallholder farms. Focusing on farm-scale strategies, the approach to simulation of soil and crop processes in FARMSIM (the sub-model FIELD) is designed to be simple, but to keep the necessary degree of complexity to capture heterogeneity in resource use efficiencies. To test our approach, the sub-model FIELD was calibrated against chronosequences of woodland clearance in three agroecological zones of Zimbabwe (with soil textures of 3, 10, 35% clay), and used to simulate: (i) the creation of soil fertility gradients, and (ii) different strategies of N, P and manure applications to maize and soyabean rotations in homefields and outfields of smallholder farms on clayey and sandy soils. The results of the simulation of management strategies were tested against on-farm experimental data from Murewa, Zimbabwe. The model produced satisfactory predictions (r^2: 0.6–0.9) of long-term changes in soil organic C, of crop responses to N and P and of nutrient use efficiencies across a wide range of yields and different field types. This demonstrated the broad applicability of the model despite the sparse data required for initialisation. However, the model results were less accurate in predicting crop responses to N and P applications in the outfields on sandy soils. Experimental evidence indicated yield limitation by Ca and Zn deficiencies in highly depleted outfields on sandy soils, which were not included mechanistically in the current version of FIELD. Repeated applications of 16 t ha^{-1} year^{-1} of manure allowed larger responses to applied N and P after 3 years of experimentation; such a corrective effect of manure was simulated to be due to improved N and P recovery efficiencies in the model. In combination with the experimental data, the simulation results suggested that soil fertility gradients affect nutrient use efficiencies, operating mostly on the efficiencies of nutrient capture rather than conversion. A typology of fields according to the type of management interventions needed is introduced, based on a generic application of FIELD with this parameterisation.

Keywords: Sub-Saharan Africa; FARMSIM; FIELD; Resource use efficiency; Rotations; Maize; Soyabean

1. Introduction

Spatial variability in crop yields within smallholder farms of Sub-Saharan Africa is often the result of gradients of declining soil fertility with increasing distance from the homestead (Tittonell et al., 2005b; Zingore et al., 2006). Such heterogeneity in soil fertility within the farm is caused largely by the differential long-term management of the various

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production units (fields). The limited labour and nutrient resources are preferentially allocated to fields close to the homestead by smallholders. The wide variability in the nutrient stocks for different units within heterogeneous farms led Smaling et al. (2002) to conclude that regional soil surveys are of limited value at the farm level, and that variability at farm scale should be considered when designing soil management strategies. While some studies suggested the need for designing management strategies to reduce the magnitude of the soil fertility gradients, homogenising productivity within the farms (Mtambanengwe and Mapfumo, 2005), others showed that preferential allocation – concentration – of limited resources such as manure and mineral fertilisers to the more fertile fields gave greatest aggregate yields at farm scale (Rowe et al., 2006). However, unravelling such discrepancies requires going beyond the aggregation of results from single fields and focusing analysis at the farm scale, considering multiple indicators of success meaningful to farmers.

Crop production in smallholder systems is limited by multiple resources that operate simultaneously, and cause resource imbalances that eventually lead to poor yields (Kho, 2000). Acknowledging this, Lopez-Ridaura et al. (2006) indicated that options for more sustainable management of resource-poor farming systems should be designed pursuing maximum marginal use efficiencies for the most limiting resources, and maximum absolute use efficiencies for resources locally in more abundant supply. This translates, for the smallholder systems under study, as the need for identifying the most limiting resources for crop production, which are likely to vary across soil fertility gradients. For example, large differences in the efficiency of use of nutrient resources (N, P, K and manure) by maize, soyabean and groundnuts grown on home gardens as opposed to outfields of small farms of Kenya (Vanlauwe et al., 2006) and Zimbabwe (Zingore, 2006) suggest different limiting factors for crop yield. N and P fertiliser applications led to better results in terms of maize yield and nutrient recovery for infields as compared with outfields of smallholder farms in the Sudan savannah zone of Togo, and the results varied strongly between dry and wet years (Wopereis et al., 2006). However, variability in yields is not due solely to heterogeneity in soil fertility. The diversity in the intensity and timing of certain agronomic practices (e.g. planting and weeding), which are often associated with the perceived fertility of different fields (Tittonell et al., 2005b), are also key factors influencing on-farm crop yield variability (Mutsaers et al., 1995).

A recent study in western Kenya pointed to the existence of resource use efficiency gradients associated with soil and management diversity within smallholder farms, and suggested that a proper analysis of ‘efficiency’ indicators such as N use efficiency, labour productivity and/or benefit:cost ratios in relation to different management practices should also consider the long-term dynamics of the system (Tittonell et al., 2006). Dynamic simulation models offer opportunities for the integrated analysis of different options available to smallholder farmers to improve productivity of their land, while considering the spatial heterogeneity of their farms, the long-term impact of their operational and strategic management decisions, changes in the biophysical and socio-economic scenarios, and monitoring multiple indicators of sustainability at different scales. A number of studies are available in which modelling approaches were used for designing sustainable management systems for African smallholders. For example, Diels et al. (2004) explored the potential of different crop rotational and fertilisation schemes to build up soil C and its associated soil properties in southern Benin, using the dynamic soil C model ROTHC (Coleman and Jenkinson, 1995). Jagtap et al. (1999) used the CERES-maize crop growth model to investigate N management and maize variety technologies in three agroecological savannah zones of Nigeria, testing the model against data from international testing nurseries. Several examples of application of the APSIM crop growth model to the plot-scale analysis of different crop and soil management alternatives in low inputs systems are available (e.g. Carberry et al., 1996), including simulations of intercropping, weed management, crop rotation and nutrient management.

In the examples reviewed above, relatively complex, process-based mechanistic models were used. However, the performance of such models may be poor in the data-scarce environments of the tropics (Smaling et al., 1997). Simpler modelling approaches that consider the main factors limiting crop production in smallholder systems may yield sufficiently accurate results to aid decision-making on resource allocation (e.g. Janssen et al., 1990)—particularly when the long term is considered (e.g. Abegaz, 2005). Van Keulen (1995) summarised the three major disadvantages of using detailed process-based models in such systems, which are: (i) extensive data requirements that often cannot be satisfied, (ii) difficulty of validation since many variables may not have been measured, and certainly not over the time-span necessary to judge their long-term behaviour, and (iii) partial knowledge of many of the underlying processes leading to unbalanced descriptions; i.e. much detail on well-known processes but gross generalisations of other processes that are poorly understood. Thus, modelling for long-term analysis of farming strategies by smallholders, with emphasis on livelihood, requires simple approaches to avoid being overwhelmed by detail, but that are sensitive enough to capture the spatial and temporal variability of the systems, and the impact of proposed technologies for improvement (Giller et al., 2006).

We hypothesised that between- and within-farm heterogeneity in resource use efficiency and in the performance of technological interventions for smallholder systems can be satisfactorily analysed by identifying key determining factors and simulating their interaction using simple models, able to capture the variability of such factors. FARMSIM (FArm-scale Resource Management SIMulator; Tittonell et al., 2005c) is a farm-scale bio-economic model that is developed with the aim of analysing trade-offs around farming systems and the environment. FARMSIM focuses on strategic decision-making and embracing the spatial and temporal variability of smallholder systems, which forms the core of the NUANCES (Nutrient Use in ANimal and Cropping systems—Efficiencies and Scales) framework (Giller et al., 2006; http://www.africanuances.nl).