Agricultural Systems 102 (2009) 89–101

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Identifying key entry-points for strategic management of smallholder farming systems in sub-Saharan Africa using the dynamic farm-scale simulation model NUANCES-FARMSIM

Mark T. van Wijk [a,*], Pablo Tittonell [a], Mariana C. Rufino [a], Mario Herrero [b], Cesare Pacini [c], Nico de Ridder [a], Ken E. Giller [a]

[a] Plant Production Systems, Department of Plant Sciences, Wageningen University, P.O. Box 430, Haarweg 333, 6700 AK Wageningen, The Netherlands
[b] International Livestock Research Institute, P.O. Box 30709, Nairobi, Kenya
[c] Università degli Studi di Firenze, DISAT, Piazalle delle Cascine 18, I-50144 Florence, Italy

ARTICLE INFO

Article history:
Received 8 October 2008
Received in revised form 8 July 2009
Accepted 23 July 2009
Available online 20 August 2009

Keywords:
Mixed crop–livestock systems
Farming system model
Sub-Saharan Africa
Sensitivity analysis

ABSTRACT

African smallholder farming systems are complex, dynamic systems with many interacting biophysical subcomponents. In these systems the major inputs and outputs are managed by human agency – the farmers. To analyse potential developmental pathways of smallholder farming systems in sub-Saharan Africa (SSA), we recognised the need for a tool that can capture the effects and consequences of decision-making on the use of resources. Here we describe and apply such a new modelling tool, developed within the NUANCES framework (Nutrient Use in ANimal and Cropping systems: Efficiencies and Scales), called NUANCES-FARMSIM (FARM SIMulator), an integrated crop – livestock model developed to analyse African smallholder farm systems. NUANCES-FARMSIM was used to analyse a representative case study farm in the highlands of Western Kenya, a site for which each of the components of FARMSIM has been thoroughly tested. We present the results of a sensitivity analysis which showed the model to be sufficiently robust to identify key management options that explain most of the variability in farm productivity, and the long-term consequences of these options for the case study farm. The analyses showed clearly that the most important decisions are those related to the interactions between the different components of the farm and therefore justify the need of integrating crop and livestock components within one modelling tool. The allocation of limited resources across the farm, and the way organic matter is recycled or redistributed within the farm determines the long-term production capacity of the system. The results of the sensitivity analyses further showed that for the case study farm in Western Kenya a strong focus on improving the reliability of the subsystem level or process descriptions will only result in minor improvement in simulating productivity at farm level.

1. Introduction

Smallholder farming in sub-Saharan Africa (SSA) takes place under a wide range of soil, climatic and socio-economic conditions. Development of these systems is strongly constrained by the limited availability of key resources such as land, plant nutrients, cash and labour (Giller et al., 2006). In mixed crop–livestock systems these resources can be used in many different ways and farmers' decisions on their allocation have both short- and long-term consequences for the farm livelihood. Furthermore, interactions between these limiting resources strongly influence the efficiency with which the resources are used. To analyse potential developmental pathways of smallholder farming systems, a tool is required that can capture the effects and consequences of decision-making on the use of resources. It should be able to quantify these consequences dynamically in time, not only in the short term, but especially in the longer term for which major problems are predicted for smallholder farmers in SSA (e.g. Stoorvogel et al., 1993; Sanchez et al., 1997; Stoorvogel and Smaling, 1998). A better *ex ante* understanding of the potential impacts of new technology packages, or new policies, on the performance of smallholder farms of different configurations will allow better targeting of resources and a better understanding of the likely impacts of development initiatives.

Modelling tools aiming at understanding the constraints of smallholder farming and identification of potential development pathways under these conditions need to be limited in their complexity. First, because the user has to be able to control model behaviour and to understand why certain outcomes arise. If many modules are coupled together, computational and mathematical complexity can result in unrealistic model behaviour. Second, because increasing model complexity automatically results in greater

* Corresponding author. Tel.: +31 (0)317 486102; fax: +31 (0)317 48 4892.
E-mail address: mark.vanwijk@wur.nl (M.T. van Wijk).

0308-521X/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.agsy.2009.07.004

data input demand by the model, both in terms of parameterization and in terms of driving variables. Both these types of knowledge are generally lacking in African systems. Van Keulen (1995) identified three drawbacks that complicate the robust application of detailed process-oriented models: (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 leads to unbalanced descriptions; i.e. much detail on well-known processes but gross generalisations of other processes that are poorly understood.

Intensification of smallholder mixed crop–livestock systems has often been identified as a potential pathway out of poverty (McIntire et al., 1992; Dixon et al., 2001; IAC, 2004; De Ridder et al., 2004). To analyse the possibilities for the longer term development of mixed smallholder farms, the individual production components of smallholder farming systems need to be quantified together with their interactions, thereby allowing an integrated assessment of the dynamic development of these systems. Thornton and Herrero (2001) suggested that integrated crop–livestock simulation models could aid the design of sustainable farming systems, by means of studies that explore opportunities to optimise crop–livestock interactions and to improve resource use efficiencies at farm scale. One of the key factors determining the opportunities for intensification and the resource use efficiency of mineral and/or organic fertilisers is soil fertility. The limited availability of organic resources often leads to the occurrence of soil fertility gradients within smallholder farming systems, which strongly affect the resource use efficiency of mineral and organic fertilisers (e.g. Vanlauwe et al., 2006; Zingore et al., 2007). Thus there is need for a tool that combines the representation of the main interactions between crop and livestock components together with the within-farm variability (for example the soil fertility of different cropping fields).

Existing tools focus especially on the crop–soil subsystem (e.g. Matthews and Stephens, 2002). Some steps have been taken to integrate crop and livestock models into analysis tools. But no simple, easily applicable tools exist that can be used across a range of systems while integrating the crop and livestock subsystems, encompassing heterogeneity in soil fertility and analysing the internal competition of the different production activities within the farm for available resources. Shepherd and Soule (1998) developed an integrated crop – livestock model and applied it to the Vihiga district in Western Kenya, but their model did not allow for variability in soil fertility between fields. Furthermore, their model calculates outcomes for a single year thereby ignoring seasonal rainfall variability. The model of Struif Bontkes and Van Keulen (2003) also considers uniform soil fertility across the farm. Matthews and Pilbeam (2005) and Matthews (2006) created a farm-scale model using detailed, process-oriented model formulations, which makes application to a range of systems within sub-Saharan Africa difficult. Other economic, or integrated ecological-economic, optimisation models, which include biophysical components as activities among the various choices for optimisation, often lack a dynamic description of the system (Janssen and van Ittersum, 2007). This makes them useful as prototyping tools (Herrero et al., 1999; Sterk et al., 2007) or tools for static scenario-based analyses (Pacini et al., 2004). They are less useful as tools to provide insight in the dynamic development of the production of the farming system under study and which enable us to identify the sequence of constraints that can limit the number of options within developmental pathways (e.g., Lynam, 2002).

Here we describe and apply a new modelling tool, developed within the NUANCES framework (Nutrient Use in ANimal and Cropping systems: Efficiencies and Scales – Giller et al., 2006), called NUANCES-FARMSIM (FARM SIMulator) which integrates the different production components of African smallholder farm systems. NUANCES-FARMSIM is a dynamic model for exploration of questions related to strategic, long-term management at farm scale. It uses descriptive sub-models and functions thereby limiting the need for input parameters. The summary functions used in the different modules are derived from experimental research, mechanistic modelling at lower hierarchical levels and expert knowledge. This approach resembles those adopted in previous models for long-term analysis of sustainability of farming systems that have focused on crop production (e.g. Wolf et al., 1989; Janssen et al., 1987). In the new model key components determining the functioning of African smallholder farms are represented: crops, soils, livestock, organic resources (manure and crop residues), labour resources, and decision-making. This allows us to analyse the relationships and interactions within the whole farm system, focusing on the farm production components.

First, we introduce the NUANCES-FARMSIM tool and how it is constructed. We then apply NUANCES-FARMSIM to a representative case study farm in the highlands of Western Kenya for which each of the components of the overall farm level model (i.e. livestock, crop, soil and manure management) has been tested thoroughly (Rufino et al., 2007, 2009; Tittonell et al., 2007a, 2008). We present results of a sensitivity analysis conducted to analyse the robustness of the tool for assessment of the long-term consequences of certain management decisions. For this purpose we quantified the uncertainties in: the descriptions of key processes in each of the individual model components; the coupling of these components (for example nutrient flows); and the interactions of the socio-economic part of the model and the biophysical part of the model (for example effects of labour shortages on crop production). This allowed us to explore the ranges of possible realistic management options (e.g., decisions regarding manure management, crop residues management, labour allocation). By performing an overall sensitivity analysis in which both process uncertainty and ranges in management options were combined in one analysis, the robustness of management recommendations can be assessed, and entry-points for recommendations and key areas for future research identified.

The results of the sensitivity analysis are discussed in relation to three research questions: (1) Are the feedbacks between the different components of the farming system important for the analysis of its long-term development? (2) Does the uncertainty in the model components allow promising farm management options to be identified? (3) Which farm management options, system drivers and/or process parameters are most influential on the model outcomes?

2. Model description

2.1. General approach

The basic approach used in the NUANCES-FARMSIM model follows the Wageningen school of agro-ecological modelling in its use of the hierarchy in growth and production factors and of the determination of efficiencies to define production levels (Van de Ven et al., 2003; Van Ittersum et al., 2003). The limiting and reducing factors are the focus of interactions between socio-economic factors such as labour availability and allocation and their effects on crop and livestock productivity (see below).

2.2. Overview of the modules

The following components of the farm system (Fig. 1) are simulated in separate modules together with the flows between the components (between parentheses the name of the module):

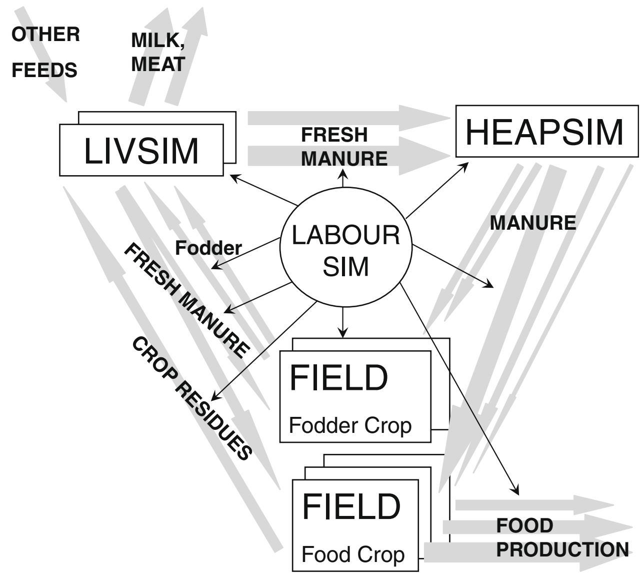

Fig. 1. FARMSIM modules together with their interactions.

– Crop and soil ('NUANCES-FIELD'; Field-scale resource Interactions, use Efficiencies and Long-term soil fertility Development – (Tittonell et al., 2007a, 2008)).
– Livestock ('NUANCES-LIVSIM'; LIVestock SIMulator – (Rufino et al., 2009)).
– Manure handling and storage ('NUANCES-HEAPSIM'; HEAP SIMulator (Rufino et al., 2007)).
– Labour availability ('NUANCES-LABOURSIM'; LABOUR SIMulator).

Previous studies have described FIELD, LIVSIM and HEAPSIM in detail (Rufino et al., 2009, 2007; Tittonell et al., 2007a). A short description of these modules together with a detailed description of the flows of organic matter and nutrients between the modules, LABOURSIM and the way decision-making is dealt with in the model are described in On-line Supplementary material. No economic module has been developed for the version of FARMSIM presented in this study. The current version of FARMSIM focuses on the biophysical productivity of smallholder farming systems, but includes labour as an important resource that is often limiting and constrains farming activities.

2.3. Model testing

The individual components of the FARMSIM model were tested in detail in previous studies (Rowe et al., 2006; Rufino et al., 2007, 2009; Tittonell et al., 2007a, 2008; Chikowo et al., 2008). As with all farm-scale models, the overall model is difficult to test as appropriate detailed data of all the components of mixed crop livestock systems, and their development over time, are lacking. The only way to 'test' the model is by discussing the outcome of the model with experts, and to see whether the results make sense. The FARMSIM model is therefore an exploration tool which quantifies the consequences of decisions taken by the farmer (e.g. allocation of resources) on the longer term productivity of the system. This approach is similar to what Thornton and Herrero (2001) called 'participatory modelling'.

2.4. Application of FARMSIM to a case study in Kakamega, Western Kenya and sensitivity analysis

In any simulation model describing a real smallholder farming system in sub-Saharan Africa the farming system needs to be simplified in order to handle complexity: not all activities taking place in a farming system (e.g. bee keeping, basket making) can be simulated. To make this simplification transparent, we base the farm system analysis on the detailed characterisation of Tittonell et al. (2005). These authors classified farms in Western Kenya in five farm types, in each of which the key production activities within the farm were identified. We then parameterised NUANCES-FARMSIM for a 'virtual' farm that represents one of these groups, a medium resource-endowed mixed crop–livestock farm household in Western Kenya. Six different cropping fields were distinguished: three maize fields of good, medium and bad soil fertility of, respectively, 0.06 ha, 0.25 ha and 0.24 ha; two fields of Napier grass (*Pennisetum purpureum* Schumach), both of 0.15 ha and one sweet potato field of 0.18 ha. The soil parameters used in the FIELD model are from Tittonell et al. (2007b). The farm has two dairy crossbred cattle: one adult cow (4.5 years and 340 kg bodyweight) and one female calf (just born with a bodyweight of 30 kg) which are fed in the stall (zero-grazing feeding). The cattle is the only source of manure within the farm. The maximum bodyweight of the crossbred cows is set to 350 kg, the maximum milk production during lactation is set to 15 kg per day, and the crude protein content of the milk was 3.2%. Cows are removed from the farm when they reach a maximum lifetime of 12 years. Replacement heifers are kept on-farm when the oldest cow reaches 10 years. This means that in the simulation of 12 years there are periods in which three animals are present, the adult animals and one young animal that will be used to replace one of the adult ones. The FIELD model was calibrated and tested using on-farm fertiliser trials that included manure as one of the treatments (Tittonell et al., 2008). Any short term nutrient immobilization effects that can occur when low quality manure is used (Palm et al., 2001), are taken into account in the parameterisation. The simulation of the model using this farm setting was run for 12 years, which is the observed average maximum lifetime of dairy cows kept in mixed farms from the highlands of Central Kenya (Bebe et al., 2003). A historical rainfall dataset (Jaetzold and Schmidt, 1982) and weather data collected at the site between 1993 and 2003 (Tittonell et al., 2009) were used in the simulations.

We first performed a baseline run to analyse the most important outputs (i.e. soil carbon, crop yield, milk production and cattle bodyweight) generated by the FARMSIM model. In this baseline run 75% of crop residues are retained in the fields, no mineral fertiliser is applied, and manure is concentrated on the maize field closest to the homestead.

Next, we performed a sensitivity analysis to assess the importance of the different model parameters and settings of the FARMSIM model. In the sensitivity analysis the effects of 30 different process parameters and management options on the simulated outcomes of the NUANCES-FARMSIM model were evaluated. The 30 parameters were selected because in earlier studies they were found to be influential on model component output, uncertain in their estimated values, or to represent important management options (Chikowo et al., 2008; Tittonell et al., 2008, 2009; Rufino et al., 2007). The model settings that were varied in the sensitivity analysis can be found in Table 1. For most parameters we defined a range of plausible values (Table 1) based on earlier model studies or on measured ranges for Western Kenya (Tittonell et al., 2006; Bebe et al., 2003; E. Righi, unpublished results). We varied the amount of rainfall by using a rainfall multiplication factor, which is multiplied with the seasonal rainfall values to estimate the effects of more or less rainfall on farm productivity. Effects of four different feed qualities and five manure qualities were assessed. The different feed qualities (Table 2) correspond to the feed qualities obtained with Napier grass cut at 4, 8, 9 and 16 weeks (Muia et al., 1999; Bebe et al., 2003). Five labour allocation strategies were evaluated in the sensitivity analysis: in Strategy 1 cattle

Table 1
Parameters and management strategies used in the sensitivity analysis together with the ranges of values. Given are variable name, with some description, the acronym that is used in Figs. 3 and 6, and the minimum and maximum value used in the sensitivity analysis. See text for further explanation of the sensitivity analysis and several of the settings of the variables/parameters.

Variable/parameter	Acronym in graphs	Minimum value	Maximum value
Feed quality	Feed quality	4 levels[a]	
Potential milk production (kg/day)	–	11	19
Maximum weight animal (kg)	–	315	385
Calving interval (year)	–	1.3	2.0
Labour scenarios (increase in value means more focus on crop activities)	Labour	10 levels	
Maize harvest index	–	0.3	0.45
Fraction intercepted radiation	–	0.53	0.65
Light conversion factor (kg dry matter MJ^{-1})	–	3.1	3.8
Shoot root ratio Napier	–	5.4	6.6
Tuber partitioning ratio sweet potato	–	0.41	0.49
Fraction of mineral N lost from soil	–	0.27	0.33
Fraction available P intercepted	–	0.45	0.55
Fraction of crop residue C that is labile	Frac Res Clab	0.63	0.77
Max. rel. decomposition rate of crop residues ($season^{-1}$)	–	0.72	0.88
Max. rel. decomposition rate of roots ($season^{-1}$)	–	0.72	0.88
Max. rel. decomposition rate of active soil C ($season^{-1}$)	–	0.22	0.26
Max. rel. decomposition rate of stable soil C ($season^{-1}$)	–	0.045	0.055
Humification fraction	–	0.45	0.55
Fraction re-stabilised from decomposition	–	0.16	0.24
Fraction of total C that is stable (initialisation)	Init Frac Cst	0.82	0.98
Fraction of soil C that is inert (initialisation)	–	0.27	0.33
Rainfall multiplication factor (multiplying to adjust current seasonal rainfall amounts)	Rain	0.8	1.2
Manure quality (5 qualities, mainly differing in carbon content; 1: 25% carbon, 2: 28%, 3: 29%, 4: 35%, 5: 50%; based on manure found on-farm)	Manure quality	5 qualities	
Buy Napier factor (determines to which relative level of potential intake the farmer buys in Napier grass to increase fodder availability)	BuyNap fact	0.5	1.0
Fraction of aboveground maize crop residues removed	FracRem	0.5	1.0
Fraction of maize crop residues to cows (rest goes to the heap)	–	0.5	0.9
Manure collection efficiency	–	0.5	0.9
Manure allocation strategies (higher number is more allocation to maize inner field)	Man All Strat	10 levels	
LabPlaPlo_effect: amount of labour for land preparation needed for best practice (man days per month per ha)		8	12
LabWeed1_effect: amount of labour for first weeding needed for best practice (man days per month per ha)		16	24
LabWeed2_effect: amount of labour needed for second weeding for best practice (man days per month per ha)		16	24
LabHeap_effect: amount of labour needed for best practice of the manure heap management (man days per month)		6.4	9.6

[a] See Table 2.

Table 2
Feed quality parameters of the four different feed qualities that were used in the sensitivity analysis; the four qualities correspond to the feed qualities obtained with Napier cutting periods of 4, 8, 9 and 16 weeks (Muia, 2000).

Feeds	DM (g kg^{-1})	DOMD (g kg^{-1})	ME (MJ kg DM^{-1})	CP (g kg DM^{-1})	NDF (kg DM d^{-1})	Napier cutting period
Quality 1	144	0.60	8.9	150	536	4 weeks
Quality 2	161	0.59	8.3	120	608	8 weeks
Quality 3	175	0.55	7.7	90	632	9 weeks
Quality 4	197	0.52	7.1	60	680	14 weeks

DM = dry matter; DOMD = dry organic matter digestibility; ME = metabolisable energy; CP = crude protein; NDF = neutral detergent fibre.

and the manure handling activities have priority which results in additional fodder of high quality and efficient heap management. The rest of the labour available is then allocated to the cropping activities, evenly distributed over the cropped fields. In Strategy 2 the priority is first given to cattle, then to the cropping activities (again evenly distributed over the different fields) and then to manure management. In Strategy 3 the available labour is distributed evenly over all activities that need to take place in a month relative to the amount needed to perform an activity optimally (so for example if 80% of the labour needed for best practices is available, all activities receive 80% of what is needed). In Strategy 4 the focus is on cropping activities, evenly distributed over the fields, and thereafter if there is still labour available, labour is allocated to cattle and manure management. In Strategy 5 the focus is again on cropping activities, labour is preferentially allocated to the maize fields, then to the other fields and finally, if there is labour available it is allocated to cattle and to manure management.

In total 23 model output variables are evaluated (Table 3), representing the most important system characteristics of the farming system simulated by FARMSIM. Outputs of each of the modules (LIVSIM, FIELD, HEAPSIM) were evaluated separately, in addition to aggregated values at farm level.

The sampling method used in the sensitivity analysis was the Latin Hypercube Sampling methodology (McKay et al., 1979; Iman et al., 1981): this methodology ensures that the whole range of parameters values is sampled and that effects of interactions between uncertain parameters, between uncertain parameters and management factors, and between management factors on model outputs are taken into account. In this way an overall evaluation of model sensitivity to all parameters and variables can take place in one analysis.

Table 3
Output variables evaluated in the sensitivity analysis. For explanation see text.

Output variable	Unit	Acronym used in Figs. 3 and 6
Number of calves sold	–	Calves sold
Number of calves born	–	Calves born
Napier bought	kg	Nap bought
Total farm maize yield in first season	kg	MY start
Total farm maize yield in last season	kg	MY end
Total farm maize yield over the 12 year period	kg	MY total
Total amount of faecal DM	kg/(12 years)	Faeces
Total amount of manure applied on the crop fields	kg/(12 years)	Tot Manure Appl
Total amount of milk produced	kg/(12 years)	Milk prod
C content in maize field 1 at the end of the simulation period	kg/ha	C MF1
C content in maize field 2 at the end of the simulation period	kg/ha	C MF2
C content in maize field 3 at the end of the simulation period	kg/ha	C MF3
C content in Napier field 1 at the end of the simulation period	kg/ha	C NapF1
C content in Napier field 2 at the end of the simulation period	kg/ha	C NapF2
Total amount of Napier dry matter produced	kg/(12 years)	Napier prod
Total amount of meat produced by the cows	kg/(12 years)	Meat production
Total sweet potato tuber yield	kg/(12 years)	TuberY
Total farm availability of mineral nitrogen for maize production over the simulation period	kg/(12 years)	AvN M
Total farm availability of mineral phosphorus for maize production over the simulation period	kg/(12 years)	AvP M
Total farm availability of mineral potassium for maize production over the simulation period	kg/(12 years)	AvK M
Total farm availability of mineral nitrogen for Napier production over the simulation period	kg/(12 years)	AvN NAP
Total farm availability of mineral phosphorus for Napier production over the simulation period	kg/(12 years)	AvP NAP
Total farm availability of mineral potassium for Napier production over the simulation period	kg/(12 years)	AvK NAP

In addition to the settings listed in Table 1 we superimposed three major scenarios

- o *No fertiliser available, no labour restrictions*: The farmer has no access to mineral fertiliser, and production depends on efficient recycling of the nutrient resources within the farm. The only external input of nutrients takes place through the purchase of Napier grass to ensure that the animals would stay above the minimum weight allowed for these crossbred cows (otherwise in the LIVSIM model this would mean that the animals die; earlier runs showed that this effect of dying animals would dominate the outcomes of the analyses whereas it is likely to be an artefact of the model rather than a realistic outcome). No financial constraints are taken into account. Labour does not constrain the productivity of the farm, which is determined by the management of the available resources.
- o *Fertiliser available, no labour restrictions*: The farmer has access to mineral fertiliser, and applies 50 kg of N, P and K per ha per season to all fields, and therefore nutrients are less limiting to farm productivity. Labour does not constrain the productivity of the farm as the farmer can hire labour. This could be a realistic scenario if mineral fertilisers are subsidised.
- o *No fertiliser available, labour restriction*: The supply of labour is limited during ploughing and planting and during weeding. This means that the farmer has to make decisions on how to allocate the limited amount of labour (only 30 man days per month are available, which is 50% of the labour that is needed to ensure that productivity is limited only by biophysical rather than by labour constraints) across cropping activities, manure management or additional fodder collection for the cattle. We assumed no mineral fertiliser is used.

The results of the sensitivity analysis are summarized using a redundancy analysis (RDA). A RDA is a multivariate correlation analysis, closely related to principal component analysis (PCA), but in a RDA the principal component axes are limited to a linear combination of the explaining variables (see Jongman et al., 1995). Using the RDA analysis method we can directly relate the strongest variations in model outputs to the parameters or model settings that cause these variations. The RDA analysis was performed with CANOCO 4.5 (Ter Braak and Smilauer, 2002), using log transformation to ensure normality.

To further assess the effect of the state of the farming system fertility on the importance of different management options and/or parameters within the farm model we also analysed the effects of within-farm variability in soil fertility on the outcomes of the sensitivity analysis. For this we used the same setup of fields and animals as for the previous analysis without fertiliser available and without labour constraints. We studied two artificial farms without a soil fertility gradient: one farm with only fields that have the relatively high soil fertility, taking the values of maize field 1 but applying them to all fields (except for slope steepness), and one farm with only fields that have a relatively poor soil fertility, taking the values of maize field 3, but applying them to all fields (again except for slope steepness).

3. Results

3.1. Baseline model run

Some key outputs of NUANCES-FARMSIM from the baseline model run are shown in Fig. 2. During several periods in the simulation the bodyweight of the animals decreased (Fig. 2A). This happens during the lactation periods, when the cow just had calved and the amount and quality of the fodder available in the farm is insufficient to maintain bodyweight. The first cow, which had an age of 4.5 years at the start of the simulation, was replaced at an age of 12 years, which means, for example, that in the simulation period between 50 and 68 months after the start of the simulation there were three animals on the farm. The other calves that were born during the simulation period were assumed to be sold immediately after birth. The cows produced milk and the total production at the farm was calculated (Fig. 2B). Besides milk, the animals also produced manure, which was collected a monthly basis with an efficiency of 75% and stored in a manure heap. The manure mass showed a monthly build up until the start of the rainy season, when the heap was emptied and the compost applied to the crop fields (Fig. 2C). The spiky pattern in maize production (Fig. 2D) was mainly caused by the seasonal and inter-annual rainfall variability. The carbon content of the soil in each of the three maize fields was followed in time (Fig. 2E). The fields showed clear differences in the soil C dynamics, caused by the allocation decision made for manure. In this scenario the manure was concen-

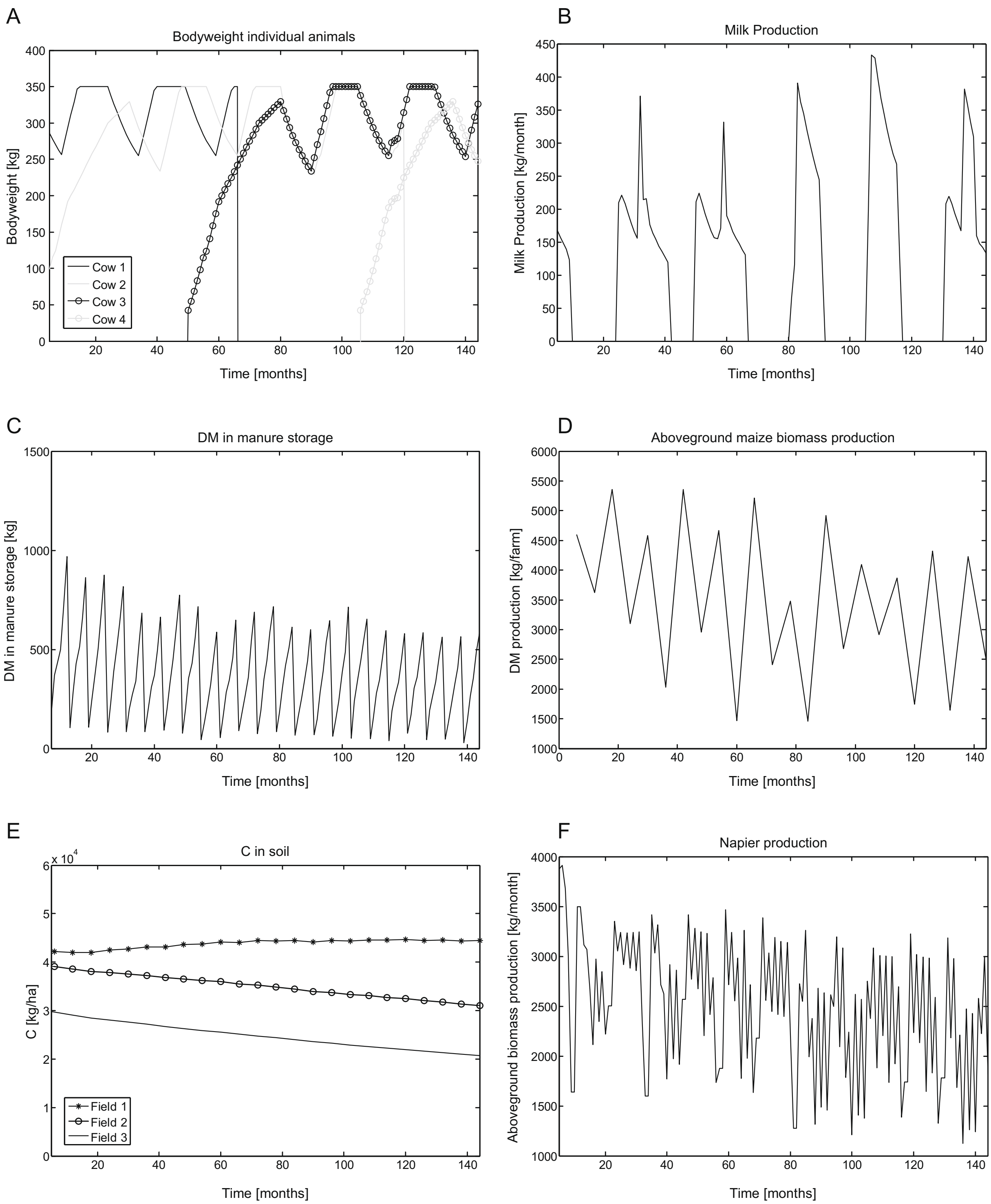

Fig. 2. Some of the key outputs of FARMSIM over time: (A) bodyweight of the individual animals; (B) total farm milk production; (C) manure dry matter in storage; (D) total farm maize production; (E) soil carbon in each of the three maize fields; (F) total farm Napier grass production.

trated in maize field number 1, which was, in the longer term, the only field that maintained its soil organic matter content, the other two fields showed a decline in soil C. Napier production was simulated on a monthly basis (the cutting interval was 2 months, and by alternating the harvests of each of the fields, a monthly output was generated) and harvested and fed to the cattle.

Overall in this simulation there was a downward trend in the mass of manure stored, and that can therefore be applied to the cropping fields, thereby resulting in a small negative trend in maize production over time. As no manure was applied to the Napier grass fields production decreased over time. No negative trend was evident in the meat or milk production of the animals, as in this simulation the farmer decided to buy additional Napier grass of good quality to sustain milk production. As no cash balance has been included in this version of NUANCES-FARMSIM, the financial consequences of this type of decision were not analysed. One of the reasons of not doing this at the moment is the large uncertainty associated with the pricing of resources and farm produce,

but it will be part of the next steps in terms of further model development. The model shows the importance of taking into account the feedback that exists between the livestock and crop components in a mixed crop–livestock farm system. Crop production in these nutrient-limited systems is often highly dependent on the manure produced on farm, which in turn is dependent on the amount of fodder produced. The tool can therefore be used to analyse the consequences of certain management strategies on the production of both components within the farm, and the possible trade-offs that exist between decisions on allocation of resources.

3.2. Sensitivity analyses

The results of the sensitivity analysis using the 'no fertiliser – no labour constraints' scenario (Scenario 1) are shown in Fig. 3A. Using the RDA analysis we can directly relate the strongest variations in model outputs to the parameters or model settings that cause these variations. Large arrows associated with output variables (the grey arrows) that point in the same direction have a strong positive correlation, large arrows that point in opposite directions have strong negative correlations. The two major components of the farm systems, the crop/soil and livestock subsystems, were associated with the first two axes of the RDA (Fig. 3A; i.e. the output variables typical for each of these components show a strong correlation to one of the two axes; this is represented in the graph by a large arrow pointing along the direction of one of the axes). The black arrows are the parameters or management settings that were varied in the sensitivity analyses, and are therefore the drivers of the variation found in the output variables. A large black arrow means that changing that parameter has a strong effect on the model outcome. A black arrow that points in the same direction as one of the output variable arrows (grey) means that an increase in that parameter leads to an increase in the value of the output variable. For example, an increase in feed quality resulted in an increase in milk production (Fig. 3A). Model variables associated with the crop subsystem explained 49% of the variability of RDA axis 1, whereas livestock related model variables explained 27% of the variability in RDA axis 2. Most important correlations between output variables were between soil carbon and maize productivity for the cropping subsystem, and between all

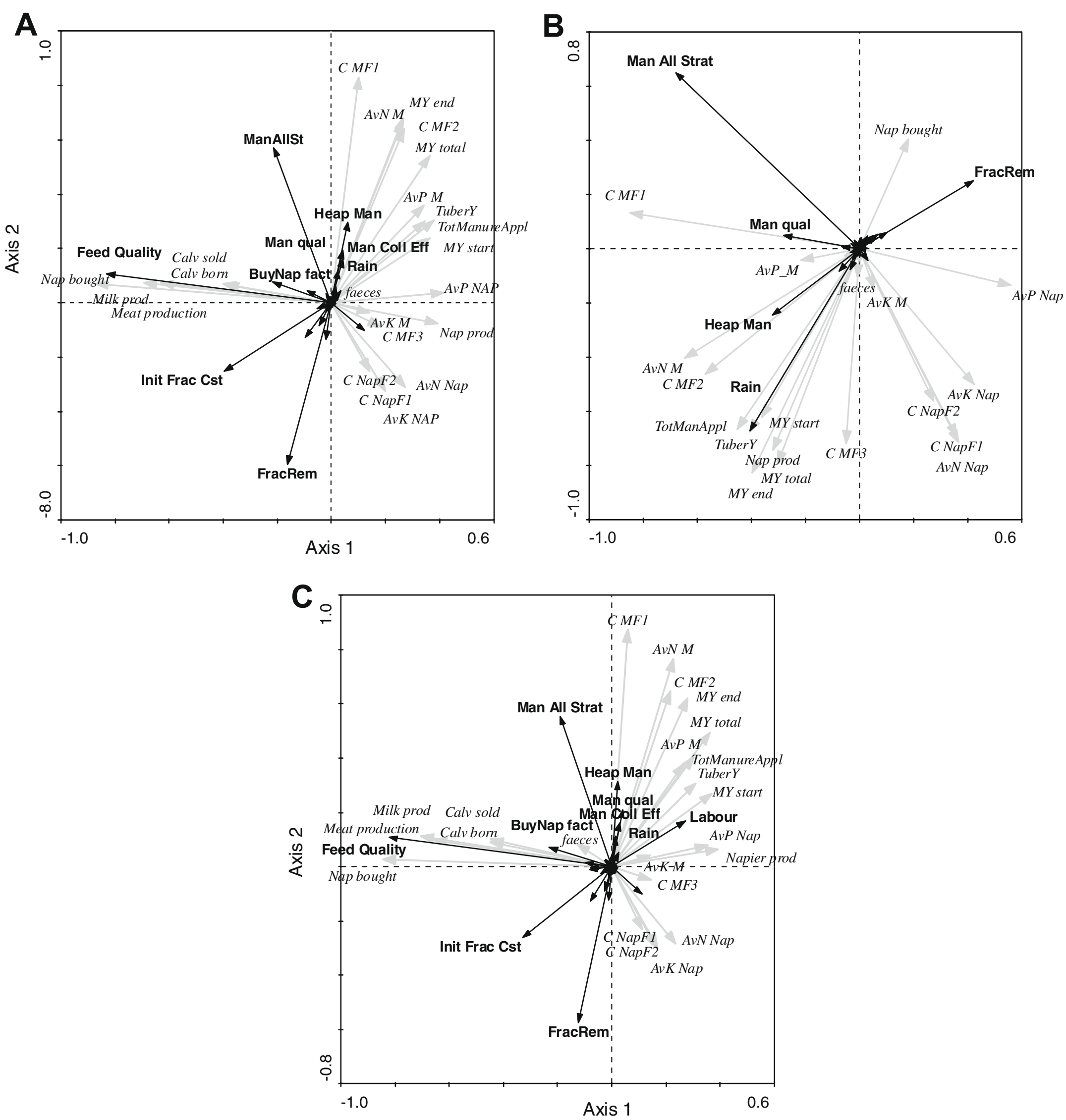

Fig. 3. Redundancy analysis (RDA) plots of the results of the sensitivity analysis of the farming system (values on axes give the ordination scores). Variables in black are input parameters, in grey are outputs of the model (see text for further explanation). Abbreviations of variables are given in Tables 1 and 3. (A) Scenario 1: analysis for a farm without input of mineral fertilizers and without labour constraints; (B) Scenario 2: analysis for a farm with input of mineral fertilizers and without labour constraints; and (C) Scenario 3: analysis for a farm without input of mineral fertilizers and with labour constraints.

the productivity variables: livestock weight gain, amount of milk and number of calves produced for the livestock subsystem. The most important drivers of these output variables were the manure allocation strategy (concentrating manure on the best maize fields results in higher overall farm maize yield) and the fraction of crop residues that is removed after harvest for the cropping subsystem: removal of crop residues affects crop yield negatively. Less important drivers of crop yield were the quality of the manure (higher manure quality gave better yields), the type of manure storage (ranging from not covering the manure heap without flooring to a roofed manure heap with concrete flooring; this variable affected the amount of manure produced), the amount of rainfall, parameters that determined the fraction of active organic matter at the start of the simulation and the relative rate of organic matter decomposition. The most important drivers for livestock productivity were fodder quality and the factor that determined at which degree of fodder deficit the farmer started buying in extra Napier grass. In this scenario, without mineral fertiliser, the way nutrients

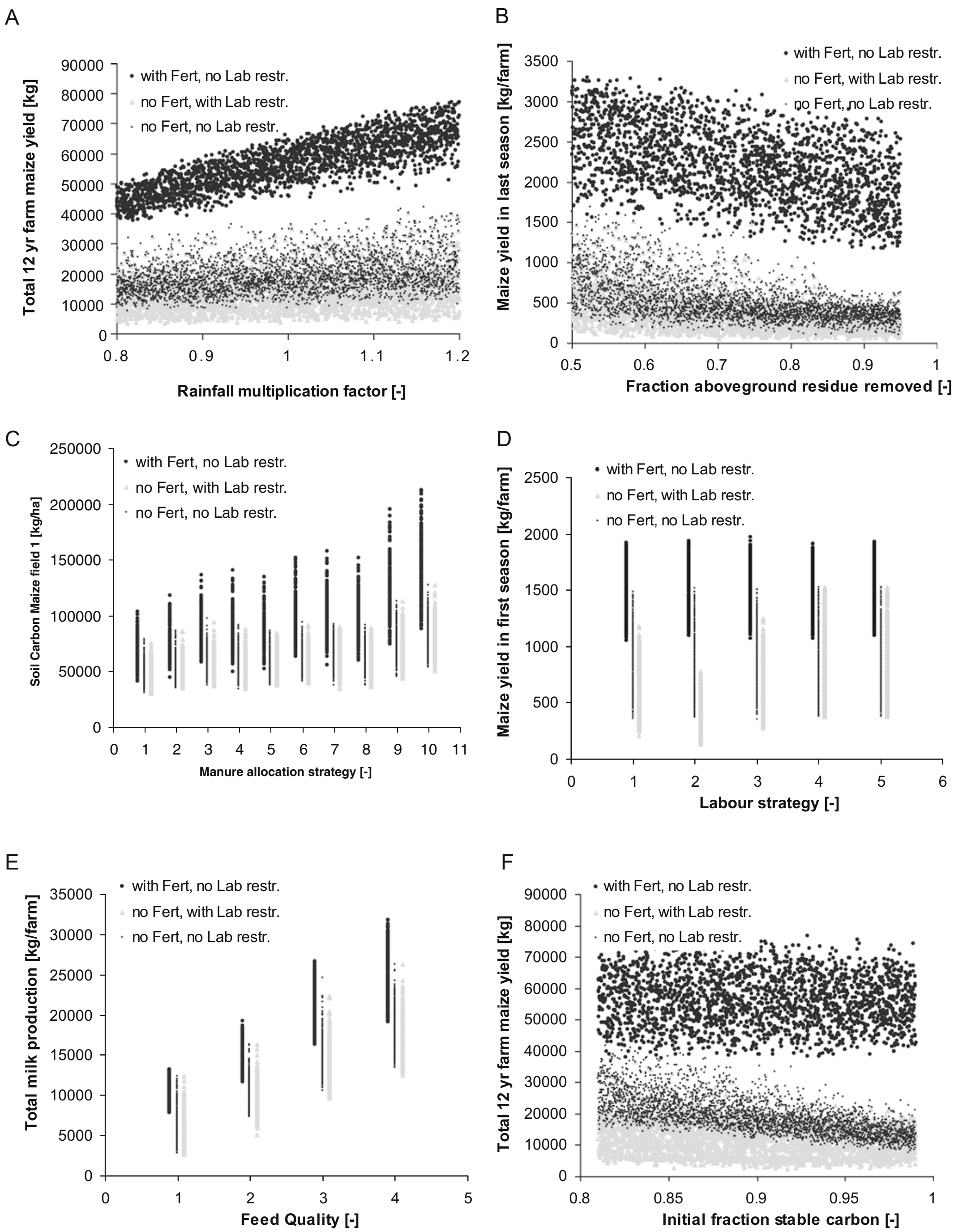

Fig. 4. Scatter plots between some of the strongest relationships found in analysing the results presented in Fig. 3 for the three scenarios: without fertilizer application and without labour limitation, with fertilizer application and without labour limitation and without fertilizer and with labour limitation (for further explanation see text); (A) total 12 year farm maize yield against the rainfall multiplication factor; (B) maize yield in the last growing season against the fraction removed of aboveground crop residues; (C) total soil carbon in maize field 1 after 12 years against the manure allocation strategy; (D) maize yield in the first growing season against the labour allocation strategy; (E) total 12 year milk production against feed quality; (F) total 12 year maize yield against the initial fraction stable soil carbon in the total soil carbon pool.

were managed and how efficiently they were recycled within the farming system were key for longer term productivity of the system.

In Scenario 2, with mineral fertiliser available and without labour constraints, a strong shift in the importance of the different parameters and factors occurred compared with Scenario 1 (Fig. 3B). The most important variability in terms of model outputs only occurred in the crop subsystem, the model output variables of the livestock subsystem were no longer visible in the first two RDA axes (which represent 72% of the model output variability). The most important difference with Scenario 1 was that the amount of rainfall became a more important variable determining maize productivity.

In Scenario 3 we analysed the situation when no fertiliser was available, and when there was a labour constraint during the weeding period. The results of the RDA analysis are shown in Fig. 3C. Similar to Fig. 3A, the two main axes of Fig. 3C were determined by the cropping and livestock subsystem, but, not surprisingly taking into account that labour was a limiting factor, the labour allocation strategy became a determining factor. The explanatory power of the first two RDA axes decreased (explained variability was 63%) due to extra uncertainty caused by the parameters that determined the labour–production relationships, although these did not stand out in the analysis as the major factors determining variability.

An RDA is a rather abstract way of representing the most important relationships within a given dataset, that does not show clearly the strength of relationships between the different variables. Therefore, we analysed the most important correlations found in Fig. 3A–C by plotting relationships between the most important input–output relationships found in the RDA analyses (Fig. 4). The rainfall multiplier (i.e. the value with which the standard rainfall dataset is multiplied to simulate different rainfall inputs, Fig. 4A) had a strong positive effect on total maize yield over 12 years when fertiliser was available, but only a weak positive effect when no fertiliser was applied. Thus the system was mainly nutrient-limited, and water became the most limiting factor for production only when nutrients were supplied in large amounts as mineral fertiliser. These results were also reflected in the RDA diagrams of Fig. 3: the size of the rainfall arrow (which reflects the explanatory power of rainfall in terms of the variability in model outputs) was largest in the 'with fertiliser' scenario. When labour was a limiting factor at farm level, grain yields could be, but not necessarily had to be, smaller than when labour was not limiting (Fig. 4A). If labour was not allocated preferentially to cropping activities, a constraint in labour availability led to lower yield, because not enough labour was allocated to weeding. However, if labour was allocated preferentially to cropping activities then crop yield was not always decreased because the available labour at farm level was sufficient for the cropping activities. The longer term effects of crop residue removal were examined by plotting the relative removal factor versus maize yield in the last growing season: a negative correlation was visible in all scenarios (Fig. 4B). The larger spread in the 'with fertiliser' scenario was caused by the strong effect of rainfall variability (see Fig. 4A). There was a positive effect on soil carbon after 12 years when the available manure coming out of the manure heap was increasingly concentrated on maize field number 1 (Fig. 4C). The values of soil carbon calculated after 12 years were sometimes unrealistically high: these C values represent parameterizations with low relative decomposition rates, high aboveground biomass production and therefore high availability of crop residues, plus a large input of manure into this field, which are unlikely to occur in practice. The labour allocation strategy had relatively minor effects on maize yield in the first season (which was the strongest relationship present in our analyses; Fig. 4D). A negative effect on maize yield was only visible with labour allocation Strategy 1, 2 and 3, the three allocation strategies concentrating on livestock and heap management. Of course no relationship between the labour allocation scenario and maize yield was visible in the scenario without labour limitation. Feed quality was clearly one of the strongest drivers within the system (Fig. 4E). The initialisation of the relative amount of stable soil carbon (Fig. 4F) had a relatively strong effect on the long-term productivity of the farm (cf. Fig. 3A and C) that overruled only by applying a large amount of mineral fertiliser.

Some of the relationships between the amount of Napier grass bought during a simulation and other variables are shown in Fig. 5. Only the average values are shown together with the standard error of the mean, as opposed to the individual values of the sensitivity analysis (Fig. 4), because often no Napier grass was bought. The amount of Napier grass bought was clearly dependent on whether or not fertiliser was used (Fig. 5A). In general, if more Napier grass was bought (which is of good quality) the bodyweight gain increased (Fig. 5A). This was driven by the threshold at which the farmer started to buy Napier grass which ranged between 50% and 100% of maximum intake. The higher this threshold, the more Napier the farmer would buy, and this had a positive effect on cattle production. The amount of Napier grass bought was also affected when labour was a limiting factor. If labour was preferentially allocated to livestock activities, resulting in a higher availability of weeds and roadside grass collected, less Napier grass needed to be purchased. However, if labour was more concentrated on cropping activities (Strategies 4 and 5), more Napier grass needed to be purchased. The effect was not strong, be-

Fig. 5. Relationships between livestock weight gain over 12 years and the extra amount of Napier grass bought in by the farmer (A) and the extra amount of Napier grass bought in by the farmer and the labour allocation strategy. Results come from the sensitivity analysis, and are presented for the three scenarios (without fertilizer application and without labour limitation, with fertilizer application and without labour limitation and without fertilizer and with labour limitation); error bars represent standard deviation.

cause allocating more labour to cropping activities also meant that more time was invested in managing the Napier grass fields, which therefore resulted in more production of Napier grass on-farm.

In the farm with only fields with relatively good soil fertility (i.e. with no pronounced soil fertility gradient; Fig. 6A) Napier grass production was one of key output variables together with the soil carbon content and the availability of N, P and K on those fields. Both the manure allocation strategy (the higher the value the more manure goes to the maize fields) and the initialisation of stable soil carbon showed a strong negative correlation with the Napier grass production. By contrast, on this farm with fertile fields, maize yield was much more independent of driving variables such as the fraction of aboveground biomass removed, the manure allocation strategy and the initial fraction of stable C. This was completely different on a farm with only relatively poor fields (Fig. 6B). Here the manure allocation strategy was strongly correlated with the total maize yield produced on the farm, and the maize production was strongly negatively correlated with Napier grass production. Strong competition for the available manure was apparent: on the farm with poor soil fertility the manure was essential to attain

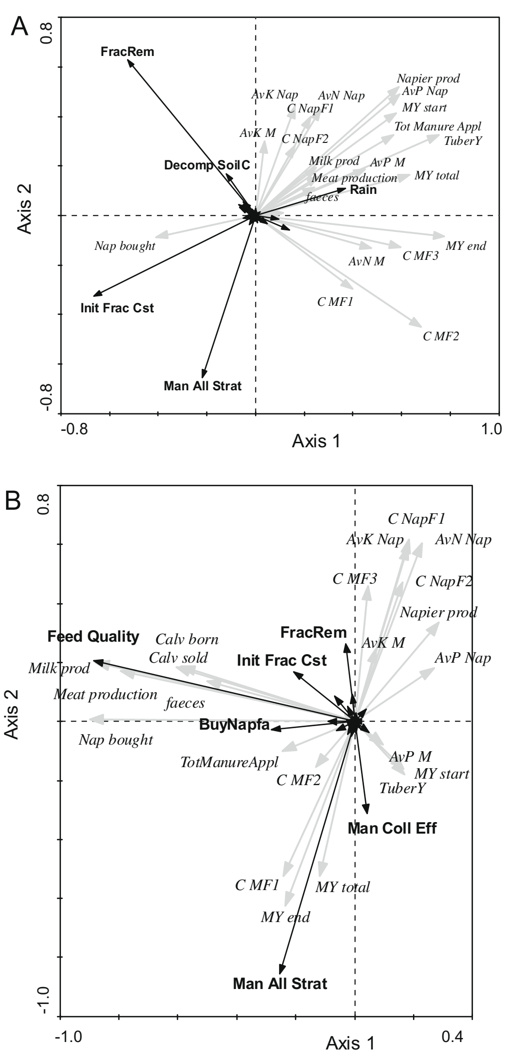

Fig. 6. Two redundancy analysis (RDA) plots of the results of the sensitivity analysis of the farming system without a soil fertility gradient: (A) a farm with relatively fertile fields; (B) a farm with relatively poor fields. Variables in black are input parameters, in grey are outputs of the model (see text for further explanation). Abbreviations of variables are given in Tables 1 and 3. Values on axes give the ordination scores.

maize production, and there was insufficient manure available to achieve good production of both Napier grass and maize. In this analysis, the manure collection efficiency was also a key variable. The efficiency with which manure was collected and recycled became an important driver of the systems because of the essential role of manure for soil productivity. The second RDA axis was determined by the livestock production variables, similar to the results of Scenario 1 (Fig. 3A).

4. Discussion and conclusions

The sensitivity analyses of the NUANCES-FARMSIM model showed that, despite the uncertainty in the model description, the model is sufficiently robust to identify the key management options within a smallholder farming system when focusing on the production side of the system. Several management options working at farm scale were the most important factors determining the variations in farm productivity, and overruled the uncertainty in process description (see Fig. 3). The sensitivity analyses showed clearly that most important decisions are taken with regard to the interactions between the different components of the farm and that strong trade-offs exist between the different production components (e.g. Fig. 6). This shows the importance of integrating crop, soil and livestock components within one modelling system, as the production capacity of one component in the longer term also affects the production capacity of other components (see Fig. 2). The amount of manure and crop residues produced and the way they are allocated across the different cropping fields determines the production capacity of the system in the long run (10–15 years. The results of the sensitivity analyses further showed that if these farm level management decisions are not understood in detail when describing the mixed crop–livestock systems, a strong focus on further improving the reliability of the field level process descriptions will result in minor improvement in the description of the behaviour of the farming system (Fig. 3). When analysing the efficiency of the smallholder farming system, improving our understanding of the way organic matter is managed on the farm is far more important than increasing our accuracy in simulating crop production at field level. The only model-specific parameter that had a strong effect on farm productivity was the one determining the initial partitioning of soil carbon into labile and stable fractions: and this could be readily explained due to its strong effect on crop production.

Our approach in the analyses presented in this study was to combine – in a dynamic way – individual tools that have been developed and tested for the key production components of the African smallholder farm: livestock, crops, and soils. This integrated system, in combination with quantification of the implications of labour shortages in different periods in the year, gave us clear insight in the determining factors at farm scale. Because of the simplicity of the individual components, the overall integrated model system was still manageable in terms of its complexity and of the number of input data required.

We believe our approach has advantages compared with existing dynamic farm model applications. The combination of an tightly integrated crop – livestock model, while taking into account within farm variability, for example soil fertility gradients, is new. Existing model applications focus either on the crop – soil components (e.g. Ncube et al., 2009; Robertson et al., 2005; Whitbread et al., 2004; Matthews and Stephens, 2002; Tittonell et al., 2006) or attempt to model the farming system without taking into account within farm variability (e.g. Struif Bontkes and Van Keulen, 2003; Shepherd and Soule, 1998). Results of the model simulations show that within mixed smallholder farming systems the feedbacks between livestock and soil fertility are strong: the two cows

in our model do not produce enough manure to maintain soil organic carbon in all three fields (see Fig. 2C), and therefore in the longer term crop production declined (Fig. 2B). Manure and fertilizer allocation strategies are important in this case because the decision to either concentrate manure in one or two fields or to spread it over all fields evenly results in different total farm level production (see Fig. 4, but also Rowe et al., 2006) because nutrient use efficiency is strongly affected by soil fertility (e.g. Vanlauwe et al., 2006; Zingore et al., 2007).

The NUANCES-FARMSIM model has been developed specifically to analyse the production of smallholder farming systems in sub-Saharan Africa (SSA). The interactions between the different sub-models describing the different production components have therefore been determined specifically for the African conditions we encountered and application outside of SSA would mean that especially at farm level new relationships and interactions will need to be defined. However, the concepts of the different sub-models, FIELD, HEAPSIM and LIVSIM, are generally applicable, and therefore there is no fundamental reason why these sub-models cannot be applied elsewhere in the world. For example the FIELD model has been tested under European conditions (Adam et al., 2008).

The sensitivity analysis presented here shows that, for the farming systems under study, the most important settings determining the outcomes at farming system scale were: organic matter management, allocation of resources and the availability of fertiliser and labour for production purposes (Figs. 3 and 6). For the livestock component, under the feeding regimes employed in this study and the fixed replacement decision-making incorporated in the model, fodder quality was the overriding parameter determining productivity. If labour is limiting, for example for proper weeding of the fields, then the decisions made with regard to the allocation of this constraining factor also become key (Fig. 3C). FARMSIM model is an exploration tool for researchers designed to quantify the consequences of decisions taken by the farmer (e.g. allocation of resources) on the long-term productivity of the system. The overall FARMSIM model cannot be evaluated or tested using datasets of farm development currently available. By testing the individual components in other studies and by presenting the way the components have been linked we gained confidence in the way the model functions and in the results the model generates, so that it can be used to explore possible effects of interventions.

The simplicity of the component models means that not all management options of smallholder farmers can be analysed. For example, the seasonal time-step of the FIELD model does not allow us to analyse irrigation schemes in which the farmer can alter the distribution of water availability throughout the season. For applications such as this, more detailed analyses using models like APSIM (e.g. Keating et al., 2003) or DSSAT (e.g. Jones et al., 2003) are necessary. If clear responses are found using more detailed models (for example between the length of a longest dry period in the rainy season and crop production) then these can be built into the NUANCES-FIELD model. However, the sensitivity analysis clearly shows that by coupling the modules to analyse the behaviour of the whole farming system, more is gained in terms of system understanding by increasing our understanding of the interactions between the components (i.e. farm management and the efficiency of recycling of resources) than by increasing the accuracy of the individual components of the smallholder farming system. For example, the uncertainty in the crop model parameters resulted in a variation in crop productivity of about 20%. However, this 20% variation was still overruled in the longer term by other driving variables and parameters like crop residue management, manure allocation and, if fertilisers are applied, the amount of rainfall. This suggests that management options to improve productivity at field scale must have a very strong effect before they can have a significant impact at farm scale.

The analyses for this medium-endowed smallholder farming system in Western Kenya showed that the management of the organic resources at farm level is absolutely key. The manure collection efficiency, the quality of manure storage and the allocation of manure over the cropping fields are important drivers of the farm production level after about 10 years (Figs. 3 and 4). Although the amount of rainfall has some effect on farm production, it is currently not the limiting factor for these farm systems (e.g. Tittonell et al., 2006). Only when nutrient availability is increased strongly, for example through application of mineral fertiliser, does the amount of rainfall (and probably also its distribution) become a major constraint for production (Figs. 3B and 4A).

How exactly the management options work out, and which of the options are the most important, depends on the soil fertility status of the farm. In the absence of a soil fertility gradient the effect of the different management options is different for a farm with good soil fertility than for a farm with poor soil fertility (Fig. 6). This means that it is difficult to derive generic recommendations. Depending on the specific characteristics of the farm, different management options will have more or less effect on farm productivity.

A clear result from the sensitivity analysis of the farm without a soil fertility gradient and with low soil fertility was the strong competition within the farm for the available organic resources (Fig. 6B). There was a strong negative correlation between simulated Napier grass and maize productivity, showing that these farms are highly resource-limited and that strong trade-offs existed in how resources can be used. In this farm there is not enough manure available to boost the productivity of both maize and Napier grass, and therefore a choice has to be made for one of these crops. This shows the importance of a whole farm perspective, because despite these soils being responsive to organic inputs (e.g., Kapkiyai et al., 1999) potential productivity of this farm was strongly limited by the amounts of such inputs that are available. It is therefore key in analysing these systems to take into account the interrelationships between livestock, manure management and crop and fodder production to understand the functioning of the farming system and the potential for intensification.

It is important to note that these results are specific for the farm that is analysed in this study and for the prevailing agro-ecological conditions. Further research should assess whether the key factors emerging from this study are also relevant for a wider range of systems. For example, it is logical that if nutrients are limiting the way nutrients are managed within the system is important. This can be seen as a more general pattern that could have been identified even without using a model. However, the study presented here demonstrates quantitatively how important soil fertility is relative to other factors in the system, which is less easy to do without an integrated crop–livestock analysis tool such as NUANCES-FARMSIM.

The only model parameter at field level that showed a consistent strong effect on the long-term productivity at farm level is the fraction of stable organic matter in the FIELD model (Fig. 4F). This parameter quantifies the relative amounts of active and stable organic carbon in the soil, and thereby determines how much of the carbon in the soil actively decomposes and supplies nutrients to the crops. This is a parameter that is difficult to derive from most soil data routinely collected in African farming systems. To date the parameter has been determined empirically by fitting the model using carbon chronosequence data (e.g. Tittonell et al., 2007a, 2008). The importance of this parameter for the long-term productivity of the farm means that this parameter should be determined with high accuracy, although this is difficult experimentally.

In comparison with existing farming system tools, the NUANCES-FARMSIM model allows a dynamic analysis of the way the farm develops over time. It includes the most important production components of smallholder farming system, and takes into account all the relationships between these components. In this way it is a more realistic representation of the farming system than is currently used in tools like linear programming. Whereas linear programming tools find their most important application in terms of prototyping (e.g. Sterk et al., 2007), it is debatable whether this is a useful way to represent these systems if one wants to analyse possible developmental pathways (Lynam, 2002). On the other hand, using more detailed models such as APSIM or RUMINANT can give important insights in the functioning of separate components of the farming system, but in general they are too demanding of input data to be used for a whole farming system analysis which can be applied easily over a range of systems. Although the current version of the tool is not completely integrated in terms of the financial consequences of certain decisions, NUANCES-FARMSIM can be used for detailed analyses of the interactions between the different components of the farm. Future developments of the model will be focused on improving the description of the socio-economic components of the farm (cash, labour, etc.) and on applying the model to analyse the consequences of interactions between different types of farmers within a village across different locations in sub-Saharan Africa.

Acknowledgement

We thank the European Union for funding this research through the AfricaNUANCES Project (Contract No. INCO-CT-2004-003729).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.agsy.2009.07.004.

References

Adam, M., Tittonell, P., Bergez, J.E., Ewert, F., Leffelaar, P., 2008. From detailed to summary models of the crop–soil system for larger scale applications. In: Oral Presentation on the X ESA Congress, 15-19 September 2008, Bologna, Italy.

Bebe, B.O., Udo, H.M.J., Rowlands, G.J., Thorpe, W., 2003. Smallholder dairy systems in the Kenya highlands: cattle population dynamics under increasing intensification. Livest. Prod. Sci. 82, 211–221.

Chikowo, R., Corbeels, M., Tittonell, P., Vanlauwe, B., Whitbread, A.M., Giller, K.E., 2008. Using the crop simulation model APSIM to generate functional relationships for analysis of resource use in African smallholder systems: aggregating field-scale knowledge for farm-scale models. Agric. Syst. 97, 151–166.

De Ridder, N., Breman, H., Van Keulen, H., Stomph, T.J., 2004. Revisiting a 'cure against land hunger': soil fertility management and farming systems dynamics in the West African Sahel. Agric. Syst. 80, 109–131.

Dixon, J., Gulliver, J., Gibbon, D., 2001. Farming Systems and Poverty, Improving Farmers Livelihoods in a Changing Wold. Food and Agriculture Organization and World Bank, Rome, Italy, and Washington, DC, US.

Giller, K.E., Rowe, E.C., de Ridder, N., van Keulen, H., 2006. Resource use dynamics and interactions in the tropics: scaling up in space and time. Agric. Syst. 88, 8–27.

Herrero, M., Fawcett, R.H., Dent, J.B., 1999. Bio-economic evaluation of dairy farm management scenarios using integrated simulation and multiple-criteria models. Agric. Syst. 62, 169–188.

IAC, 2004. Realising the Promise and Potential of African Agriculture. Science and Technology Strategies for Improving Agricultural Productivity and Food Security in Africa, InterAcademic Council, The Netherlands. 266pp.

Iman, R.L., Helton, J.C., Campbell, J.E., 1981. An approach to sensitivity analysis of computer models, Part 1. Introduction, input variable selection and preliminary variable assessment. J. Qual. Technol. 13, 174–183.

Jaetzold, R., Schmidt, H., 1982. Farm management handbook of Kenya. Natural Conditions and Farm Management Information. Part A: West Kenya, vol. II. Kenya Ministry of Agriculture, Nairobi, Kenya.

Janssen, B.H., Lathwell, D.J., Wolf, J., 1987. Modeling long-term crop response to fertilizer phosphorus. II. Comparison with field results. Agron. J. 79, 452–458.

Janssen, S., van Ittersum, M.K., 2007. Assessing farm innovations and responses to policies: a review of bio-economic farm models. Agric. Syst. 94, 622–636.

Jones, J.W., Hoogenboom, G., Portera, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. Eur. J. Agron. 18, 235–265.

Jongman, R.H.G., Ter Braak, C.J.F., Van Tongeren, O.F.R., 1995. Data Analysis in Community and Landscape Ecology. Cambridge University Press, Cambridge.

Kapkiyai, J.J., Karanja, N.K., Qureshi, J.N., Smithson, P.C., Woomer, P.L., 1999. Soil organic matter and nutrient dynamics in a Kenyan nitisol under long-term fertilizer and organic input management. Soil Biol. Biochem. 31, 1773–1782.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron. 18, 267–288.

Lynam, J., 2002. A history of farming systems research. Book review. Agric. Syst. 73, 227–232.

Matthews, R., 2006. The people and landscape model (PALM): towards full integration of human-decision-making and biophysical simulation models. Ecol. Model. 194, 329–343.

Matthews, R.B., Pilbeam, C., 2005. Modeling the long-term productivity and soil fertility of maize/millet cropping systems in the mid-hills of Nepal. Agric. Ecosyst. Environ. 111, 119–139.

Matthews, R.B., Stephens, W., 2002. Crop–Soil Simulation Models. Applications in Developing Countries. CABI publishing, Wallingford, UK. 277pp.

McIntire, J., Bourzat, D., Pingali, P., 1992. Crop–Livestock Interactions in Sub-Saharan Africa. World Bank, Washington, DC, US.

McKay, M.D., Conover, W.J., Beckman, R.J., 1979. A comparison of three methods for selecting values of input variables in the analysis of output from a computer code. Technometrics 21, 239–245.

Muia, J.M.K., 2000. Use of Napier Grass to Improve Smallholder Milk Production in Kenya. Wageningen University, Wageningen. p. 252.

Muia, J.M.K., Tamminga, S., Mbugua, P.N., Kariuki, J.N., 1999. Optimal stage of maturity for feeding Napier grass (*Pennisetum purpureum*) to dairy cows in Kenya. Trop. Grass. 33, 182–190.

Ncube, B., Dimes, J.P., van Wijk, M.T., Twomlow, S.J., Giller, K.E., 2009. Productivity and residual benefits of grain legumes to sorghum under semi-arid conditions in south-western Zimbabwe: unravelling the effects of water and nitrogen using a simulation model. Field Crop. Res. 110, 173–184.

Pacini, C., Wossink, A., Giesen, G., Huirne, R., 2004. Ecological-economic modelling to support multi-objective policy making: a farming systems approach implemented for Tuscany. Agric. Ecosyst. Environ. 102, 349–364.

Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G., Giller, K.E., 2001. Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agric. Ecosyst. Environ. 83, 27–42.

Robertson, M.J., Sakala, W., Benson, T., Shamudzarira, Z., 2005. Simulating response of maize to previous velvet bean (*Mucuna pruriens*) crop and nitrogen fertiliser in Malawi. Field Crop. Res. 91, 91–105.

Rowe, E.C., Van Wijk, M.T., De Ridder, N., Giller, K.E., 2006. Nutrient allocation strategies across a simplified heterogeneous African smallholder farm. Agric. Ecosyst. Environ. 116, 60–71.

Rufino, M.C., Tittonell, P., Van Wijk, M.T., Castellanos-Navarrete, A., De Ridder, N., Delve, R.J., Giller, K.E., 2007. Manure as a key resource within smallholder farming systems: Analysing farm-scale nutrient cycling efficiencies with the NUANCES framework. Liv. Sci. 112, 273–287.

Rufino, M.C., Herrero, M., Van Wijk, M.T., Hemerink, L., de Ridder, N., Giller, K.E., 2009. Lifetime productivity of dairy cows in smallholder farming systems of the Central Highlands of Kenya. Animal 3, 1044–1056.

Sanchez, P., Shepherd, K., Soule, M., Place, F.M., Buresh, R.J., Izac, A.M.N., 1997. Soil fertility replenishment in Africa: an investment in natural resource capital. In: Buresh, R.J., Sanchez, P.A., Calhoun, F. (Eds.), Replenishing Soil Fertility in Africa. ASSA, CSSA, SSSA, Wisconsin, pp. 1–46.

Shepherd, K.D., Soule, M.J., 1998. Soil fertility management in west Kenya: dynamic simulation of productivity, profitability and sustainability at different resource endowment levels. Agric. Ecosyst. Environ. 71, 131–145.

Sterk, B., van Ittersum, M.K., Leeuwis, C., Wijnands, F.G., 2007. Prototyping and farm system modelling – partners on the road towards more sustainable farm systems? Eur. J. Agron. 26 (4), 401–409.

Stoorvogel, J.J., Smaling, E.M.A., 1998. Research on soil fertility decline in tropical environments: integration of spatial scales. Nutr. Cycl. Agroecosys. 50, 151–158.

Stoorvogel, J.J., Smaling, E.M.A., Janssen, B.H., 1993. Calculating soil nutrient balances in Africa at different scales. 1. Supra-national scale. Fert. Res. 35, 227–235.

Struif Bontkes, T., Van Keulen, H., 2003. Modelling the dynamics of agricultural development at farm and regional level. Agric. Syst. 76, 379–396.

Ter Braak, C.J.F., Smilauer, P., 2002. CANOCO Reference Manual and Canodraw for Windows User's Guide: Software for Canonical Community Ordination (Version 4.5), Microcomputer Power, Ithaca, NY, USA.

Thornton, P.K., Herrero, M., 2001. Integrated crop–livestock simulation models for scenario analysis and impact assessment. Agric. Syst. 70, 581–602.

Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Shepherd, K.D., Giller, K.E., 2005. Exploring diversity in soil fertility management of smallholder farms in western Kenya – II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. Agric. Ecosyst. Environ. 110, 166–184.

Tittonell, P., Leffelaar, P.A., Vanlauwe, B., Van Wijk, M.T., Giller, K.E., 2006. Exploring diversity of crop and soil management within smallholder African farms: a

dynamic model for simulation of N balances and use efficiencies at field scale. Agric. Syst. 91, 71–101.

Tittonell, P., Zingore, S., Van Wijk, M.T., Corbeels, M., Giller, K.E., 2007a. Nutrient use efficiencies and crop responses to N, P and manure applications in Zimbabwean soils: exploring management strategies across soil fertility gradients. Field Crop. Res. 100, 348–368.

Tittonell, P., van Wijk, M.T., Rufino, M.C., Vrugt, J.A., Giller, K.E., 2007b. Analysing trade-offs in resource and labour allocation by smallholder farmers using inverse modelling techniques: a case-study from Kakamega district, western Kenya. Agric. Syst. 95, 76–95.

Tittonell, P., Corbeels, M., van Wijk, M.T., Vanlauwe, B., Giller, K.E., 2008. Combining organic and mineral fertilizers for integrated soil fertility management in smallholder farming systems of Kenya – explorations using the crop-soil model FIELD. Agron. J. 100, 1511–1526.

Tittonell, P., van Wijk, M.T., Herrero, M., Rufino, M.C., de Ridder, N., Giller, K.E., 2009. Beyond resource constraints – exploring the physical feasibility of options for the intensification of smallholder crop-livestock systems in Vihiga district, Kenya. Agric. Syst. 101, 1–19.

Vanlauwe, B., Tittonell, P., Mukalama, J., 2006. Within-farm soil fertility gradients affect response of maize to fertiliser application in western Kenya. Nutr. Cycl. Agroecosys. 76, 171–182.

Van de Ven, G.W.J., de Ridder, N., van Keulen, H., van Ittersum, M.K., 2003. Concepts in production ecology for analysis and design of animal and plant–animal production systems. Agric. Syst. 76, 507–525.

Van Ittersum, M.K., Leffelaar, P.A., Van Keulen, H., Kropff, M.J., Bastiaans, L., Goudriaan, J., 2003. On approaches and applications of the Wageningen crop models. Eur. J. Agron. 18, 201–234.

Van Keulen, H., 1995. Sustainability and long-term dynamics of soil organic matter and nutrients under alternative management strategies. In: Bouma, J. (Ed.), Ecoregional Approaches for Sustainable Land Use. Kluwer, The Netherlands, pp. 353–375.

Whitbread, A., Braun, A., Alumira, J., Rusike, J., 2004. Using the agricultural simulation model APSIM with smallholder farmers in Zimbabwe to improve farming practices. In: Whitbread, A., Pengelly, B.C. (Eds.), Tropical Legumes for Sustainable Farming Systems in Southern Africa and Australia, ACIAR Proceedings, No. 115, Canberra, Reprint No. 5035, pp. 170–180.

Wolf, J., de Wit, C.T., van Keulen, H., 1989. Modelling long-term crop response to fertilizer and soil nitrogen. I. Model description and application. Plant Soil 120, 11–22.

Zingore, S., Murwira, H.K., Delve, R.J., Giller, K.E., 2007. Soil type, management history and current resource allocation: three dimensions regulating variability in crop productivity on African smallholder farms. Field Crop. Res. 101, 296–305.