Evaluation of Resource Management Options for Smallholder Farms Using an Integrated Modelling Approach

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Introduction

Improved efficiency with which nutrients are used and cycled between the soil, crops and livestock components is imperative for increasing overall farm production (Giller et al., 2005). Crop-livestock interactions are mediated by the use of crop residues to feed livestock, and the reciprocal use of manure to fertilize crops (Powell et al., 2004). Smallholder farmers face complex decisions on the allocation of scarce. Therefore, technologies attractive to farmers must be within their capacity to provide labour and nutrients, to achieve food security and should also be economically viable. For improved understanding of the multiple constraints that farmers face and the factors driving their decision making processes, there is a need for tools that holistically assess current and optional resource management strategies and that provide comparative analysis of food sufficiency, economic viability and maintenance of soil fertility at the farm level (Jones et al., 1997; Thornton and Herrero, 2001).

A combination of farm characterization, optimisation and simulation modelling tools was used to analyse and compare the impact of different resource management options at the farm level. The integrated modelling framework used is shown in Figure 1. The Integrated Modelling Platform for Mixed Animal-Crop Systems (IMPACT), a comprehensive farm level database, captures data for crop, soil and livestock management on a monthly basis (Herrero et al., 2002) and calculates as a baseline monthly financial balance, family's monthly nutritional status and annual partial balances for soil nitrogen (N), phosphorus (P), potassium (K) and carbon (C). IMPACT was linked to a generic multi-goal optimization Household model for analysis of optimisation of resource use and trade-offs under a set of constraints at household level. It includes information on food security-related factors, off-farm income generation, and labour constraints. Thus, the Household model determines the best combination of farm resources that satisfy a set of objectives according to a series of both management and economic interventions.

The Household model can test the effects of alternative nutrient management within the farm by including simulated outputs from other models. The Agricultural Production Systems Simulation Model (APSIM) model (Keating et al., 2003) was used to simulate crop-soil management options for targeting different types of fertilizers to different fields. APSIM has been widely tested and validated across different farming systems and environments, including those in Zimbabwe (Delve and Probert, 2004). The RUMINANT model (Herrero et al., 2004) was used to simulate production of milk by cows and cycling of nutrients by cattle under different crop residue feeding regimes.

The aims of this study were to:

(i) Evaluate current resource management in terms of food security, cash balance, nutrient balances and labour requirement on two contrasting smallholder farms.
(ii) Analyse optimal land use and crop allocation strategies by linking the IMPACT database to the Household multi-goal optimization model.
(iii) Assess the utility of combined model results for appraisal of biophysical and socio-economic factors at the farm level.

Methodology

Resource flow mapping was used to collect basic farm data and map use of resources on farms in different socio-economic groups (Zingore et al., 2005). In addition, data on family structure, livestock management, labour allocation, dietary pattern, sales and expenses, and cost of inputs and outputs for each farm activity was also collected. The current management of plots in term of crop allocation and fertilizer use are shown in Table 1. Both farms were located on granitic sandy soils (Lixisols) with low inherent fertility. The poor farm, whose household head was a widow had an area of 1.2 ha; only one person was available to work full-time and chickens were the only livestock owned. The wealthy farm was larger in size (2.9 ha) with two full-time workers. The wealthy farm was also well endowed in cattle, goats and chickens. The plots on the wealthy farms were demarcated into different plots according to soil fertility status.

Baseline analysis

Food security status, household economics, and farm scale N and P balances for current resource use were assessed using the analysis tool in IMPACT. Food security is evaluated in IMACT by calculating the household's annual intake of energy and protein based on collected information on dietary pattern. The total annual energy and protein required by each family was computed by adding consumption required by each household member, which differed according to age and sex as per standard guidelines (WHO, 1999). Food intake in sub-Saharan Africa is about 70% of WHO requirement (FAO, 1998) and we thus set the constraint for energy and protein intake at as this value. Household economics were assessed by accounting for farm expenses and income. Net revenue was calculated in three categories: crops, livestock and other (non-agricultural activities and off-farm earnings). Calculations for partial N and P balances for the cropping system within IMPACT considered the N and P content of the fertilizer inputs into the arable fields and those of products removed.

Resource use optimisation by the Household model

Net cash balance was maximised and the output assessed in terms of (i) net cash balance, (ii) labour demand and (iii) farm nutrient balance. Labour was not selected as a constraint activity (therefore labour availability did not influence model results), but the model calculated labour required for each scenario of resource use. The major constraints factored in the simulations are listed in Table 2. The management scenarios tested by the Household model for the poor and wealthy farms are presented in Table 3.

Optional crop-soil management strategies simulated using APSIM

APSIM was used to generate data for optional scenarios of targeting the main crops to different fields and different options for distributing fertilizer resources between the different crops and fields. Soil N, C and P contents were measured in the different field types and these values were used initialise three soils files with low, medium and high fertility. APSIM was used to generate response curves for crop production in these three fields with different initial fertility.

Optional livestock feeding strategies simulated using RUMINANT

The RUMINANT model was used to simulate effects of feeding groundnut stover to lactating cows on milk production. Groundnut residues were fed to cows for six months starting at the beginning of the dry season in May (after groundnut harvest), until October when the rains start resulting in produces abundant natural forage. Different amounts of groundnut stover, depending amount of groundnut stover produced, were fed to cows, as a supplement to rangeland grass, in the communal grazing area. Maize residues were exclusively used as fodder.

Results and discussion

Evaluation of current management practices on net revenue, food security and nutrient balances

The overall annual revenue on the poor farm was negative under existing resource management (Table 3). This was as a result of the negative cash balance from the cropping system that outweighed the small amounts of cash provided livestock (sale of eggs and chickens) and other non-farm activities, e.g. sale of labour. In contrast, the wealthy farm had a positive annual net revenue of US$172, mainly from the cropping system (Table3).

The cash balance for the poor farm clearly indicated its reliance on selling unskilled labour for income generation. The poor farmer was disadvantaged in that they had to sell labour during periods of peak demand at planting and weeding, thus compromising the productivity of their own farm due to delays in planting and timely weeding. Much of the cash generated on the wealthy farm came from the cropping activities where good crop yields on sandy soils, good management, including investment in mineral fertilizers, use of manure and sufficient weeding of plots. The farm cash balance is sufficient for the farmer to invest in fertilizers and seed for the following season and purchase cattle build up the herd. The wealthy farmer thus had several options for consolidating the productivity of his farm.

Energy and protein consumption for both farms revealed a major imbalance in relation to the food requirements indicated by WHO. The low energy consumed by the wealthy farm could directly be linked to the drought, although energy consumption in sub-Saharan Africa generally falls short of the recommended values (FAO, 1998). Crop products dominated the diet on the wealthy farm (45%), followed by purchased products (40%) and animal products (15%).

Partial balances for N were positive but small on the poor farm, whilst the P balance was zero (Table 3), which could be attributed to little fertilizer inputs. The partial N and P balances would be expected to be negative if there were no fertilizer donations. The wealthy farm was characterised by positive N and P balances (Table 3) due to large amounts of manure and mineral fertilizers used.

Analysis of crop allocation options

The Household model was set to reallocate crops across the different plots on the basis of net cash balance, potential performance of each cropping strategy and household dietary requirement. This resulted in the poor farm raising the net cash balance by US$81 by increasing the area under groundnut and beans at the expense of maize (Table 3). It is thus more advantageous for the poor farmer to sell groundnuts and beans and buy maize for consumption, as groundnuts grown without fertilizer inputs are more profitable than maize grown with sub-optimal amounts of N. Increasing the area under groundnut would also increase the N balance by 11 kg ha^{-1}, but reduce the P balance by 2 kg ha^{-1}, although both would still be positive. A farmer is also unlikely to substitute all the maize plots for groundnut and beans, as maize is the staple food security crop. A more likely crop allocation where a third of the farm arable land is allocated to the groundnut showed that a net cash balance of US$71 could still be attained, with a reduced labour deficit of 46 man-days (Table 3). Optimisation of crop allocation revealed that the wealthy farm could increase net cash balance from US$172 to US$448 by changing cropping strategies, by expansion of the area of maize grown with cattle manure and mineral N fertilizer (Table 3).

Analysis of fertilizer allocation on the poor farm

As an example an assessment of the opportunities to improve net cash balance by targeted application of mineral fertilizers on the poor farm to maize plots was analysed by linking the crop yields simulated by APSIM to the IMPACT and the Household model. Fertilizers were used most efficiently when applied to two of the plots, rather than concentrated on one plot or spread across all three plots when optimal weeding was assumed (Table 4). However, optimal weeding of two plots may not be possible, as this would require the poor farmer to hire 29 man-days of labour. To address this constraint an alternative scenario of optimal weeding in plot 1 and 50% weeding in plot 2 reduced net cash balance by US$14, and showed that labour could still be a limitation as 10 extra days were required. The partial N and P balances were highest for the fertilizer allocation patterns where fertilizers were either concentrated on one plot or applied to all plots, indicating poor nutrient uptake efficiencies associated with these strategies, as much of the N is lost from the system.

Conclusions

The modelling approach used in this study was useful for integrating biophysical and socio-economic factors influencing decision making on smallholder farms and evaluate trade-offs for resource use in terms of nutrient balances, labour use, food sufficiency and cash balance. This study underscores the need to consider site-specific conditions at the farm level when designing interventions for improving efficiency of resource use, as some options have opposing effects, especially when comparing farms of contrasting wealth. For example, spreading fertilizer resources across the maize plots was more profitable on the rich farm, but less profitable on the poor farm. The poor farm faced multiple constraints including poor availability of cash and labour, and lack of manure and draught power. Under these conditions resources would be used more efficiently if maize was grown on smaller, well-managed areas and the mineral fertilizers concentrated rather than spread widely across the farm. On the wealthy farm, expansion of the area fertilised with manure would be ideal, although this would be highly labour demanding and require large amounts of manure. Net cash balance would be higher if manure was targeted at the outfield and basal mineral fertilizer on the homefield, rather than the reverse.

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Table 1: Sizes of different plots[1] and crop and fertilizer allocation patterns on the farms in different wealth categories in Murewa

	Wealthy Farmer			Poor Farmer		
Plot	Plot size (ha) and (Plot type)	Crop	Fertilizer	Plot size (ha)	Crop	Fertilizer
1	0.40 (homefield)	Maize	AN[2], manure	0.25 (homefield)	Maize	Urea, CPD
2	0.40 (homefield)	Maize	AN, CPD[3]	0.16 (homefield)	Maize	Urea
3	0.05 (mid-field)	Sweet potato	Ash, manure, CPD	0.05 (mid-field)	Groundnut/beans	
4	0.20 (mid-field)	Groundnut		0.40 (mid-field)	Maize/sunflower	Urea, CPD
5	0.50 (mid-field)	Lent out		0.05 (garden)	Assorted vegetables	Leaf litter, chicken manure
6	0.60 (outfield)	Maize	AN, CPD			
7	0.30 (outfield)	Fallow				
8	0.05 (garden)	Assorted vegetables	Manure, leaf litter, AN			

[1] Plot is used here to represent a 'management unit' consisting of a piece of land where the same type of crop with similar fertilizer, planting, weeding and harvesting regimes.

[2] AN = ammonium nitrate

[3] CPD = compound D fertilizer (7%N, 14%P_2O_5, 8%K)

Table 2. Important constraints in the Household model for the conditions on smallholder farms in Zimbabwe

Constraint	
Area of farm and fields	These were restricted actual size on the farms as we assumed no expansion of cultivated area.
Productivity of different field types	There were small differences in productivity between the different types of fields on the poor farm and we thus assumed similar production for each cropping strategy on the different field types. For the wealthy farm, coefficients of production (0 -1) for each cropping strategy for each field were generated using APSIM (see example in Table 5).
Dietary requirement	Energy and protein >= 70% WHO requirement (depending on age and sex of each household member).
Labour availability	Restricted to 9 hr per day, six days a week for adults who work full time on the farm. Hired labour and contribution of children to labour restricted as specified by the farmers.
Importance of food commodity in the diet	Restrictions were placed on the importance of commodities consumed (both produced from the farm and purchased) base on a coefficient a scale (0 -1): 0 = not important, 1 = important and cannot be substituted in the diet. Values attached to important commodities were: Maize (0.9), groundnut (0.7), vegetables (0.7), and sweet potato (0.5). This constraint allowed the diet to be varied within the boundaries representative of the normal diet (instead of the model only suggesting the cheapest commodity for consumption).

Table 3. Effects of different resource use options evaluated by the Household model on net cash balance, labour demand and partial nutrient balances for the wealthy and poor farms in Murewa.

Farm	Management	Description		Cash balance (US$)	Labour deficit (man-days)	Nutrient balance (kg ha^{-1})	
						N	P
Poor	1. Current management	(a)	Family's annual energy and protein demand throughout the year met 70% WHO requirement without any land-use changes.	-7	3	7	0
	2. Changing land-use	(a)	Household model selected the best land-use activities based on of current crop management options and energy and protein requirement by the family.	81	211	18	-2
		(b)	Expansion of the area under groundnuts (to about a third of the farm) at the expense of the area under maize.	72	46	10	-1
Wealthy	1. Current management	(a)	Family's annual energy and protein demand throughout the year met 70% WHO requirement without any land-use changes.	172	43	86	8
	2. Changing land-use	(a)	Household model selected the best land-use activities based on current crop management options and energy and protein requirement by the family.	448	153	357	38
		(b)	Expansion of the area under groundnuts to (about a third of the farm) at the expense of the area under maize.	165	198	84	9

Table 4. Impact of different fertilizer use strategies on net cash balance, labour demand and nutrient balances on the poor farm in Murewa.

Management strategy	Description	Net cash balance (US$)	Labour deficit (man-days)	Nutrient balance ($kg\ ha^{-1}$) N	P
Options for targeting N, P fertilizers across the plots on the farm.	(a) All fertilizers applied in plot 1, rest of the maize plot uncultivated.	21	3	-4	5
	(b) Fertilizer applied at equal rates in plots 1 and 2, optimal weeding in these plots. Plot 3 uncultivated.	40	29	-35	3
	(c) Fertilizer distributed equally in plots 1 and 2, optimal weeding in all plot 1, 50% optimal weeding in plot 2. Plot 3 uncultivated.	26	13	-26	5
	(d) Fertilizer inputs distributed equally across plots 1, 2 and 3, optimal weeding in all plots.	23	56	-24	6
	(e) Fertilizer inputs distributed equally across plots 1, 2 and 3, optimal weeding in all plot 1, 50% optimal weeding in plots 2 and 3.	10	26	-17	7

Figure 1. Schematic framework of the integrated modelling framework used to explore options of resource use on smallholder farms at Murewa, Zimbabwe. IMAPCT and the models Household, APSIM and RUMINANT are described in the text.