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Beyond resource constraints – Exploring the biophysical feasibility of options for the intensification of smallholder crop-livestock systems in Vihiga district, Kenya

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ABSTRACT

During participatory prototyping activities in Vihiga, western Kenya, farmers designed what they considered to be the ideal farm [Waithaka, M.M., Thornton, P.K., Herrero, M., Shepherd, K.D., 2006. Bio-economic evaluation of farmers' perceptions of viable farms in western Kenya. Agric. Syst. 90, 243–271]: one in which high productivity is achieved through optimising crop-livestock interactions. We selected four case study crop-livestock farms of different resource endowment (Type 1–4 – excluding the poorest farmers, Type 5, who do not own livestock) and quantified all relevant physical flows through and within them. With this information we parameterised a dynamic, farm-scale simulation model to investigate (i) current differences in resource use efficiencies and degree of crop-livestock interactions across farm types; and (ii) the impact of different interventions in farm Types 3 and 4 on producing the desired shifts in productivity towards the ideal farm. Assuming no resource constraints, changes in the current farm systems were introduced stepwise, as both intensification of external input use (fertilisers and fodder) and qualitative changes in the configuration of the farms (i.e. changing land use towards fodder production, improving manure handling and/or changing cattle breeds). In 10-year simulations of the baseline, current scenario using historical weather data the wealthiest farms Type 2 achieved food self-sufficiency (FSS) in 20% of the seasons due to rainfall variability, whereas the poorer Type 4 only achieved FSS in 0 to 30% of the seasons; soil organic C decreased during the simulations at annual rates of −0.54, −0.73, −0.85 and −0.84 t C ha^{-1} on farms of Type 1–4, respectively; large differences in productivity and recycling efficiency between farm types indicated that there is ample room to improve the physical performance of the poorer farms (e.g. light and water use efficiency was 2–3 times larger on wealthier farms). Simulating different intensification scenarios indicated that household FSS can be achieved in all farm types through input intensification, e.g. using P fertilisers at rates as small as 15 kg farm^{-1} season^{-1} (i.e. from 7 to 28 kg ha^{-1}). Increasing the area under Napier grass from c. 20 to 40% and reducing the area of maize, beans and sweet potato in farms of Type 3 and 4 increased their primary productivity by c. 1 t ha^{-1} season^{-1}, their milk production by 156 and 45 L season^{-1}, respectively, but decreased the production of edible energy (by 2000 and 250 MJ ha^{-1} season^{-1}) and protein (by 20 and 3 kg ha^{-1} season^{-1}). By bringing in a more productive cow the primary productivity increased even further in Farm Type 3 (up to 5 t ha^{-1} season^{-1}), as did milk production (up to c. 1000 L season^{-1}), edible energy (up to c. 10,000 MJ ha^{-1} season^{-1}) and protein (up to c. 100 kg ha^{-1} season^{-1}). The impact of livestock management on the recycling of nutrients and on the efficiency of nutrient use at farm scale can be large, provided that enough nutrients are present in or enter the system to be redistributed. An increase in N cycling efficiency through improved manure handling from 25 to 50% would increase the amount of N cycled in the case study farms of Type 1 and 2 by only ca. 10 kg season^{-1}, and only 1–2 kg season^{-1} in Type 3 and 4. The various alternatives simulated when disregarding resource constraints contributed to narrow the productivity and efficiency gaps between poorer and wealthier farms. However, the feasibility of implementing such interventions on a large number of farms is questionable. Implications for system (re-)design and intensification strategies are discussed.

1. Introduction

Sustainability assessments in much of sub-Saharan Africa (SSA) inform us that smallholder farming systems are inefficient, face se-

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vere resource limitations and degradation processes, and are vulnerable to changes in external driving variables; i.e. in the institutional, market and biophysical environments (e.g. Smaling et al., 1996; Barrett et al., 2002; Thomas and Twyman, 2005). Areas of high population density – originally of high agricultural potential – represent severe cases of ongoing deterioration of often-century-old smallholder systems, where demographic pressure leads to degradation or extinction of communal resources. These areas are common in the most fertile highland and midland agroecological zones of SSA, of which western Kenya is probably one of the most conspicuous examples (Braun et al., 1997). The challenge of achieving agricultural sustainability in densely-populated regions poses strong demands to agricultural research and development. The (re-)design of sustainable smallholder farming systems should aim to make these systems more stable, reliable and adaptable in face of external changes and, due to economic and environmental reasons, more efficient in the productive use of resources.

Thornton and Herrero (2001) proposed the use of integrated crop-livestock simulation models to aid the design of sustainable farming systems, by means of *ex-ante* evaluation or exploratory studies that search for ways of balancing crop-livestock interactions to capitalise synergies and improve resource use efficiencies at farm scale. Recent approaches to promote development in rural areas, however, have relied on intervention without rigorous *ex-ante* evaluation. In western Kenya, for example, an entire rural community (village) has been delimited as a benchmark, and since 2004 it became a pilot site for the simultaneous implementation of multiple technologies and social promotion activities with the aim of quantifying the investment necessary to meet the UN Millennium Development Goals – i.e. the ''Millennium Village'' (www.unmillenniumproject.org). We believe that the design of more sustainable and equitable agricultural systems should rest on, minimally: (i) thorough diagnosis of the baseline situation and understanding of the causes that render the systems unsustainable; (ii) social desirability of proposed alternatives and their compatibility with the local culture; (iii) ability to foresee, project or simulate internal and external changes in time and their consequences, in terms of the achievability and long-term stability of the newly-designed systems.

This study builds on a wealth of previous studies in the highlands of western Kenya. A key study that guided our questions is the evaluation of what farmers perceived as 'ideal farms', an application of participatory prototyping in the design of viable farms by Waithaka et al. (2006). In designing the ideal farms, the participating farmers assumed socio-economic and biophysical environments that were highly conducive. Thus, the ideal farms – which resembled farms of the wealthier families in the region – would have also 'ideal soils' that remained productive in time. The viability of such ideal farm prototypes was evaluated by Waithaka et al. (2006) for an average season integrating the results of a livestock-feeding simulation model and a household economic optimisation model. We used a dynamic approach in which relatively simple crop, soil and livestock simulation models are linked in a farm-scale modelling shell (FARM SIMulator – www.africanuances.nl). This integrated tool is then used to simulate the short and long-term dynamics of simplified but realistic systems chosen to represent farms with different resource endowments and livelihood strategies (i.e. Farm Types) derived from a typology of households in western Kenya. We hypothesised that the current configuration of wealthier farm types can be assimilated to what farmers in the region consider ideal farms, that there are alternative ways of shifting the configuration of average farms towards the ideal farm through intensification, and that such shift should be pursued gradually and sustainably. To test these hypotheses we analysed potential intensification pathways that ranged from increased (nutrient) input use intensity – a 'green revolution' type of approach – to changes in the configuration of the systems that demand more labour, management intensity and investments – i.e. qualitative or structural changes.

Our objectives were: (i) to evaluate the current biophysical performance of crop-livestock farms in terms of key flows determining resource use efficiency at farm scale (baseline characterisation), (ii) to assess the potential impact of options for their gradual and sustainable intensification towards the ideal farm prototypes designed by farmers (social desirability), and (iii) to explore whether these prototypes represent realisable improvements of the current farm systems to be achieved within reasonable time frames (achievability). The evaluation, assessment and explorations were based on analysing: farm productivity (food and feed self-sufficiency); resource use efficiencies; crop-livestock integration; and nutrient cycling and soil fertility. The analysis combined both short and the long-term, since some interventions typically induce positive responses after a number of seasons (e.g. rehabilitation of degraded soils with organic and mineral fertilisers). Emphasis was placed on identifying realisable biophysical frontiers for the intensification of crop-livestock interactions through innovative management within these systems. Thus, the role of farm labour and the financial constraints for the implementation of different management strategies and their consequences were not analysed quantitatively.

2. Materials and methods

2.1. Characterisation of the case study

The study was conducted in Vihiga district, which despite its relatively good agroecological potential is one of the poorest districts in Kenya, with an average of 58% of the households living below the poverty line. The area is densely-populated (i.e. 800–1100 people km^{-2}) and most of the land is used by smallholders farming very small pieces of land (i.e. 0.5 ha on average; Kiptot et al., 2007). Rainfall is bimodal, totalling 1850 mm $year^{-1}$, and allowing two cropping seasons (the long and the short rains) a year. Dominant soil types include deep reddish Nitisols, Ferralsols and Acrisols distributed in the upper positions of a heavily dissected plateau (Tittonell et al., 2005a; Tittonell et al., 2005b). Farms are predominantly integrated crop-livestock (maize-cattle) systems. Crops provide feed and bedding material (fodder, crop residues, weeds) for the cattle, and the cattle provide manure to fertilise the crops. A survey by Waithaka et al. (2002) indicated that 77% of the agricultural households in Vihiga kept cattle, of which 42% owned only zebu, 42% zebu and cross and/or pure exotic breeds, and 16% had solely cross or exotic pure breeds. Cattle productivity was poor, with average ages of first calving around 41 months, calving intervals of 22 months and milk production of 2.7 L cow^{-1} day^{-1}, associated with poor disease control, housing and management, and inadequate feeding. The land is allocated mostly to food crops, with about 10% allocated to cash crops (tea grown by the wealthiest farmers and vegetables by others), 11% to fodder crops (mostly Napier grass, *Pennisetum purpureum*), 12% to compound fields around the homestead and fallow land, and 5–10% to eucalyptus woodlots. Off-farm income is important for the households in the region. The sources of off-farm income to which households have access, and the regularity of this income, have strong impacts on the choice and performance of farming activities (Crowley and Carter, 2000).

The ideal farms designed by groups of farmers participating in prototyping activities conducted in four localities of Vihiga district (Waithaka et al., 2006) consisted of basically the same enterprises that can be seen today in typical farms of Vihiga. Participating

farmers placed emphasis on having dairy cattle and tea as a cash crop and had little diversity of food crops. Their size varied between 0.4 and 0.8 ha, and most of their area was allocated to the staple crop maize – even if it was amply available on the market. This is consistent with the fact that farmers had food security as their primary household objective, with surpluses for sale. To achieve the ideal farm intensification based on better management of crop-livestock interactions was deemed necessary, applying manure to fertilise crops and using crop residues to feed cattle. There was a limited understanding of input–output relationships, as farmers had high expectations of crop yields with minimal nutrient inputs, whilst the feed requirements of lactating cows were underestimated. Crop and milk yields estimated for the ideal farms were much larger than those achieved in the real farms; such differences were ascribed to the lack of land, of technical skills, of access to markets, of livestock breeding services, of capital to purchase high cost inputs (e.g. fertilisers, artificial insemination) and labour (e.g. late planting, poor weeding), and to cultural conventions (e.g. keeping low-yielding zebu cattle to pay dowries).

While these prototypes do not seem to be unachievable, their realisation would require a substantial shift towards increased resource endowment. Such a shift cannot include increasing the area cropped, since this is not possible in densely-populated areas such as Vihiga. Then, beyond current resource constraints, are there feasible technological options to operate such shifts through intensification, provided that the necessary investments are available? Major differences between the ideal and the current farms were the tighter management of crop-livestock interactions, that the ideal farms seemed to exist in an environment of more favourable input/output price ratios, and that farmers had an optimistic view on their biophysical productivity.

Tittonell et al. (2005a) classified farming systems in western Kenya into five farm types, of which Types 1–4 owned cattle (Table 1). These four livelihood strategies can be characterised as: Type 1 – subsidised; Type 2 – self-sufficient; Type 3 – expanding; Type 4 – subsisting. The fifth category, Type 5 – dependent, represents the poorest households often without cattle and are excluded from this analysis. Model explorations were run on four simplified crop-livestock farm systems representing Farm Types 1–4. Considering the results of the participatory prototyping described earlier, we assumed that farms of Type 1 and 2 represent two alternative models of the ideal farm; one in which off-farm income affords inflows of nutrients as feeds and fertilisers (Type 1), and one in which cycling of own farm resources allows less dependence on external nutrient inputs (Type 2). To explore interventions that could favour an upward shift of the current Farm Types 3 and 4 we analysed intensification scenarios consisting of: (i) increased use of external nutrient inputs; (ii) changes in land allocation between food and fodder crops and; (iii) changes in the productivity and efficiency of the livestock subsystem.

2.2. Overview of the model

FARMSIM (FARM SIMulator – van Wijk et al., in press) constitutes the farm-scale decision making shell of the NUANCES (Nutrient Use in ANimal and Cropping systems – Efficiencies and Scales) framework (Giller et al., 2006), where household objectives, constraints and resource (including labour) allocation patterns are simulated and economic balances calculated, linking the simulation results from different sub-models. Crop and soil modules are combined at field plot scale in the model FIELD (Field-scale resource Interactions, use Efficiencies and Long-term soil fertility Development – Tittonell et al., 2007). Different combinations of crop types and soil properties can be simulated to explore the interactions occurring within the farm for different field types (e.g. infields and outfields, annual and perennial crops, etc.). LIVSIM (LIVestock SIMulator – Rufino et al., 2009) is a model that simulates animal production and nutritive requirements of different cattle breeds, categories, and feed characteristics. The dynamics of nutrients through manure collection, storage and use as well as changes in quality due to management are simulated by HEAPSIM (manure HEAP SIMulator – Rufino et al., 2007), in which a fuzzy-logic approach is used to estimates C and nutrient transfer efficiencies through manure collection and storage under different livestock production systems and management. The variability in weather and market conditions, the dynamics of resource availability from common lands and the inflow of cash or kind from off-farm sources constitute inputs to FARMSIM that are accounted for and/or modified for scenario simulation, or simulated using auxiliary models.

Experimental data and, when possible, calibrated process-based models are used to generate functional relationships that are built into the various sub-models of FARMSIM. For instance, functional relationships that are built in FIELD, such as the effect of plant spacing on the fraction of radiation seasonally intercepted, have been derived using the model APSIM (Chikowo et al., 2008). Thus, these sub-models constitute summary models that incorporate processes and interactions in a descriptive rather than an explana-

Table 1
Functional typology for household categorisation applied in western Kenya by Tittonell et al. (2005a, 2009).

Farm Type	Resource endowment* and production orientation	Main source of income	Family structure**	Major constraints
1	High to medium resource endowment, mainly self-subsistence oriented	Permanent sources of off-farm income (e.g. salary, pension, etc.)	Variable age of the household head, small families	Mostly land availability (lack of family labour compensated by hiring-in)
2	High resource endowment, market-oriented	Cash crops and other farm produce sold on the market	Aged household head, numerous family (land subdivision starts)	Mostly labour (hired-in) due to large farm areas
3	Medium resource endowment, self consumption and (low-input) market-oriented	Marketable surpluses of food crops or annual cash crops	Young to mid-aged household head, expanding family	Mostly capital and sometimes labour
4	Predominantly low to medium resource endowment, self-subsistence oriented	Mostly non-farm activities (e.g. ox-plough service, handicrafts) plus marketable surpluses	Young to mid-aged household head, variable family size	Availability of land and capital
5	Low resource endowment, self-subsistence oriented	Selling their labour locally for agricultural practices	Variable age of household head and family size, often women-headed farms	Land and capital, (becoming labour-constrained due to selling labour)

* Referring to assets representing classical wealth indicators (i.e. land size, livestock ownership, type of homestead, etc.).
** In relation to the position of the household in the 'farm development cycle' (Crowley and Carter, 2000).

tory way, and operate with different time steps: monthly for livestock and manure, seasonal for annual crops, and in steps defined by cutting intervals for fodder crops (e.g. 60–80 days for Napier grass). For exploration of medium- to long-term changes in crop productivity and soil quality such summary models may suffice (Bouman et al., 1996). The data requirements of these models can be relatively easily satisfied for most African farming systems, and their results can be used for exploration of long-term management strategies since the dynamic character of the combined FARMSIM model allows simulation of all interactions and feedbacks illustrated in Fig. 1. A detailed description of the various components of the farm-scale model can be found in van Wijk et al. (in press). The individual crop-soil and livestock-manure modules of FARMSIM have been parameterised and tested individually for the highlands of Kenya in different previous studies (Chikowo et al., 2008; Rufino et al., 2007, 2009; Tittonell et al., 2008).

2.3. Systems definition

2.3.1. Simplified crop-livestock systems for scenario analysis

Relatively wealthy, market-oriented dairy farmers of Type 1 and 2 keep cross-bred cattle (usually crosses of Friesian, Ayrshire or Jersey with Zebu) in roofed and hard-floored zero grazing units, where Napier grass is fed in combination with concentrates and crop residues (Fig. 2). While farms in Type 2 tend to be self-sufficient in fodder production and sometimes are able to market surpluses, farms of Type 1 obtain fodder and other feeds from the market. These farmers often also have zebus grazing in the compound fields. Mid-class, semi-commercial farms of Type 3 often keep their cross-bred or local zebu cattle tethered in the compound, where they complement their grazing with Napier grass and crop residues; in times of scarcity poor quality fodder such as dry maize stover or banana leaves are offered to the animals. Poor, subsistence-oriented farmers that can afford to own cattle normally have local zebu breeds of small frame (±200 kg body weight) tethered in their compound, grazing standing crop residues in the crop fields and/or herded to graze communal patches of grass.

To represent Farm Types 1–4, four case study farms were selected in Emuhaya, Vihiga district and characterised quantitatively in the field (Karanja et al., 2006; Castellanos-Navarrete, 2007) (Tables 2 and 3). Household nutritional requirements and labour availability throughout the simulation period were calculated using IMPACT (Herrero et al., 2007a). Fertilisers were not used or used at low rates in the different case study farms. Most of the crop residue (i.e. 90%) was removed from the fields to feed the livestock in Farm Types 3 and 4, and about half of it remained in the field in Farm Types 1 and 2, where about half of the area was allocated to fodder production (c. 20% or less was allocated to fodder in farms of Type 3 and 4). Cross-bred dairy cattle were kept in Farm Types 1 and 2 and zebu breeds in the rest. To reflect differences in cattle breeds, and based on on-farm measurements, maximum milk productivity was set, respectively, at 18 and 9 L day^{-1} at the peak of the lactation curve. These values were used to parameterise *potential* milk production in LIVSIM, but are rarely observed in these systems (cf. Bebe et al., 2003).

Concentrates were used regularly for categories such as early lactating cows by Farm Types 1 and 2 and only occasionally by the rest. Purchasing fodder is a common practice in the region (Waithaka et al. 2006). Decisions on buying extra fodder to complement the diet were taken based on the difference (ΔF) between fodder on offer during a certain month and fodder requirements, as a function of potential intake calculated in LIVSIM. However, farmers may decide not to cover the full requirement but only enough to keep the animals alive. This was implemented by multiplying ΔF with a correction factor ($0 < CF < 1$) that accounted for whether farmers cover the full requirement ($CF \sim 1$) or just sufficient to keep the animals alive (i.e. a CF = 0.3 means that farmers covered 30% of the deficit with respect to the nutrient requirement for potential growth and production). The minimum values of CF were obtained through trial and error, by running the model repeatedly for each Farm Type and ensuring that the simulated amounts of fodder bought were in agreement with field observations (Castellanos-Navarrete, 2007) for these case study farms.

Roadside grasses, weeds, banana stalks and residues from outside fields (Fig. 2) were used to complete the diet in Farm Types

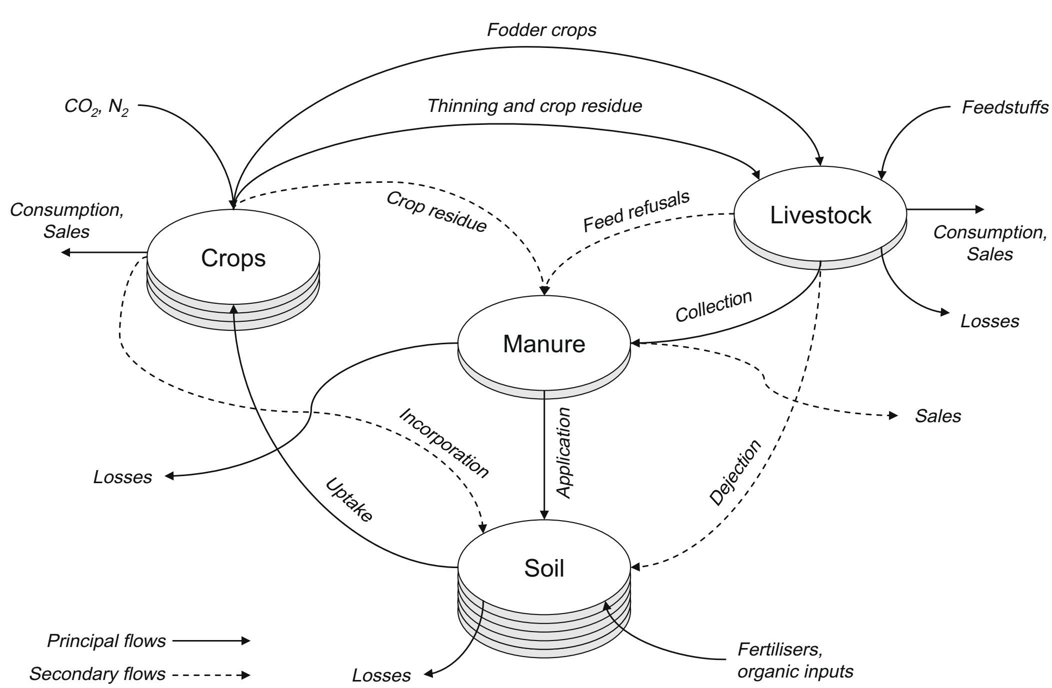

Fig. 1. Schematic representation of the various components flows within the crop-livestock system, the unit of analysis in this study, as implemented in the model.

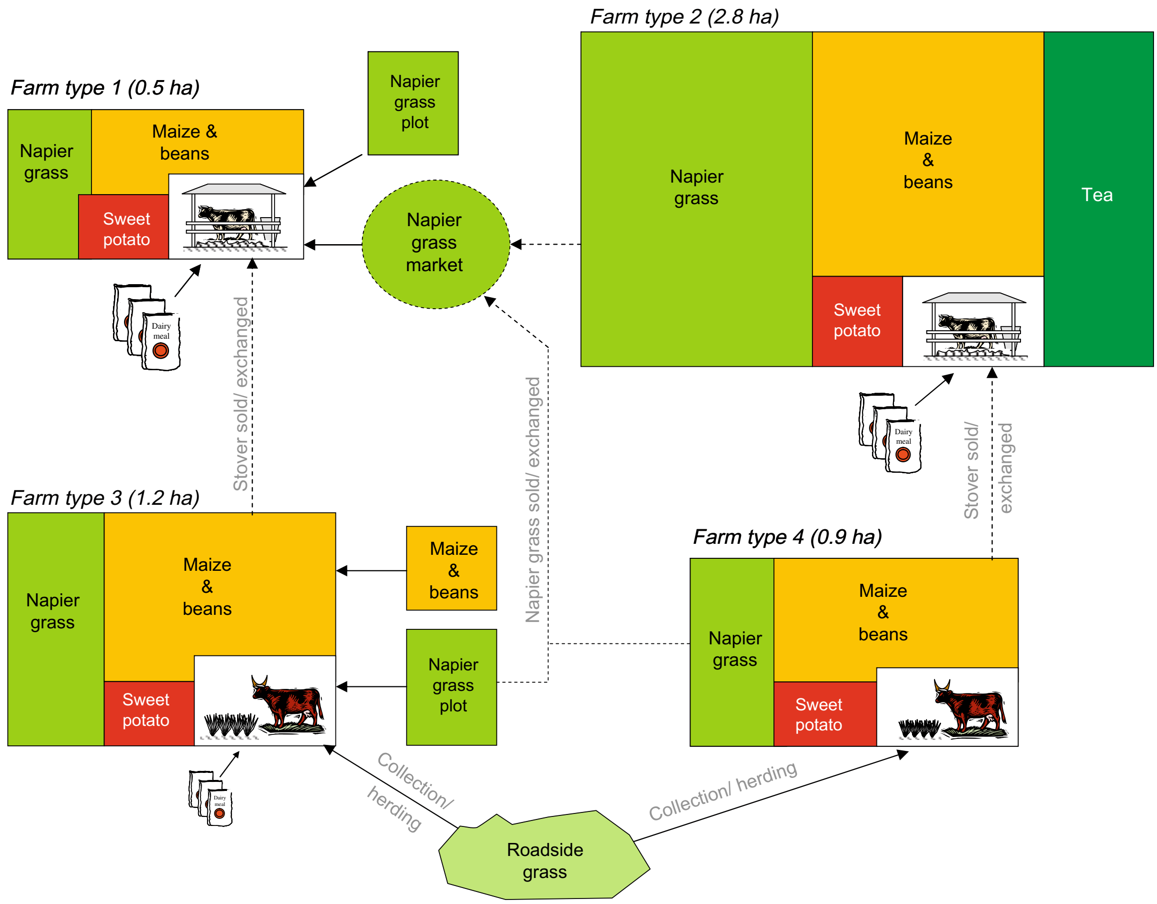

Fig. 2. Schematic representation of the four case study farms belonging to Farm Types 1–4 described in Table 1. Dotted lines indicate intermittent flows (e.g. occasional exchange of crop residues or fodder between farm types). The configuration of cropping activities does not represent the actual shape, number and distribution of fields, but simply their relative importance in terms of area. External boxes represent fields that are rented outside the farm to increase production. The livestock production system in Farm Types 1 and 2 is more complex than in Types 3 and 4, including zero-grazing stalls, improved dairy cattle breeds and more intensive use of concentrates (represented by bags in the drawing).

3 and 4. Manure was collected frequently after cleaning the shed and piled in a heap, protected from direct sun in Farm Types 1 and 2. Poorer farmers tend to throw the collected manure into a pit together with other household waste and crop residues; when animals are tethered either within or outside the boundaries of the farm, manure is collected less frequently from night stalls. Manure cycling efficiencies as affected by collection and storage conditions were calculated using a fuzzy-logic approach parameterised with field data as described by Rufino et al. (2007). Less efficient use of on-farm nutrient resources and mineral fertilisers led to poorer current nutrient stocks and heterogeneity in soils of Farm Types 3 and 4 (Fig. 3). The strongest negative gradients of soil fertility were observed for P and K, decreasing sharply at increasing distance from the homestead. All fields in Farm Type 4 and most in Farm Type 3 had available P values below the threshold for crop responses of 10 mg kg^{-1} found earlier in western Kenya (Vanlauwe et al., 2006). N availability (not shown) followed a similar trend within farms as soil C in Fig. 3.

2.3.2. Key assumptions

Since our objective was to explore the biophysical boundaries to the intensification of the crop-livestock system, assuming that resource constraints could be overcome through investments, the analysis concentrated on biophysical flows and assumed that labour was available as required (which is often not the case) and that all necessary investments in inputs and assets could be made. It was also assumed that most fields of the farms were planted to maize and beans, Napier grass and sweet potato. Tea was only grown in Farm Type 2 and not considered as part of the primary productivity of the farm. Garden crops such as local vegetables, bananas or fruit trees, and woodlots were not dynamically simulated and their contribution to primary productivity was disregarded. Crop rotation or spatial rotation of activities within the farm and the contribution of livestock other than cattle were not considered. The number of fields per farm was reduced by grouping fields under similar land use and location within the farm and the landscape. Labour requirements and allocation to different activities has been optimised for all these systems (van Wijk et al., in press). These values were kept constant for all of the simulations. Resource allocation patterns were derived from resource flow mappings (Tittonell et al., 2005b) and general management decisions, such as the amount of the total manure produced allocated to each field, were kept constant throughout the baseline scenarios. Although conception can be simulated stochastically by the model LIVSIM (Rufino et al., 2009), calving intervals were kept constant (provided that the body condition of the cows allowed conception and gestation) to represent the baseline situation observed on the case study farms (Castellanos-Navarrete, 2007).

The assumptions made in simplifying the real systems allow a fair representation of key resource flows and their interactions. Simulation results are presented for periods of 10 years, due to a number of reasons. First, longer simulation periods would imply possible shifts of farms from one type to another (e.g. following their trajectory throughout a farm developmental cycle – Crowley,

Table 2
Main characteristics of the four case study farms who keep livestock in western Kenya, and are representative of Farm Types 1–4.

Farm Type	Family size	Consumption units*	Energy required (MJ d^{-1})	Protein required (g d^{-1})	Labour available (man–days $farm^{-1}$)	Farmed area (ha)	Land:labour ratio (man–days ha^{-1})
(a) Household							
1	6	5.6	63	247	3.5	0.52	0.15
2	9	8.4	90	365	4.0	2.20	0.55
3	5	4.4	45	160	2.5	1.22	0.49
4	6	5.0	53	208	3.5	0.89	0.25

Farm Type	Cattle head**		Total cattle live weight (kg $farm^{-1}$)	Feeding system	Manure handling and storage
	Adults	Calves			
(b) Livestock					
1	2	1	590	Zero grazing; use of concentrates	Heap under shadow; frequent collection
2	2	2	720	Zero grazing; use of concentrates	Heap under shadow; frequent collection
3	1	1	370	Tethered in compound fields	Waste/compost pit; frequent collection
4	1	1	270	Tethered in or outside the farm	Waste/compost pit; sporadic collection

Farm Type	Soil stocks per family member (kg $person^{-1}$)					
	Soil organic C	Total soil N	Available P	Exchangeable K	Exchangeable Ca	Exchangeable Mg
(c) Soil fertility						
1	3640	190	1.8	87	443	90
2	9490	690	3.0	134	1545	188
3	8160	695	2.5	127	1129	242
4	4410	495	1.5	30	471	94

* Calculated on the basis of household composition (age structure) using coefficients to account for gender and age developed for Kenya (Sehmi, 1993).
** Only female cattle were considered; males were assumed to be sold soon after birth.

Table 3
Parameterisation of management decisions per field for the four simplified farm types. (a) Farm Types 1 and 2, with current fertiliser use indicated; (b) no fertiliser was currently used in all fields of Farm Types 3 and 4; scenarios of fertiliser allocation used in the simulation of management alternatives are presented instead.

Field	Area (ha)	Crop grown	Residue removed (%)	Manure allocated		*Current* fertiliser use	
				Fraction	kg dm ha^{-1}	kg N ha^{-1}	kg P ha^{-1}
(a)							
Farm type 1							
Home garden	0.27	Maize/beans	60	0.3	1278	11.1	5.6
Mid field	0.12	Napier	n/a	0.3	2875	16.7	41.7
Outfield	0.05	Sweet potato	30	0	0	0	0
Valley bottom	0.08	Napier	n/a	0.4	5750	0	0
Farm type 2							
Home garden	0.13	Maize/beans	30	0.3	6346	0.0	11.5
Close field	0.45	Maize/beans	50	0.2	1222	22.2	8.9
Mid field	0.50	Napier	n/a	0.2	1100	0	0
Mid field	0.45	Maize/beans	50	0.1	611	55.6	24.4
Outfield	0.25	Sweet potato	20	0	0	0	0
Valley bottom	0.42	Napier	n/a	0.2	1310	0	0

Field	Area (ha)	Crop	Residue removed (%)	Manure allocated		N, P fertiliser allocation *scenarios* (kg $farm^{-1}$)			
				Fraction	kg dm ha^{-1}	7.5	15	30	60
(b)									
Farm Type 3									
Home garden	0.14	Maize/beans	90	0.4	2286	7.1	7.1	14.3	28.6
Close field	0.32	Maize/beans	70	0.2	500	9.4	21.9	43.8	87.5
Mid field	0.12	Napier	n/a	0.2	1333	0	0	0	0
Mid field	0.36	Maize/beans	50	0.2	444	8.3	19.4	38.9	77.8
Outfield	0.18	Sweet potato	20	0	0	0	0	0	0
Valley bottom	0.10	Napier	n/a	0	0	0	0	0	0
Farm Type 4									
Home garden	0.16	Maize/beans	90	0.6	1688	15.6	31.3	62.5	125.0
Close field	0.44	Maize/beans	70	0.4	409	11.4	22.7	45.5	90.9
Mid field	0.10	Napier	n/a	0	0	0	0	0	0
Outfield	0.12	Sweet potato	50	0	0	0	0	0	0
Mid field	0.07	Napier	n/a	0	0	0	0	0	0

1997). Second, the lifetime of a dairy cow in the highlands of Kenya is about 12–13 years; in scenarios where a dairy cow was brought into the system the first two years of its life were not considered to allow analysis of the system in a stable productive phase. Certain processes such as changes in soil carbon contents or technology adoption by farmers typically exhibit a temporal lag in the order

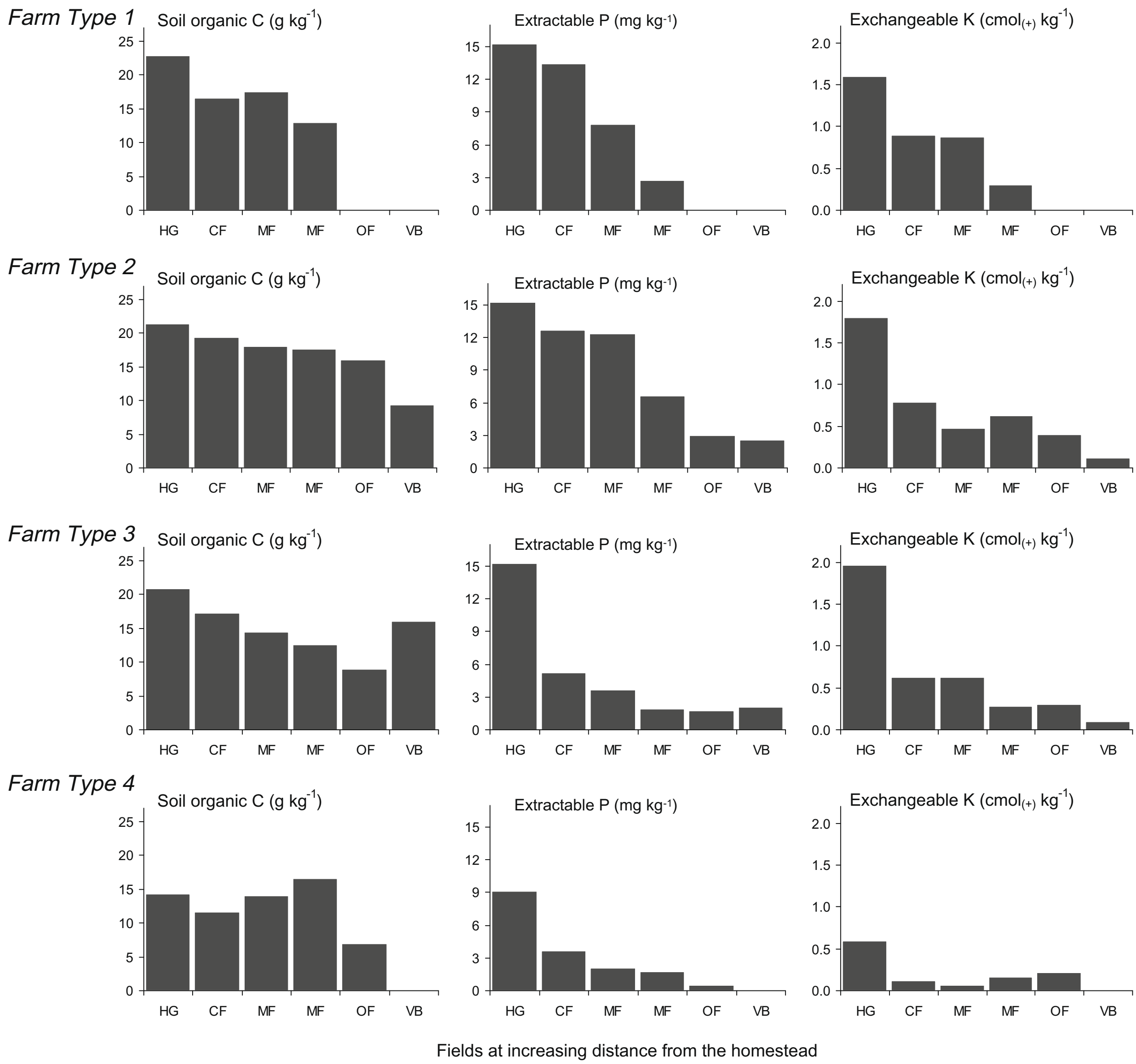

Fig. 3. Soil fertility indicators measured in the various fields of the four case study farms. Fields are ordered according to their approximate distance from the homestead: HG, home gardens; CF, close fields; MF, mid-fields; DF, distant fields and VB, valley bottomland.

of lustrums to decades. Finally, in ten years from now 2015, the target year for achieving the UN Millennium Development Goals will have passed a relevant time horizon to evaluate the impact of interventions.

2.4. Model simulations

2.4.1. Baseline model runs

In the baseline runs the configuration of Farm Types 1–4 were kept as current (Fig. 2; Tables 2 and 3) and the results compared in terms of productivity, resource use efficiency, degree of crop-livestock interaction and soil fertility status. A historical rainfall dataset (Jaetzold and Schmidt, 1982) and weather data collected at the site between 1993 and 2003 were used to run the simulations. All results were summarised and presented on a seasonal basis.

2.4.2. Model runs with N and P fertiliser applications

Small rates of mineral N and P fertilisers were applied to maize-bean fields in the case study farms of Type 3 and 4 following the allocation strategies presented in Table 3b. N and P application rates simulated for the various fields were intended to mimic realistic rates already in use by farmers in Type 1 and 2 (cf. Table 3a). At the Fertiliser Summit held in 2006 in Abuja, Nigeria, African leaders set the challenging goal of achieving fertiliser use intensities of 50 kg nutrients ha^{-1} across sub-Saharan Africa. If a household farming 1 ha of land receives a bag of 50 kg of diammonium phosphate (DAP, 18:46:0) and a bag of 50 kg of calcium ammonium nitrate (CAN, 46:0:0) per season, N and P could be applied at rates of 46 kg ha^{-1} and 9 kg ha^{-1}, respectively. In the simulations, application rates remained within such ranges, combining applications of 0–60 kg N farm^{-1} with 0 to 15 kg P farm^{-1}. The rest of the management parameters in the model were kept as in the baseline.

2.4.3. Model runs with increased areas under fodder

The area of the farm allocated to Napier grass production was doubled, increasing from 18 to 41% (0.22 to 0.50 ha) and from 19 to 37% (0.17 to 0.33 ha) in the case study farms of Type 3 and 4, respectively, reducing the area under food crops. Since more fodder was available, 75% of the crop residue was kept in the fields and incorporated. Small amounts of concentrates, maize thinnings,

roadside grass, weeds, banana stalks and residues from outside fields were still used to complement the diet. Since Napier grass could be harvested more frequently and less was bought from the market, the average quality of the fodder fed to livestock improved (e.g. from 60 to 80 g kg^{-1} of crude protein content in Farm Type 3). This availability of feed allowed an additional cow to be kept in Farm Type 3. Manure was collected more frequently and allocated to maize and Napier grass fields in a 50:50 ratio; the fractions allocated to the various fields (cf. Table 3b) were: 0.1 to maize-beans field 1 (0.06 ha), 0.2 to maize-beans field 2 (0.25 ha), 0.2 to maize-beans field 3 (0.30 ha), 0.3 to Napier grass field 1 (0.30 ha), 0.2 to Napier grass field 2 (0.20 ha) and 0 to the sweet potato field (0.18 ha) in Farm Type 3; 0.3 to maize-beans field 1 (0.10 ha), 0.2 to maize-beans field 2 (0.37 ha), 0.3 to Napier grass field 1 (0.18 ha), 0.2 to Napier grass field 2 (0.15 ha) and 0 to the sweet potato field (0.09 ha) in Farm Type 4. These new configurations were run under baseline scenario (no fertilisers) and with application of N and P as described above. This is referred to as the *Napier grass scenario*.

2.4.4. Model runs with improved livestock system

An improved, cross-bred dairy cow was introduced in the case study farms of Type 3 and 4, keeping the new configuration of increased fodder production. Concentrates and additional fodder were bought to cover the requirements of the new animals, on the basis of potential intakes calculated in LIVSIM. Calving intervals were shortened to 18 months, as in the wealthier farms. Manure collection and storage were improved by assuming more frequent collection from hard-floored stalls (rather than open field, as currently) and by roofing the storage facilities. Concentrates were fed *ad libitum* to all except dry cows (e.g. 1–2 kg dm day^{-1} to lactating cows, as recommended locally to dairy farmers), increasing the concentrate use from 10 to 100 kg $farm^{-1}$ $month^{-1}$, and from 10 to 60 kg $farm^{-1}$ $month^{-1}$ for farms of Type 3 and 4, respectively. Road side grasses were no longer used as feeds. This is referred to as the *Dairy cow scenario*.

3. Results

3.1. Current biophysical productivity, resource use and cycling

3.1.1. Self-sufficiency of food and feeds

The 10-year baseline simulations with the integrated farm-scale model indicate that the four farm types differed in their capacity to meet the energy requirements of the household with their respective on-farm food production (i.e. self-produced calories, SPC%). The relative number of seasons in which SPC < 100% was 9, 2, 7 and 10 out of 10 for the case study farms of Type 1–4, respectively (Fig. 4). In drier seasons even the wealthier case study farm of Type 2 produced less food than required, according to the simulations. For protein requirements and self-production a similar pattern across farms was observed (not shown). Wide differences were also seen in primary and animal productivity and in the size of C and nutrient stocks and flows, which are presented as averages over the 10 years of the simulation in Table 4. The primary production of farms of Type 1 and 2 consisted largely of Napier grass (Table 4b). Crop residues, road side grass or weeds were important ingredients of the cattle diet in farms of Type 3 and 4, in which concentrates were sparsely used (Table 4b). Napier grass was bought regularly in farms of Type 1 and 2 and only to cover specific gaps in farms of Types 2 and 3. Although milk production was greater in Farm Type 2, Farm Type 1 produced more milk per unit area (Table 4c). However, if the area necessary to produce all the extra Napier grass bought in Farm Type 1 was considered in the calculation of milk yields, these will be almost halved with respect to the current milk yields presented in Table 4c. Surveys in western Kenya (Waithaka et al., 2002) indicated an average *per capita* milk consumption of 105 L $year^{-1}$ (125 L $year^{-1}$ is recommended by the World Health Organisation). With this value as reference, the average on-farm production would be just about or below household consumption in Farm Types 3 and 4, with little or no surplus for the market.

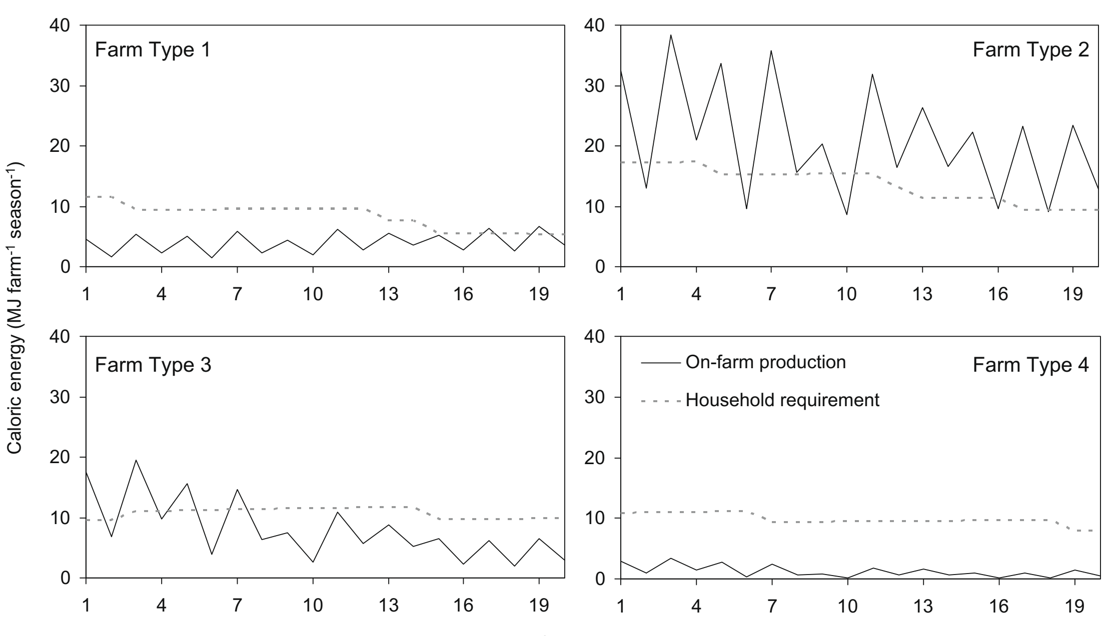

Fig. 4. Simulated household energy requirement and self production of calories on farm during the 10-year baseline scenario. Variability in calorie production is due to rainfall variability. Changes in household requirements are due to assumed changes in family composition (i.e. ages of the family members were recorded and simulated, assuming that children left the household at 18 for females and at 21 for males). As there are two cropping seasons per year, 10 years are equivalent to 20 seasons.

Table 4
Indicators of productivity, resource use efficiency, crop-livestock interactions and carbon stocks and flows for the case studies of the four farm types under the 10-year baseline scenario. The values presented correspond to averages over the entire period of simulation expressed per season (sn).

Farm Type	Primary productivity (t dm ha^{-1} sn^{-1})	Biomass yield (t dm ha^{-1} sn^{-1})	Food crops[*] (kg dm farm^{-1} sn^{-1})			Edible energy (MJ ha^{-1} sn^{-1})	Edible protein (kg ha^{-1} sn^{-1})	SPC (%)
			Maize	Beans	Sweet potato			
(a) Crop production[a]								
1	8.2	5.3	218	45	34	3254	32	53
2	6.1	6.0	1277	290	77	9543	91	137
3	2.8	3.8	484	124	32	6596	65	75
4	1.7	2.4	68	32	10	1392	17	12

Farm Type	Napier grass (kg dm farm^{-1} sn^{-1})			Extra resources fed to livestock (kg dm farm^{-1} sn^{-1})				
	Produced	Bought	Fed	Crop residue	Concentrates	Weeds	Road side grass	Others
(b) Fodder and feed								
1	2071	1681	3338	463	28	28	370	84
2	8831	141	7206	935	112	171	501	251
3	1431	21	1166	304	1	188	201	69
4	997	26	823	77	0	43	143	143

Farm Type	Secondary productivity (t ha^{-1} sn^{-1})	No of animals	Live weight (kg farm^{-1})	Weight gain (kg sn^{-1})	Milk production (L sn^{-1})	Milk yield (L ha^{-1} day^{-1})	Dry matter intake (kg dm sn^{-1})	Crude protein intake (kg sn^{-1})
(c) Livestock production[b]								
1	1.4	3.3	901	52	650	6.9	3776	243
2	1.1	4.8	1971	81	2320	5.8	7329	660
3	0.2	1.2	360	14	200	0.9	1452	99
4	0.1	1.1	271	8	120	0.8	1098	79

Farm Type	Excreted DM (kg sn^{-1})	Excreted elements (kg sn^{-1})			Urine N (kg sn^{-1})	Other inputs[c] (kg dm sn^{-1})	C in manure heap (kg sn^{-1})	
		N	P	K			Input	Output
(d) Manure handling								
1	1521	22.6	16.2	67.4	9.6	281	432	257
2	2531	66.7	33.5	130.8	33.6	1166	998	528
3	601	9.4	6.1	25.9	4.3	207	209	118
4	452	7.9	4.6	19.6	3.9	116	141	68

Farm Type	Soil C stock (t ha^{-1})	Rate of change in soil C (t ha^{-1} sn^{-1})	C fixed by crops (t ha^{-1} sn^{-1})	Soil C losses (t ha^{-1} sn^{-1})	Manure C application (t farm^{-1} sn^{-1})	Crop residue C (t farm sn^{-1})		
						Available	Fed	Incorporated
(e) Farm C stocks and flows								
1	37.4	−0.27	3.7	1.53	0.26	0.57	0.23	0.34
2	34.1	−0.37	2.7	1.11	0.53	1.24	0.62	0.62
3	26.6	−0.43	1.3	0.80	0.12	0.56	0.50	0.06
4	22.0	−0.42	0.8	0.62	0.07	0.17	0.15	0.02

SPC, self-produced calories.
[a] Primary productivity is the production of biomass by the simulated crops maize/beans, sweet potato and Napier grass over the entire farm area (biomass of tea and other perennial and garden crops not considered); Biomass yield is the average productivity of all individual fields irrespective of the crop grown; Edible calories and proteins do not include milk.
[b] Secondary productivity is the sum of milk production and animal weight change on a dry matter basis; number of animals expressed as tropical livestock units.
[c] Other inputs of dry matter to the manure heap, including feed refusals, bedding material and crop residue entering the manure pool without being fed to livestock.
[*] Food crops: dry weight of grains, pulses and tubers, respectively.

3.1.2. Resource use efficiency

Despite the variability from season to season, primary production per unit area for farms of Type 1 and 2 was two to three times larger than that for Types 3 and 4, and the four case study farms showed different ratios of primary-to-secondary productivity (Fig. 5a), indicating a different degree of livestock intensification. The value of this ratio varied over the 10-year simulations, following the fluctuations and decreasing trends in primary productivity (cf. Fig. 4). This is partly the result of not having automated the decisions on stocking or de-stocking in function of fodder and food production in the model, which farmers are likely to make in reality. The four farm types differed also in their efficiency of use of natural resources (Fig. 5b) and particularly in their capacity to transform solar energy into food energy (e.g. from more than 0.5 to less than 0.1 $MJ_{(Food)}$ 1000 $MJ^{-1}_{(Radiation)}$ in Farm Types 2 and 4, respectively, and varying between seasons). As a reference, average rainfall use efficiencies of up to 20 kg ha^{-1} of maize biomass per mm of rainfall can be attained in western Kenya under optimum crop growing conditions (Tittonell et al., 2008). For resources cycled within the farm system, such as the conversion of fodder into milk, the four farm types differed both in the absolute amounts cycled (DM fed and milk produced) and in the efficiency of fodder utilisation, with averages ranging from 160 to 280 kg milk t^{-1} DM intake from the least (Farm Type 4) to the most efficient farm (Type 2) during the 10 years of the simulation. During periods of feed scarcity, milk was produced at the expense of body weight and body condition (Fig. 5c). The extent to which this compensation takes place results from the mechanistics of partitioning and efficiencies as implemented in the livestock model (LIVSIM), which has been calibrated for cross-bred (Holstein × Zebu) dairy cows in Kenya; little is known about such processes for local zebu breeds (Jenet et al., 2006). Live weight gains took place at average rates of 3–5% of the stock, decreasing from farms of Type 1 and 2 to Type 3 and 4 (Table 4c).

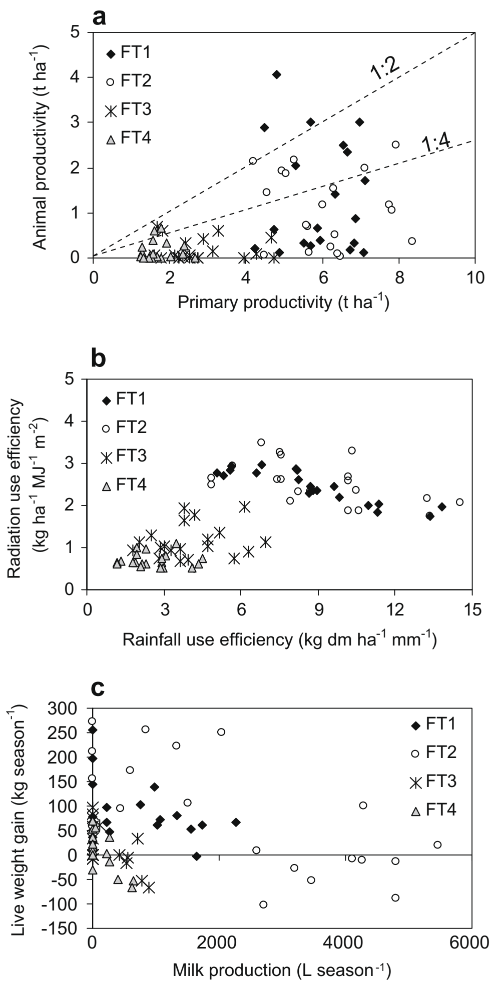

Fig. 5. Farm-scale indicators of productivity and resource use efficiency derived from the 10-year baseline simulation for the four case study farms. (a) Primary *vs.* animal productivity (milk and weight changes), with dotted lines indicating the 1:4 and 1:2 productivity ratios. (b) Radiation use efficiency plotted against rainfall use efficiency at farm scale, expressed in units commonly found in literature. (c) Seasonal changes in live weight of the entire cattle herd plotted against seasonal milk production.

3.1.3. Degree of crop-livestock interaction

Larger stocking rates, expressed as total cattle live weight per ha of farmland, were associated with greater average crop biomass production over the same area (Fig. 6a), due to larger rates of manure application to crops (Fig. 6b). The total amount of manure cycled within the system and the consequent flow of C and nutrients back to the soil was small in farms of Type 3 and 4 (Table 4d and e), also due to poorer efficiency and/or frequency of manure collection for storage (Fig. 6c). However, it is in these farm types where most of the crop residue was removed from the fields and fed to livestock, representing 20–30% of the diet (Fig. 6d); on a seasonal basis, crop residues may represent up to 50% of the diet in western Kenya (Waithaka et al., 2002). Manure recovery efficiencies larger than 1, as depicted for Farm Type 2 in Fig. 6c, were possible due to the continuous addition of crops residues and feed refusals to the manure heap throughout the season. Of the total amount of N taken in by livestock in the diet around 30% entered the manure heap for storage and/or composting and from this 25–50% was recovered for application to croplands (Fig. 6e and f). In all farms about 50% of the excreted N was in the urine, which was not collected in any of the systems (Table 4d).

3.1.4. Soil fertility and nutrient cycling

The stock of soil organic C decreased in all farms during the 10-year simulations, at average rates of −0.28, −1.61, −1.03 and −0.75 t C year^{-1} from farms of Type 1–4, respectively (Fig. 7a); these rates correspond to differences in the average soil C content of −5.4, −7.3, −8.5 and −8.4 t C ha^{-1} between the initial and the final year (Table 4e). Slower rates of soil C decrease in Farm Type 1 resulted from the larger rates of manure application to its small crop fields (cf. Fig. 6b), resulting also in larger crop productivity and C input to the soil through crop residues and roots. The decrease in soil C stocks translated into lower farm food production, particularly in Farm Type 3 (Fig. 7b); in Farm Type 4 both soil C stocks and productivity were already poor at the beginning of the simulation. The capacity of these four case study farms to store organic C in their soils also differed due to their capacity to fix atmospheric C into crop biomass C and retain it in the soil (Fig. 7c). Higher efficiencies of utilisation of light, water and nutrients allowed larger rates of CO_2 fixation in farms of Type 1 and 2. In accordance with the trends in soil C stocks, C losses due to respiration and erosion were greater for these farms than for Type 3 and 4, but proportionally smaller with respect to what was fixed each season. The total amount of C fixed in crop residue available at the end of each season and the fraction of it that is effectively incorporated in the soil also differed widely across farms (Table 4e). During manure handling and storage, farms with higher stocking rates emitted more CO_2—C per unit area (Fig. 7d); however, such losses represent 5–10% of what was fixed from the atmosphere in crop biomass. When fertiliser use is infrequent, the main flow of P back to the soils occurs through application of manure or other organic resources. The higher the stocking rate, the larger the chance that P would be returned to the soils (although often not to the same fields from where it has been removed). P and C were applied together in manure, and fields that received P produced greater crop yields and eventually larger C inputs to the soil through roots and crop residues, resulting in a favourable positive feedback (Fig. 7e and f).

3.2. Intensification pathways

The analysis presented above illustrates the wide gap in physical efficiencies achievable by the four farm types under baseline conditions. This section presents simulation scenarios in which the intensification of Farm Types 3 and 4 was pursued to narrow this gap by increasing the use of N and P fertilisers applied to food crops, allocating more land to fodder production while intensifying food production in smaller areas, and replacing the less productive local zebu by cross-bred dairy cattle.

3.2.1. Input intensification under the current farm configuration

Increasing rates of N and P fertiliser use at farm scale led to increasing farm primary productivity for Farm Types 3 and 4, eventually to cover the entire household energy requirement (Table 5). The application rates resulting from the amounts of N and P fertiliser used (0–60 kg N farm^{-1} and 0–15 kg P farm^{-1}) are within the range of maximum crop responses on these soils (cf. Tittonell et al., 2008). Although little fodder was bought by these farm types, increasing maize productivity through fertiliser use allowed more maize thinnings and stover to be used to feed cattle, reducing the need to buy Napier grass. Livestock productivity increased little with increasing fertiliser use; milk production increased by 10–20% on both farms, but given the small amounts produced under the baseline conditions the absolute increase was not substantial (not shown). Almost irrespective of the amount of N applied between 0 and 30 kg N farm^{-1}, the rate of replenishment of soil P stocks through fertiliser application determined the boundaries of food productivity of the farm system, as illustrated for the case

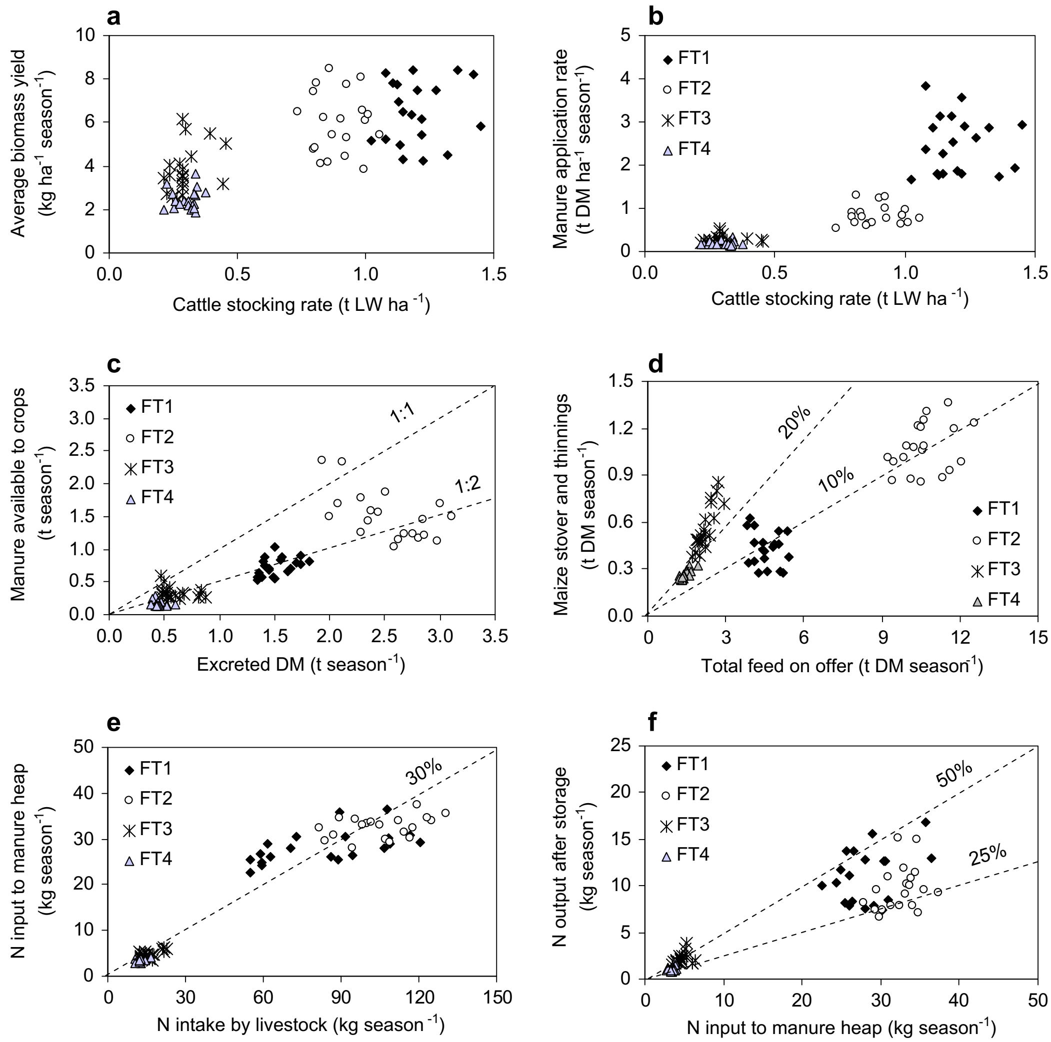

Fig. 6. Farm-scale indicators of the degree of crop-livestock interaction derived from the 10-year baseline simulation for the four case study farms. (a) Average biomass yields of food and fodder crops and (b) average manure application rates plotted against cattle stocking rates expressed as live weight per area. (c) Dry matter of manure available for application to crops after storage *vs.* dry matter excreted, with dotted lines indicating 50% and 100% apparent efficiencies (i.e. other organic materials may be added to manure during storage). (d) Maize stover and thinnings fed to cattle over the total amount of dry matter on offer, with lines indicating 10% and 20% fractions. (e) Nitrogen input to the manure heap *vs.* N taken in by livestock on a seasonal basis, with 30% efficiency indicated. (f) N coming out of the manure heap after storage *vs.* N input to the heap, with 15% and 50% recovery efficiencies indicated.

study farm of Type 3 in Fig. 8a. In this case, seasonal applications of 15 kg P farm^{-1} corresponded to replenishment rates < 2% of the soil P stock per season. Synergies were predicted when N was applied at 60 kg farm^{-1} together with 15 kg P farm^{-1}, as evidenced by the increase in farm primary productivity in Table 5. Higher soil organic C contents were associated with higher food productivity, with decreasing crop yields as the simulation progressed under the baseline conditions (Fig. 8b and c). Application of N fertiliser had a marginal effect on food productivity across the entire range of soil C contents. Applications of P fertiliser together with N allowed maintenance of greater stocks of soil C at farm scale and induced substantial increases in food production. In principle, greater crop productivity could be expected with even higher rates of N and particularly P application (e.g. simulation results indicated positive responses to N and P applied at rates of up to 120 and 60 kg farm^{-1}, respectively, in Farm Type 3 – not shown). However, C inputs to the soil via crop residues and manure remained too small to allow considerable build up of soil organic C and soil fertility (Table 5). The annual rate of CO_2 emission at farm scale also increased with fertiliser use as a consequence of greater crop and livestock productivity.

3.2.2. Structural changes in the cropping and livestock sub-systems

Increasing the area under Napier grass and reducing the area of maize, beans and sweet potato in farms of Type 3 and 4 had a positive impact on farm primary productivity, but decreased the production of edible energy and protein, leading to less food self-sufficient farms (*Napier grass scenario* – Table 6; cf. Table 4). Napier grass production was more than doubled on both farms and their secondary productivity increased, particularly on Farm Type 3 where an additional cow could be kept with the additional fodder production (although the amount of Napier grass that had to be bought at certain times of the year also increased). Less crop residue was fed to livestock on Farm Type 3 and about the same amounts of concentrates were used sporadically, as in the baseline runs. Milk production increased to satisfy household self-sufficiency, and more C and nutrients circulated through the livestock-manure sub-systems, with a consequent increase in the amount of C returned to the soil as manure. In this scenario, 25% of the crop residue was fed to livestock or used as bedding and the remaining 75% incorporated in the soil, representing about half a tonne of C per ha incorporated every season.

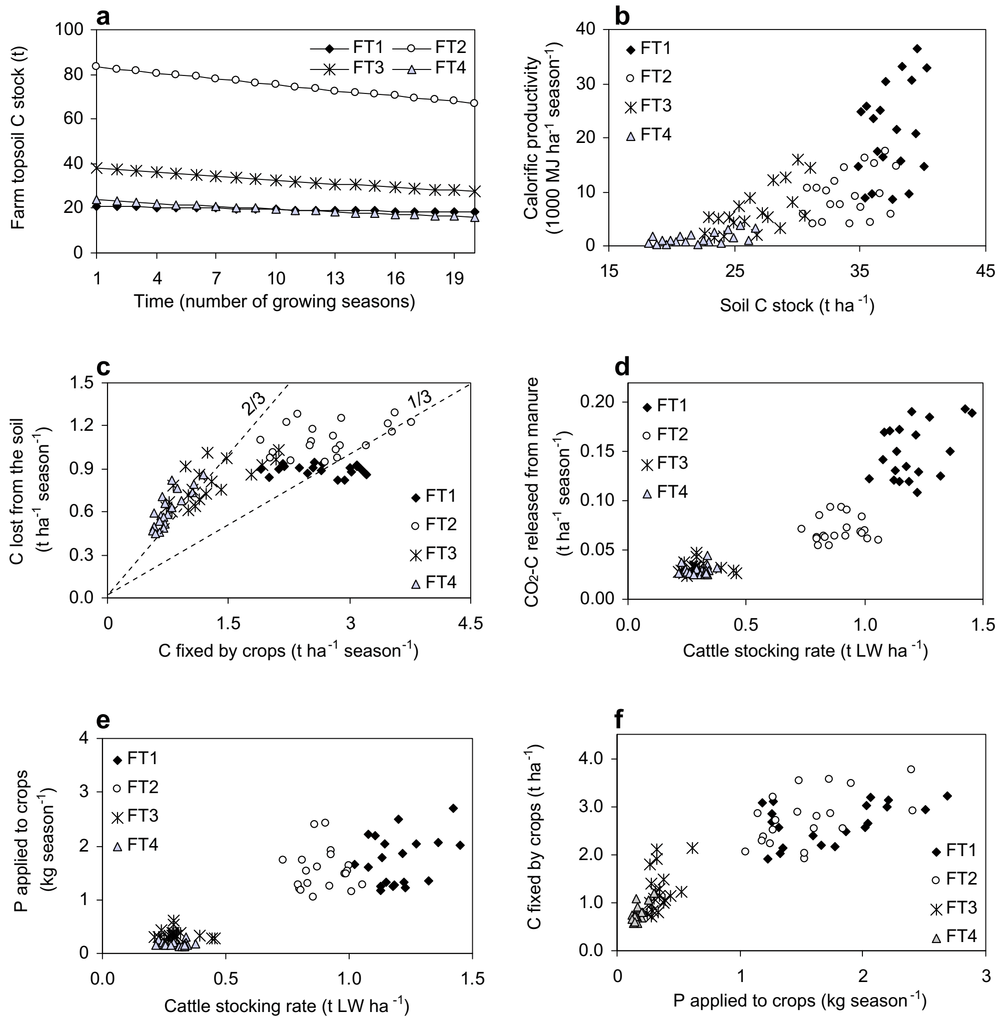

Fig. 7. Farm-scale indicators of C and nutrient stocks and flows derived from the 10-year baseline simulation for the four case study farms. (a) Changes in the stock of topsoil C at farm scale. (b) Production of food calories plotted against the stock of C expressed per unit of farm area. (c) Seasonal C losses in soil respiration and erosion *vs.* C fixed in crop biomass, with dotted lines indicating loss fractions of 33 and 66%. (d) Seasonal respiration C losses from the manure heap. (e) P applied to crops in manure plotted against cattle stocking rates expressed as live weight per unit area. (f) Seasonal rate of C fixation in crop biomass plotted against the total amount of P applied to crops in manure.

By bringing in a more productive cow the average primary productivity of the entire system over the 10 year simulation increased even further in Farm Type 3, producing more food than necessary to cover household requirements and boosting milk production (*Dairy cow scenario* – Table 6). Livestock productivity was more than doubled; average milk yields increased to 4.6 L ha^{-1} day^{-1} (greater than in baseline Farm Type 1) due to the presence of a more productive cow that was better fed and had calving intervals of 18 months. Crop productivity increased due to more manure available for application in smaller fields as compared with the baseline (current) situation (cf. Table 4), with extra nutrients brought into the system in concentrates and fodder that were also cycled more efficiently by better manure handling, and with more C fixed and recycled within the farm system (Table 6). The total animal live weight on the farm and the amount of DM excreted per season were comparable with those of Farm Type 1 under the baseline (current) situation (cf. Table 4; Fig. 6c). The average stock of soil organic C was 4.6 t ha^{-1} larger than in the baseline situation, while the amounts of N and P excreted by cattle (and potentially available to crops via manure) were c. 30 and 10 kg $farm^{-1}$ $season^{-1}$ larger with respect to the baseline. Note that similar amounts of N and P brought into the system as mineral fertilisers (e.g. 30 N and 7.5 P) produced substantial changes in farm productivity (cf. Table 5). In brief, bringing in a more productive cow lifted the overall productivity of the system to a higher level.

In Farm Type 4, the impact of introducing a more productive cow on farm productivity was small in relation to the increase already achieved by increasing the area under Napier (Table 6). Milk production increased substantially, allowing surpluses for the market, but such production was sustained on additional fodder and concentrates. Inefficient handling and storage of manure (cf. Table 7) led to poorer C and nutrient cycling, and crop productivity did not improve further, in fact greater amounts of potentially recyclable C and nutrients were lost. However, the main factor limiting productivity on this case study farm was not the efficiency of resource capture and cycling within the system but the total amount of resources cycled. Fig. 9 depicts the amounts of N entering the manure storage heap in faeces, crop residue and other organic materials each season in the four farm types (Fig. 9a, b, c and f), and under the various scenarios simulated for farms of Type 3 and 4 (note the difference in the scale of the *y*-axis for Farm Type 4) (Fig. 9d, e, g and h). In all farms the amounts of N cycled through manure were not constant but varied between seasons following

Table 5
Changes in key indicators of farm productivity and efficiency in farms of Type 3 and 4 when N and P fertilisers are applied to food crops, without changes in land use. Averages over a 10-year simulation presented per season (sn).

Fertiliser use (kg farm^{-1} sn^{-1})	Primary productivity (t ha^{-1} sn^{-1})	Self-produced calories (%)	Proportion of food secure No. of sn's	Fodder bought (kg sn^{-1})	Manure application (kg farm^{-1} sn^{-1})	Residue C incorporated (kg farm^{-1} sn^{-1})	Farm CO_2 emission (kg farm^{-1} sn^{-1})
Farm Type 3							
0 N	2.8	77	0.25	20.8	292	127	977
15 N	2.9	82	0.30	20.3	298	132	990
30 N	3.0	88	0.30	18.7	303	136	1002
60 N	3.2	100	0.50	18.0	314	145	1027
0 N 7.5 P	3.7	126	0.60	13.3	335	165	1066
15 N 7.5 P	3.8	136	0.75	11.7	344	172	1084
30 N 7.5 P	4.0	146	0.80	11.4	354	179	1103
60 N 7.5 P	4.3	168	0.80	9.8	373	194	1141
0 N 15 P	4.7	190	0.85	4.2	390	209	1170
15 N 15 P	4.9	209	0.90	2.6	405	223	1200
30 N 15 P	5.2	229	0.95	1.2	421	236	1230
60 N 15 P	5.8	269	1.00	0.0	454	263	1291
Farm Type 4							
0 N	1.7	12	0	25.5	193	76	532
15 N	1.8	16	0	24.4	197	80	541
30 N	1.9	20	0	22.2	201	85	550
60 N	2.1	29	0	18.5	210	94	569
0 N 7.5 P	2.2	31	0	14.4	209	97	569
15 N 7.5 P	2.3	39	0	12.3	218	106	586
30 N 7.5 P	3.0	73	0.25	0.0	241	136	638
60 N 7.5 P	3.0	73	0.30	0.0	241	136	638
0 N 15 P	2.7	57	0.10	3.4	226	122	612
15 N 15 P	3.0	74	0.30	0.0	240	137	638
30 N 15 P	3.4	94	0.45	0.0	258	154	665
60 N 15 P	4.2	137	0.75	0.0	291	190	722

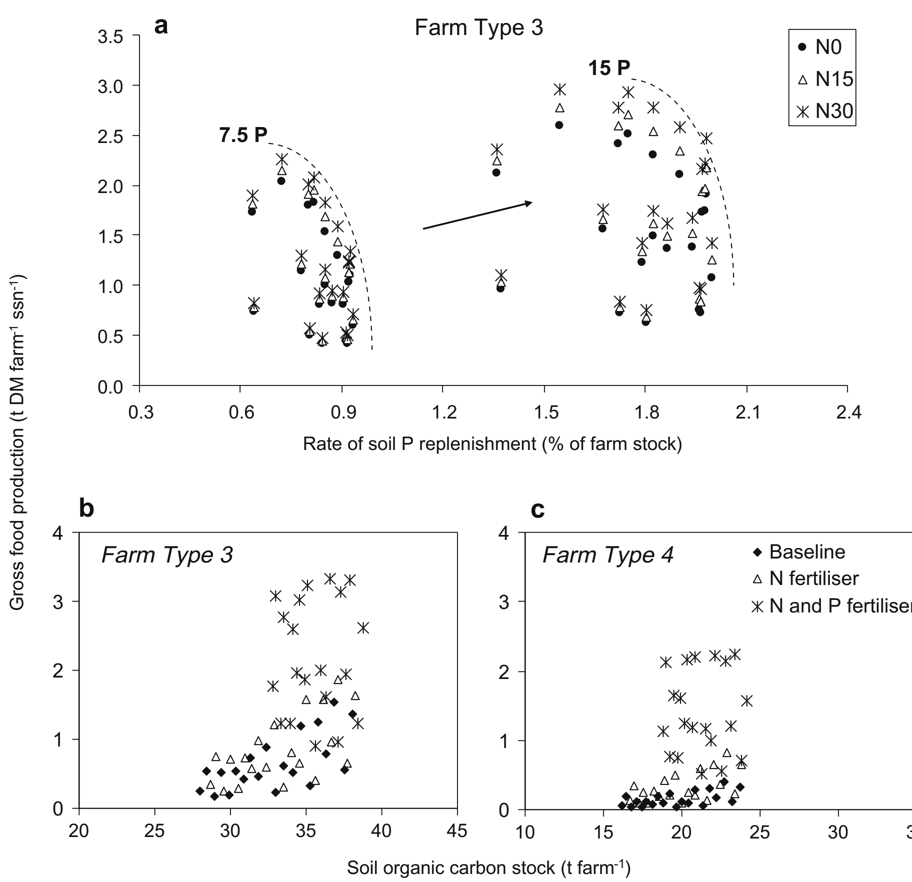

Fig. 8. Simulation results from the 10-year scenario of N and P fertiliser use. (a) Gross food production *vs.* rate of farm-scale soil P replenishment with mineral fertiliser when 7.5 and 15 kg P farm^{-1} season^{-1} are used in case study Farm Type 3 as indicated in Table 3b, without or with application of N at 0, 15 and 30 kg farm season^{-1} (N0, N15, N30, respectively), with 'hand-drawn' lines illustrating P-limitation to farm productivity. (b and c) Gross food production in Farm Types 3 and 4, respectively, without fertilisers (baseline), with 60 kg N farm^{-1} season^{-1} (N fertiliser) and with 60 kg N + 15 kg P farm^{-1} season^{-1} (N and P fertiliser) plotted against farm-scale soil C stocks (note the differences in the scale of the *x*-axes).

Table 6
Indicators of productivity and efficiency for Farm Types (FT) 3 and 4 under the *Napier grass* and *Dairy cow* scenarios. Averages over a 10-year simulation presented per season (sn).

Scenario	Primary productivity ($t\ dm\ ha^{-1}\ sn^{-1}$)	Biomass yield ($t\ dm\ ha^{-1}\ sn^{-1}$)	Edible energy ($MJ\ ha^{-1}\ sn^{-1}$)	Edible protein ($kg\ ha^{-1}\ sn^{-1}$)	Energy requirement met (%)
(a)					
Napier grass					
FT3	3.8	4.2	4558	45	52
FT4	2.7	2.5	1138	14	10
Dairy cow					
FT3	5.0	5.4	10632	100	123
FT4	2.9	2.7	2039	23	18

Scenario	Napier grass ($kg\ dm\ farm^{-1}\ sn^{-1}$)			Extra feeds* ($kg\ dm\ farm^{-1}\ sn^{-1}$)		Dry matter intake ($kg\ dm\ farm^{-1}\ sn^{-1}$)
	Produced	Bought	Fed	Crop residue	Concentrates	
(b)						
Napier grass						
FT3	3308	77	2724	208	3	2669
FT4	1996	5	1602	62	1	1279
Dairy cow						
FT3	3416	310	3043	405	104	2976
FT4	2027	296	1918	91	47	1690

Scenario	Secondary productivity ($t\ ha^{-1}\ sn^{-1}$)	No of animals ($TLU\ farm^{-1}$)	Live weight ($kg\ farm^{-1}$)	Weight gain ($kg\ farm^{-1}\ sn^{-1}$)	Milk production ($L\ farm^{-1}\ sn^{-1}$)
(c)					
Napier grass					
FT3	0.31	2.4	662	23.9	356
FT4	0.20	1.2	308	11.7	165
Dairy cow					
FT3	0.86	2.2	909	35.4	1024
FT4	0.71	1.1	456	16.8	613

Scenario	Excreted DM ($kg\ farm^{-1}\ sn^{-1}$)	Excreted elements ($kg\ farm^{-1}\ sn^{-1}$)			C in manure heap ($kg\ sn^{-1}$)	
		N	P	K	Input	Output
(d)						
Napier grass						
FT3	1079	16	12	48	345	219
FT4	511	7	6	23	180	108
Dairy cow						
FT3	1252	39	15	53	492	315
FT4	582	15	8	30	203	119

Scenario	Soil C stock ($t\ ha^{-1}$)	Manure C application ($t\ ha^{-1}\ sn^{-1}$)	C fixed by crops ($t\ ha^{-1}\ sn^{-1}$)	C incorporated ($t\ ha^{-1}\ sn^{-1}$)	Soil C losses ($t\ ha^{-1}\ sn^{-1}$)
(e)					
Napier grass					
FT3	27.0	0.18	1.7	0.65	0.8
FT4	23.8	0.13	1.2	0.46	0.7
Dairy cow					
FT3	31.2	0.26	2.3	0.85	1.2
FT4	25.5	0.14	1.3	0.50	0.8

* Only feed items that changed with respect to previous scenarios are presented.

the variability in farm productivity. This has practical consequences for recommendations on soil fertility management, particularly when mineral fertilisers are applied in combination with animal manure to complement crop nutrient demands. In terms of N losses, the scenario with a cross-bred cow was less efficient in cycling N through manure in Farm Types 3 and 4 (cf. the ratio N output after storage: N input in faecal DM – Fig. 9e and h). However, the amount of N recovered from the heap after storage in this case was almost equivalent to that entering storage under the other scenarios.

Under the new farm configurations, the *Napier grass* and *Dairy cow* scenarios, mineral fertilisers could be used more efficiently (Table 7). For instance, the use of 15 kg P in both farms under these scenarios induced greater primary productivity than 60 kg N $farm^{-1}$ + 15 kg P $farm^{-1}$ per season under the baseline situation. In Farm Type 4, food self-sufficiency was surpassed with application of 15 kg P $season^{-1}$ under the Napier grass and dairy cow scenarios. Although changes in animal production induced by fertiliser application were small, the amount of C and nutrients cycled within the system and the consequent stocks of soil C were larger. Due to the fixed spatial patterns of fertiliser and manure allocation in the simulations, the difference between the soil C content of the best yielding field and the farm average became wider as more nutrients were cycled in the system.

4. Discussion

By contributing to quantify the productivity gaps between poorer and wealthier households in western Kenya, this study provides an indication of the scope to improve resource use efficiency on crop-livestock farms in the region through intensification. For example, the current radiation and rainfall use efficiencies

Table 7
Indicators of productivity and efficiency for Farm Types (FT) 3 and 4 under the baseline, *Napier grass* and *Dairy cow* scenarios with application of N and P fertilisers. Averages over a 10-year simulation presented per season (sn).

Scenario	Farm Type	Primary productivity ($t\ ha^{-1}\ sn^{-1}$)	Self-produced calories (%)	Live weight ($kg\ farm^{-1}$)	Weight gain ($kg\ sn^{-1}$)	Milk production ($L\ sn^{-1}$)	Excreted DM ($kg\ sn^{-1}$)
(a)							
15 kg P farm^{-1} season^{-1}							
Baseline	FT3	4.7	190	366	14	207	613
	FT4	2.7	57	285	9	135	485
Napier grass	FT3	7.8	298	678	26	407	1122
	FT4	6.2	188	312	12	172	524
Dairy cow	FT3	7.8	300	899	33	1123	1279
	FT4	6.4	202	504	24	640	665
60 kg N and 15 kg P farm^{-1} season^{-1}							
Baseline	FT3	5.8	269	368	15	208	619
	FT4	4.2	137	300	9	157	517
Napier grass	FT3	8.6	348	679	27	416	1129
	FT4	8.0	281	317	13	173	537
Dairy cow	FT3	8.6	349	906	34	1171	1299
	FT4	8.1	289	520	22	689	689

Scenario	Farm Type	Inputs to manure heap ($kg\ sn^{-1}$)			Residue C incorporated ($t\ sn^{-1}$)	Average soil C stock ($t\ ha^{-1}$)	Soil C stock in best field ($t\ ha^{-1}$)	Farm CO_2 emission ($t\ sn^{-1}$)
		C	N	P				
(b)								
15 kg P farm^{-1} season^{-1}								
Baseline	FT3	248	5.4	1.0	0.2	28.3	39.0	1.2
	FT4	113	3.8	0.5	0.1	22.8	25.4	0.6
Napier grass	FT3	471	10.5	2.1	2.6	36.2	66.3	2.1
	FT4	227	4.5	0.9	2.1	31.4	54.4	1.3
Dairy cow	FT3	553	22.4	2.5	2.6	36.4	66.6	2.1
	FT4	230	8.7	1.0	2.2	31.7	54.4	1.3
60 kg N and 15 kg P farm^{-1} season^{-1}								
Baseline	FT3	290	5.8	1.2	0.3	29.1	39.3	1.3
	FT4	145	4.2	0.7	0.2	23.9	28.6	0.7
Napier grass	FT3	494	10.8	2.2	2.9	37.5	66.4	2.2
	FT4	314	5.4	1.3	2.7	35.0	57.2	1.6
Dairy cow	FT3	584	22.7	2.6	2.9	37.6	66.7	2.3
	FT4	268	9.1	1.2	2.7	35.3	57.1	1.6

achieved on the poorest farms could in principle be doubled or tripled through intensification (cf. Fig. 4). The gaps between poorer and wealthier households were particularly noticeable when comparing food self-sufficiency (cf. Fig. 3), and the poorest households were excluded from the analysis as they do not own livestock. In these systems, however, the fact that a farm is not self-sufficient in food production does not necessarily imply that the household is food insecure. Farmers of Type 1 derive most of their income from off-farm activities and often produce milk or vegetables for the market, while buying their staple food on the market. Farms of Type 3 often hire or borrow land to increase food production and eventually meet their requirement, often with a small surplus for the market (not considered here). Building on the conclusions of Waithaka et al. (2006), who concluded the prototyped ideal farms had only weak economic viability, our results indicate that the trajectory of change towards achieving the ideal farm is hardly feasible for the majority of farmers. Using functionally integrated dynamic models to simulate feedbacks and long-term dynamics, and considering the spatial heterogeneity of soil and crop production, our assessment provided insight in some key biophysical aspects of smallholder crop-livestock systems that have implications for the design of research and development strategies, as highlighted below.

4.1. Crop-livestock integration and soil fertility

The positive relationship between cattle densities and crop productivity observed in the model results due to increased amounts of manure being available is often observed in smallholder farming systems of East Africa (Tittonell et al., in press). The efficiencies of nutrient cycling during manure collection and storage used in the model were derived from measurements on these case study farms (Castellanos-Navarrete, 2007) and implemented in the model through a fuzzy-logic system that relates management aspects with factors that modify (multiply) decomposition and nutrient loss rates (Rufino et al., 2007). Higher efficiencies of N recovery in the case study farm of Type 1 were associated with more frequent collection of manure from the stall and covered manure storage. The efficiencies of manure handling varied between the farm types, as well as the absolute amounts of nutrients cycled within the systems (Figs. 7 and 9). Even if sufficient labour and resources were allocated to improve nutrient cycling efficiencies within farms of Type 3 and 4, the impact on overall farm productivity would still be limited. An increase in N cycling efficiency through improved manure handling from 25 to 50% would increase the amount of N cycled in the case study farms of Type 1 and 2 by only ca. 10 kg season^{-1}, and only 1–2 kg season^{-1} in Type 3 and 4 (cf. Fig. 6f).

The average soil C contents in all farms at the beginning of the simulation were close to the measured equilibrium soil C contents for these soils after 100 years of cultivation with little C input (Solomon et al., 2007). However, increasing pressure on the land and shrinking communal grazing areas during the last decades have led to faster rates of soil C decrease due to the complete removal of crop residues to feed livestock (Crowley and Carter, 2000). Under this situation, the new equilibrium soil C calculated by the

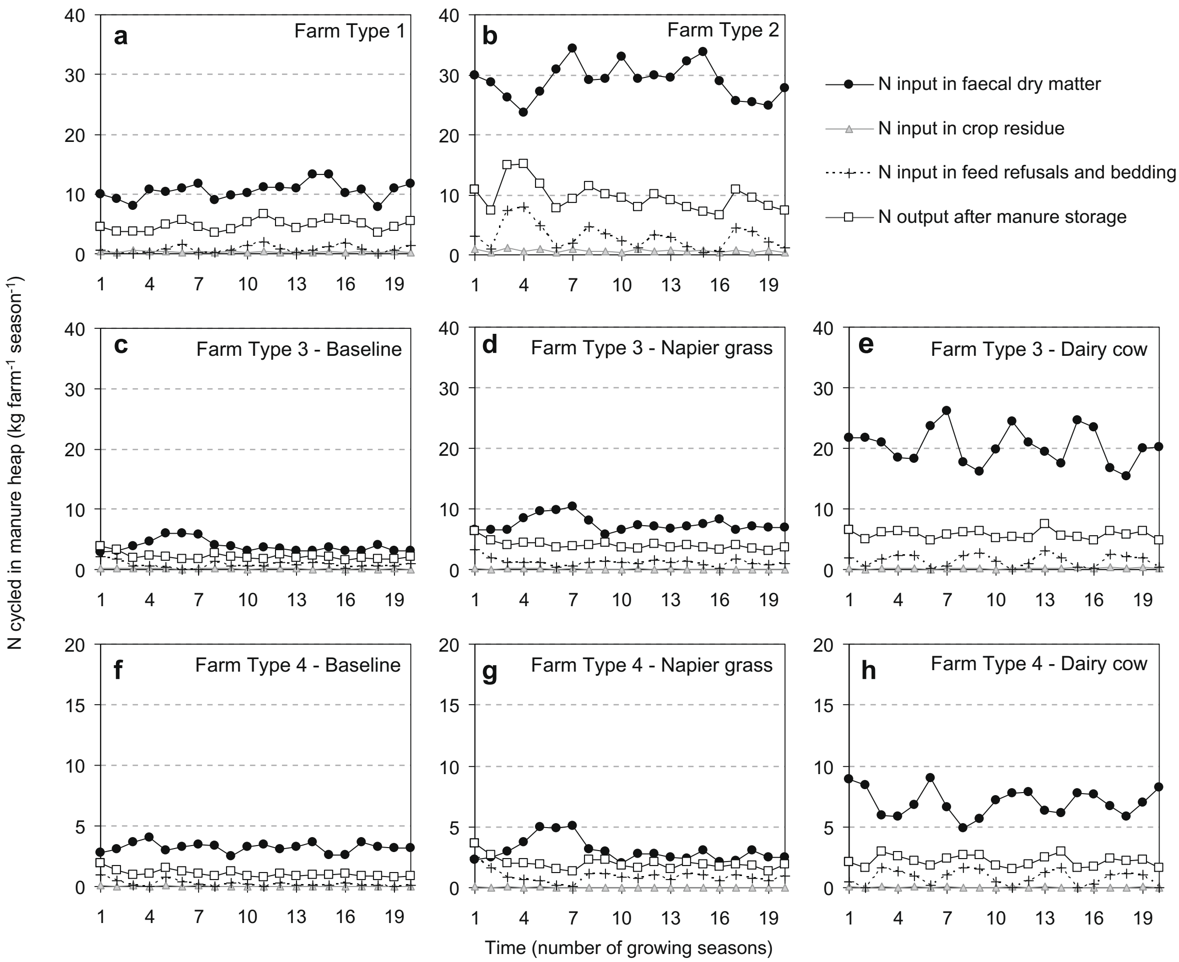

Fig. 9. Seasonal amount of N cycled in the manure heap across farm types, indicating inputs of N in faecal dry matter, crop residue, feed refusals and bedding materials added to the heap and N coming out of the heap after storage. (a, b, c and f) Farm Types 1–4 under the baseline scenario; (d and e) Farm Types 3 and 4 under the *Napier grass* scenario; (e and i) Farm Types 3 and 4 under the *Dairy cow* scenario. (Note the different scale in the *y*-axis for figures f–h).

model was as small as 22 and 18 t C ha^{-1} in the upper 0.2 m of the soil for Farm Types 3 and 4, respectively, after 10 years of simulation. If the initial average mass-corrected factors for these two farms are considered, these stocks would represent 21 and 25 t C ha^{-1} for the first 2000 t ha^{-1} of soil, equivalent to C concentrations of 1.0% and 1.3%, respectively. Soil C mass fractions around 1% have been often measured in the poorer fields of western Kenya farms, for example by Ojiem et al. (2007).

To maintain or increase soil C stocks, crop productivity must be improved and crop residues retained in the fields to add organic C to the soils. Crop productivity in western Kenya is largely limited by N and P, and more sporadically by K availability (Shepherd et al., 1996). Management-induced concentration of organic C and available P in a few fertile fields within individual farms has been repeatedly observed in these systems. Such co-variation between management and consequent biophysical processes as a consequence of farmers' management decisions leads to the creation of gradients of soil fertility within these farms (Tittonell et al., 2005b). In our farm-scale simulations, the amount of manure returned to the soil increased considerably with respect to the baseline conditions when fertilisers were used. However, the application rates of manure to the soils remained small, much smaller that the rates of manure application used in field experiments in different regions of SSA. Such experiments indicate that substantial responses in crop production are observed with large manure application rates of 10 to 20 t dm ha^{-1} (e.g. Kapkiyai et al., 1999; Zingore et al., 2007). On both farms, Type 3 and 4, mineral P application induced greater responses in terms of crop productivity than N application, in agreement with previous observations in the region (cf. Vanlauwe et al., 2006; Tittonell et al., 2008; cf. Fig. 3).

4.2. Towards the ideal farm

To analyse the capacity of rural households to adapt to increasing stresses such as increasing population density or climate change, Thornton et al. (2007) used a graphical Cartesian framework in which the *y*-axis represents household well-being and the *x*-axis livelihood options or alternative farming activities. These ideas are developed further in Fig. 10, which illustrates the pathway of intensification towards the ideal farm as conceptualised in this study. The improvement of household well-being takes place through discontinuous, alternating processes of input intensification within the current system state and qualitative jumps to a new system state brought about by investment and/or diversification. In System state I, the different farm production activities represented as A and B in the graph have poor efficiency and responsiveness to input intensification. The low ceiling of productivity of activities A and B in response to external input use is rapidly reached. For example, in our case studies, soil fertility builds up slowly with repeated nutrient additions if the crop residue is removed every season to feed livestock, and the responsiveness to mineral fertilisers remains poor.

In System state II qualitative changes induce a substantial increase in the efficiency and responsiveness of activity A to external inputs. For example, more land is allocated to fodder production reducing the need of maize stover to feed livestock, crop production is intensified in smaller areas concentrating manure and external nutrient inputs, allowing soil fertility to build up in the long-term, eventually requiring less external inputs. In System state III, activity A requires only half the amount of external inputs to achieve the same productivity level as in System state II. Resources are used and recycled more efficiently within the system due to a substantial increase in the efficiency of activity B and complementarities with activity A. Due to these complementarities, activity A becomes more productive even without external inputs, simply due to the increase in productivity of activity B. This means that a more productive livestock subsystem may allow more intensive cycling of nutrients within the farming system from soil stocks and/or imported as fertilisers or animal feeds.

As demonstrated by Thornton et al. (2007), external system stresses may induce changes in livelihood options that can support well-being. In our case study area, increasing population density and the consequent lack of communal grazing land has led to intensification of dairy production through zero grazing. A market niche was then opened for fodder crops such as Napier grass, which is being grown in the area as a cash crop even by farmers who own no cattle (Tittonell, 2003). Acute permanent stresses and/or shocks, however, may displace the trajectory of intensification inducing lower levels of well-being for a given livelihood option; i.e. the trajectory would be 'less steep'. The potential shift of rainfall patterns from two to one season each year in East Africa (Thornton et al., 2006), creating discontinuity in forage and food supply and reducing primary productivity of the system, constitutes a stress in the face of which major changes in farming systems must occur if rural households are to adapt. In other words, alternative development pathways must be sought. Different configurations of the final system state (i.e. a totally different ideal farm) through diversification of activities and processes would be necessary.

4.3. Implications and perspectives

The steepness in the trajectory towards the ideal farm as well as the total distance to be covered is likely to differ between the various farm types (cf. Table 1), due to their capacity for innovation, adaptation and investment priorities, as observed by Herrero et al. (2007b). In some cases, households counteract stresses by substantial diversification, such as off-farm income-dependent livelihood strategies (e.g. the Farm Type 1). Alleviation policies, investments, marketing incentives or other forms of intervention should be designed to counteract the effect of such stresses, allowing a steep trajectory towards intensification. The scheme in Fig. 10 also indicates that simply providing external inputs to farmers will only serve (at most) to intensify activities within the current system state, without necessarily inducing qualitative changes that would eventually render the systems on higher states.

On the other hand, options for external input-based intensification may have a high cost. For instance, according to the latest population surveys Vihiga district has 105,000 households, of which approximately 60% fall in the categories of Farm Types 3, 4 and 5

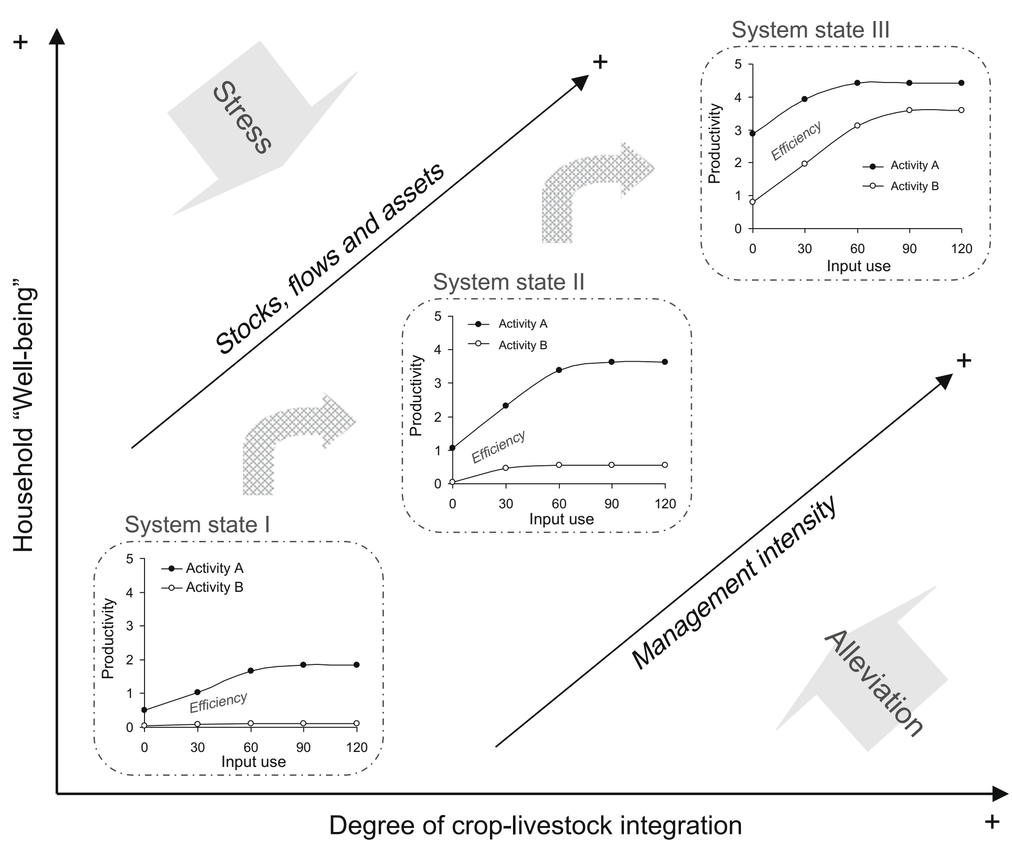

Fig. 10. Schematic conceptualisation of pathways towards intensification and their potential impact on household well-being. In this case, the impact of intensifying crop-livestock interactions (*x*-axis) on different aspects of household well-being (*y*-axis) such as food security or cash income follows a discontinuous trajectory in which input intensification (quantitative) must be followed by qualitative changes in the productive structure of the farm to induce 'jumps' of the system towards higher states. Resource use efficiencies, the degree of complementarities between production activities, resource endowment and management intensity increase from System states I–III. Stressing factors (e.g. population density) and alleviation interventions may modify the slope of the trajectory towards enhanced well-being for a certain degree of intensification.

(Henry, 2006). If one bag of 50 kg of DAP and one bag of CAN fertiliser was provided to each household, approximately 12,000 t fertiliser per year would be necessary. That amount is equivalent to 16% of the average annual fertiliser use of Kenya as a whole (www.earthtrends.org), which includes the high-input export sectors of flowers, vegetables and coffee production, plus commercial farming in the White Highlands of Kenya. Ideally, fertilisers should not be provided for free but rather demanded by farmers who recognise the need to recover or maintain the fertility of their soils. High transaction costs and limited availability at local markets deter their use and adoption by farmers. For example, a bag of 1 kg of fertiliser at the beginning of the long rains of 2007 was sold at 35 KSh in a village market, which is equivalent to 492 US$ t^{-1} (1 US$ = 71 KSh), about 5 times its international market price at the time. Yet, when mineral fertilisers induce responses of 30 kg maize kg^{-1} fertiliser, their use may still be economically profitable, given the current fertiliser:grain price ratios in western Kenya (Tittonell et al., in press). In addition, several other reasons may be put forward to explain the currently limited use of mineral fertilisers: lack of 'cash in hand' at the beginning of the planting season, competing demands for money such as school fees at that time of the year, lack of knowledge on their use, or simply that farmers do not see clear benefits from using them.

The potential feedbacks, constraints and opportunities for systems design from higher (village, region) scales should not be ignored. Bringing in an improved cow to Farm Types 3 and 4 implies that part of the fodder to cover their requirements, to get through months of fodder scarcity or drier seasons, must be purchased on the market (Table 6). In the hypothetical case in which most farmers would demand Napier grass from the market, either the price of fodder may increase, generating an attractive market for farmers without livestock, as described earlier, or the demand might not be covered by local production, which may compromise the sustainability of the system. Likewise, most of the milk produced by smallholder dairy farmers in western Kenya is sold locally (Salasya, 2005). If most farmers in the area produce milk for the market, local milk prices would most likely fall – which may benefit the poorer families – and substantial investments in infrastructure would be necessary to export milk surpluses to other regions. Towards intensification, the intensity of management and the resource endowment of the household should increase in parallel, thus gradually removing inefficiencies and resource constraints. A more efficient management, necessary to capitalise positive crop-livestock interactions, requires substantial financial investment and more labour – two elements not considered explicitly in our analysis.

The results obtained from the simulations must be interpreted in the light of the assumptions made to simplify the farming systems. In reality, systems are more complex and diverse. While there is little doubt that agriculture without external inputs is necessarily extractive, de Ridder et al. (2004) warned that the rates of resource degradation reported for sub-Saharan Africa may be exaggerated. Partial nutrient balances calculated in western Kenya farms indicate alarming rates of soil depletion; in most fields the outputs of N are more than double the inputs, irrespective of the amount of N inputs used by farmers of different wealth classes (Tittonell et al., 2005b). Despite this, farming continues in the area, and although most fields exhibit C and nutrient stocks in equilibrium with poor input rates, there must be other elements of resilience not captured by these simple indicators. For example, recent studies highlighted the contribution of weeds used as local vegetables to the dietary diversity and nutritional security of the household in Vihiga (Figueroa et al., 2008). In complex, dynamic and spatially heterogeneous systems interactions take place across spatio–temporal scales that lead to emergent properties and self-regulatory mechanisms (Holling, 1973). Often different buffering mechanisms operating at village scale emerge from collective action (Meinzen-Dick et al., 2004). Next to regulatory feedbacks that may prevent smallholder systems from collapsing, farmers adaptive capacity and alternative strategies (e.g. through rural–urban connectivity) play a major role in systems resilience. By analogy with the concept of informal economies (de Soto, 2000), such alternatives represent informal resource flows, often unaccounted for in farming systems analysis.

5. Conclusions

This model-based study is a contribution to the design of propoor livelihood strategies, with implications for truly Integrated Soil Fertility Management (ISFM) in smallholder farming systems. Options for the sustainable intensification of these systems should go beyond exploring the best input (e.g. fertiliser × germplasm) combinations to consider the nature and degree of integration between the various system components or farm activities. Next to input intensification, it is necessary to induce qualitative, structural changes that allow positive shifts in the magnitude of stocks and flows of resources within and through the farming systems. One option to achieve this is crop-livestock integration, but the impact of livestock on the recycling of nutrients and on the efficiency of nutrient use at farm scale will be substantial only when enough nutrients are present (or enter) the system to be redistributed. When the absolute amounts of resources cycled within the system are small, improving cycling efficiencies through better handling of manure and composting will only increase productivity marginally.

Promoting intensification through increased use of external nutrient inputs, for instance by providing one bag of fertiliser per household, is also a partial solution that does not necessarily promote a shift toward higher system states. The response of the system to one bag of fertiliser depends on the productive structure of the farm, chiefly on the presence of livestock, and on the intensity of management practices put in place to ensure efficient resource use (all of which depends also on farmers' priorities). Degraded soils often need to be rehabilitated through restitution of their organic matter content before they respond to mineral fertilisers (e.g. Zingore et al., 2007; Tittonell et al., 2008). Although in our study the use of mineral fertiliser led to food self-sufficiency on the poorer farms, the associated inefficiency costs were substantial, and such inefficiencies cannot be sustained over time.

By analysing productivity and efficiency of contrasting and coexisting farming systems types throughout baseline scenarios we show that there is ample scope to improve the biophysical performance of the majority of farms in the region. However, higher productivity on wealthier farms was not sustained by the adjustment of one sole factor, but by the interaction and adjustment of several resource endowment and management variables. This calls for the need of approaches to systems research and design that consider system–scale processes and long-term impacts rather than effects of single inputs on a particular activity. In other words, to move from measuring the effect of input *x* on activity *y* towards assessing the impact of process *x* on system *y*.

The ideal farms designed by farmers in Vihiga district appear utopian for the majority, implying that other farm prototypes are necessary, perhaps using configurations and farming activities not identified by the farmers. Although some of the scenarios of intensification explored here are hard – if not impossible – to accomplish, they are similar to those emanating from international recommendation panels and reflected in current policies (e.g. the '50 kg of nutrient per ha for sub-Saharan Africa' goal agreed by the Abuja Fertiliser summit in 2006, the 'one farmer-one cow' policy in Rwanda, or the policy of 'fertiliser + improved seed packages' for agricultural intensification in Malawi). Such interventions are rarely supported by empirical evidence at the relevant scale of

analysis or by a sound understanding of the dynamics of the farming systems.

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