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An integrated evaluation of strategies for enhancing productivity and profitability of resource-constrained smallholder farms in Zimbabwe

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ABSTRACT

In African smallholder agriculture, improved farm-scale understanding of the interaction between the household, crops, soils and livestock is required to develop appropriate strategies for improving productivity. A combination of models was used to analyse land use and labour allocation strategies for optimizing income for wealthy (2.5 ha with eight cattle) and poor (0.9 ha without cattle) farms in Murewa, Zimbabwe. Trade-offs between profitability, labour use and partial nutrient balances were also evaluated for alternative resource management strategies. Farm data were captured using the Integrated Modelling Platform for Mixed Animal-Crop Systems (IMPACT), which was directly linked to the Household Resource use Optimization Model (HROM). HROM was applied to optimize net cash income within the constraints specific to the households. Effects of alternative nutrient resource management strategies in crop and milk production were simulated using the Agricultural Production Systems Simulator (APSIM) and RUMINANT models, respectively, and the output evaluated using HROM. The poor farm had a net income of US\$ 1 yr^{-1} and the farmer relied on selling unskilled labour to supplement her income. The poor farm's income was marginally increased by US\$18 yr^{-1} and the soil nitrogen (N) balance was increased from 6 to 9 kg ha^{-1} yr^{-1} by expanding groundnut production from the previous 5–25% of the land area. Further increases in area allocated to groundnut production were constrained by lack of labour. On the poor farm, maize production was most profitable when cultivated on a reduced land area with optimal weeding. The wealthy farm had a maize-dominated cropping system that yielded a net cash balance of US\$290 yr^{-1}, mainly from the sale of crop produce. Net income could be increased to US\$1175 yr^{-1}, by re-allocating the 240 hired labour-days more efficiently, although this reallocation substantially reduced partial soil N and phosphorus (P) balances by 74 kg N ha^{-1} and 11 kg P ha^{-1}, respectively, resulting in negative nutrient balances. Few opportunities existed to increase productivity and income of the smallholder farms without inducing negative nutrient balances. On the wealthy farm, groundnut was the least profitable crop; shifting its production to the most fertile field did not improve income unless the groundnut residues were fed to lactating cows. The analysis carried out in this paper highlights the need to develop practical technological recommendations and development interventions that consider farm resource endowment (land, fertilizers, manure and labour), variability in soil fertility within farms and competing resource use options.

1. Introduction

Smallholder farming systems in sub-Saharan Africa are complex due to intricate interactions between the soil, crops and livestock under unfavourable socio-economic conditions (Thornton and Herrero, 2001). In such systems, crop-soil and livestock simulation models offer limited insight into the suitability of technological options at the farm scale as these models represent the biophysical components of the farming systems (crop-soil and livestock systems) without considering the key socio-economic factors that drive farmers' decision making (Dent, 1995). Recognition of this limitation has led to development of tools that integrate biophysical and socio-economic data at the farm scale and allow a more holistic evaluation of both the performance and practicality of technologies (Thornton and Herrero, 2001; Castelán-Ortega et al., 2003).

Differences in access to resources for crop production by farmers and variability of soil fertility within and between farms are key

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determinants of crop productivity and food sufficiency at the household level in northeast Zimbabwe (Mtambanengwe and Mapfumo, 2005; Zingore et al., 2007a). Livestock contributes significantly to increased crop production through provision of manure and draught power. Labour is commonly in short supply and is a major factor in determining farmers' choice of crops and production methods. Wealthy farmers can hire the casual labour necessary to improve management of their farms, while poor farms are often forced to sell their labour, leading to poor management. Soil fertility in smallholder farming systems in northeast Zimbabwe varies considerably within farms and between farms and this disparity has major implications for crop productivity, profitability and suitability of crop production technologies (Zingore et al., 2007b).

Lack of adequate nutrient resources and shortage of labour are key factors that limit productivity of smallholder farming systems. Farmers have limited opportunities for increasing availability of resources, therefore, improving the efficiency with which nutrients, land and labour are used is imperative for increasing crop productivity (Giller et al., 2006). Key questions for targeted resource allocation to increase productivity and profitability arise at the farm scale. Such questions include: how should the limited fertilizer and labour resources available be targeted to optimize production of various crops grown for food or income generation and to plots that differ in soil fertility? Should crop residues be used for animal feed or incorporated into the soil for maintenance of soil fertility? Should land use be adjusted to respond to changes in prices of crop products?

Shepherd and Soule (1998) developed and applied a dynamic bio-economic model to study the impact of resource management strategies on Kenyan smallholder farms with contrasting characteristics and found that cropping was profitable and nutrient balances were positive only on mixed farms when farmers used mineral fertilizer in combination with cattle manure. Stoorvogel et al. (2004) used a trade-off model that combined econometric and biophysical models to design strategies for optimal management of the potato-pasture production system in the Ecuadorian Andes. Using this approach, they showed that the price of potatoes was the main factor driving farmers' decisions regarding the land area allocated to potato production, intensity of fertiliser use and pest management. Despite the successes of the approaches outlined above in addressing production and economic components of farming systems, key socio-economic factors that can influence farmers' decisions and the performance of farms, such as dietary requirement and labour demand for activities were not taken into account. Castelán-Ortega et al. (2003) used existing biological models and a farm-scale database to generate input data for a linear programming (LP) model to find the optimal combination of resources and technologies that maximised farmers' incomes. This framework allowed detailed characterization of farms and provided flexibility in the analysis of an array of socio-economic and biophysical factors and their interactions. Waithaka et al. (2006) used a similar approach to assess strategies for improving resource use in integrated crop-livestock systems in western Kenya and showed that a minimum farm size of 0.4 ha and the introduction of high-value cash crops were necessary to substantially increase the incomes of smallholder farmers.

Although the studies of Castelán-Ortega et al. (2003) and Waithaka et al. (2006) analysed the effects of several factors affecting crop and livestock production and profitability at the farm scale, labour was not a major constraint in the systems studied. Farm-scale analysis of trade-offs between increasing income and nutrient balances has also been given little attention. In this paper, a combination of a generic farm-scale database, a linear programming (LP) model and simulation models was applied to evaluate performance of two case study farms differing in access to resources to explore opportunities to increase income by increasing productivity of limited nutrients, labour and land. The farmers were engaged in developing and testing scenarios for improving targeting of crops, and nutrient and labour resources to fields varying in area and soil fertility. Partial balances of nitrogen (N) and phosphorus (P), the most limiting nutrients, were calculated for all scenarios to assess the potential effects of changes in resource management on net supply of nutrients to the soil. A sensitivity analysis was also conducted to assess the likely impact of changes in the prices of key crops on farm income, and to evaluate crop allocation strategies for optimizing income at various commodity prices.

2. Study method

2.1. The study site and farms

The study was conducted in Murewa district, northeast Zimbabwe (population density 104 people km^{-2}). The area has a high potential for crop production, with an annual rainfall of 750–1000 mm. Poor soil fertility is a major constraint to crop production in the region, which is mostly covered by granitic sandy soils (Lixisols) with low inherent fertility. Farmers practice mixed crop-livestock farming with maize (*Zea mays* L.) as the dominant staple crop. Other common crops include groundnut (*Arachis hypogaea* L.), sweet potato (*Ipomoea batatas* L.) and assorted vegetables. Cattle are the main livestock and they graze freely in communal rangelands during the day and are tethered in kraals near the homesteads at night. Close interaction between crops and livestock occurs through the use of crop residues as fodder for the cattle and the reciprocal use of cattle manure to fertilize the crops.

This work builds on previous research conducted to characterize the heterogeneity of soil fertility, resource endowment and resource management between smallholder farmers in Murewa, Zimbabwe (Zingore et al., 2007a). Case study farms that represented a broad range of socio-economic and biophysical characteristics were selected in a village of 120 households. Focus group discussions were held to identify indicators of farmers' wealth status, and based on these indicators, four levels of wealth were defined. A survey of farmers was conducted using a random sample of 50 households in the village to characterize the households and classify them into one of the four wealth groups (referred to as Resource Groups (RGs) 1–4, Table 1). Having confirmed the resource endowments of the farms through the surveys and farm walks, eight case study farms (two from each of the four wealth categories) were selected for detailed characterization. A more detailed description of the selection process is available in Zingore et al. (2007a).

On the wealthy farms, plots closest to homesteads (homefields) received the largest amounts of manure and were consequently more fertile than plots distant from homesteads (midfields and outfields). Soil organic carbon (SOC), total nitrogen (N) and available phosphorus (P) in the soil decreased from an average of 7 g kg^{-1}, 0.05 g kg^{-1} and 9 mg kg^{-1}, respectively, in the homefields to 4 g kg^{-1}, 0.03 g kg^{-1} and 5 mg kg^{-1} in the midfields and 3 g kg^{-1}, 0.03 g kg^{-1} and 2 mg kg^{-1} in the outfields (Zingore et al., 2007a). On the poor farms, all plots showed low fertility as they received few nutrient inputs, with SOC < 4 g kg^{-1}, total N < 0.02 g kg^{-1} and available P < 4 mg kg^{-1}.

2.2. Characteristics of case study farms

The scenario analysis in this study includes two farms with contrasting attributes; one is a male-headed household in the wealthy category (RG1) and the other is a female-headed household in the poor category (RG4). The two farms were representative of the wealthy and poor households in the study village (Table 1).

Table 1
Mean resource endowment for the farms in different farmer resource groups (RGs) in the Chiwara village, Murewa (total sample size = 50 farms).

Farm type	No. of farms	Household size	Farm size (ha)	Cattle	Oxen	Goats	Chickens	Ox-drawn carts	Manure available (t season^{-1})
RG1	8	7	3.1	12	2	2	8	1	10
RG2	14	5	2.5	7	1	3	5	0.4	6
RG3	12	6	2.2	0	0	2	6	0	0
RG4	16	4	1.0	0	0	0	3	0	0
Wealthy farm	1	7	2.9	6	2	4	6	1	8
Poor farm	1	3	1	0	0	0	3	0	0

Adapted from Zingore et al. (2007a).

The existing crop allocation and fertilizer use in different plots is summarized in Table 2. Maize was the dominant crop according to both land and fertilizer allocation. Both farms were located on granitic sandy soil with low inherent fertility. The poor farm comprised an area of 1.2 ha, of which 0.91 ha was arable. The farmer was the only full-time worker on the farm, and chickens were the only livestock owned. In the 2003/2004 cropping season, 60% of the fertilizer used by the poor farm was donated by the government. The wealthy farm was larger (2.9 ha; 2.5 ha arable) with five household members working full-time on the farm. The wealthy farmer also hired labour during periods of peak demand. The wealthy farmer owned 10 head of cattle, four goats and several chickens. The plots on the wealthy farms were demarcated according to soil fertility status: the homefield were the most fertile, followed by the midfield, and outfield.

2.3. Farm-scale analysis framework

A combination of a farm characterization tool, the Integrated Modelling Platform for Mixed Animal-Crop Systems (IMPACT) (Herrero et al., 2007); a linear programming model, Household Resource use Optimization Model (HROM) (González-Estrada et al., 2008); a crop/soil simulation model, the Agricultural Production Systems Simulation Model (APSIM) (Keating et al., 2003); and a livestock-feeding model (RUMINANT) (Herrero, 1997) was used to analyse and compare the impact of different resource management options at the farm scale. IMPACT has direct connectivity with HROM, and data input for optimization runs is automatically generated from IMPACT. HROM assesses the impact of management interventions on the performance of farms and the livelihoods of households (Herrero and Fawcett, 2002; Waithaka et al., 2006; González-Estrada et al., 2008). Summary statistics of simulation model outputs on alternative nutrient management strategies for farm fields and cattle were manually entered into IMPACT. Activities for crop production were based on existing management practices captured in IMPACT and optional ones generated by APSIM. Results produced by APSIM were used to calculate coefficients for fertilizer and labour variables for optional crop management. Crop productivity for each field type under different management practices, covering different fertilizer and manure application rates and weeding intensity, constituted the technical coefficients used by HROM to select the optimal crop allocation strategies (Table 3). RUMINANT generated optional activities and technical coefficients for cattle productivity (changes in weight and milk production by cows) under different feeding strategies (Table 4). As no cattle were sold from the farms studied during the simulation year, the contribution to net income of changes in livestock weight was not considered.

2.3.1. IMPACT and data collection

IMPACT is a comprehensive farm-scale database that captures data for crop, soil and livestock management on a monthly basis (Herrero et al., 2007). The information is organised in seven groups: (i) climate; (ii) household structure; (iii) land use and management; (iv) livestock management; (v) labour allocation; (vi) household dietary pattern; (vii) farm sales and expenses. In addition, IMPACT processes these data to provide a baseline analysis of the performance of the farm. This baseline analysis includes the monthly financial balance, the family's monthly nutritional status and annual partial balances for SOC, N, P, and potassium. This paper reports on only soil N and P balances, as these are the most limiting nutrients in the sandy soils in the study area (Grant, 1981).

Detailed data collection for case study farms was conducted on a monthly basis using survey forms designed to capture the household, crop, livestock, labour and economic data required by IMPACT. Data on availability of nutrient resources and their allocation among various plots, crops and livestock was verified using resource flow mapping. Farmers actively participated in drawing resource flow maps of their farms indicating nutrient re-

Table 2
Plots sizes[a] and crop and fertilizer allocation patterns on Murewa farms categorized by wealth. Application rates for nutrient resources (kg ha^{-1} yr^{-1}) are shown in parentheses.

Wealthy farmer					Poor farmer				
Plot no.	Plot type	Plot size (ha)	Crop	Nutrient resource	Plot no.	Plot type	Plot size (ha)	Crop	Nutrient resource
1	Homefield	0.40	Maize	AN[b] (150), manure (16,000)	1	Homefield	0.25	Maize	Urea (15), CPD (40)
2	Homefield	0.40	Maize	AN (100)	2	Homefield	0.16	Maize	Urea (20)
3	Midfield	0.05	Sweet potato	Ash (15), manure (1000), CPD[c] (20)	3	Outfield	0.05	Groundnut	
4	Midfield	0.20	Groundnut		4	Outfield	0.40	Maize	Urea (15), CPD (10)
5	Midfield	0.50	Lent out		5	Garden	0.05	Assorted vegetables	Leaf litter (120), chicken manure (400)
6	Outfield	0.60	Maize	AN (50), CPD (30)					
7	Outfield	0.30	Lent out						
8	Garden	0.05	Assorted vegetables	Manure (1200), leaf litter (1000), AN (40)					

[a] Plot represents a management unit consisting of a piece of land where the same type of crop with similar fertilizer, planting, weeding and harvesting regimes are applied.
[b] AN = ammonium nitrate.
[c] CPD = compound D fertilizer (7% N, 14% P, and 8% K).

Table 3
Maize and groundnut productivity data table generated by APSIM for different fertilizer and manure applications and weeding frequencies. Output was evaluated in terms of grain and stover yields and nutrient content.

	Dimension			
Wealthy farm				
	Fertilizer N application rate (kg ha^{-1})	Fertilizer P application rate (kg ha^{-1})	Manure application rate(kg ha^{-1})	Weeding frequency
Maize productivity homefield	0; 40; 80; 120; 160	0; 10; 20; 30	0; 4000; 8000; 12,000; 16,000	2
Maize productivity midfield	0; 40; 80; 120; 160	0; 10; 20; 30	0; 4000; 8000; 12,000; 16,000	2
Maize productivity outfield	0; 40; 80; 120; 160	0; 10; 20; 30	0; 4000; 8000; 12,000; 16,000	2
Groundnut productivity		0; 10; 20; 30	0; 4000; 8000; 12,000; 16,000	2
Poor farm				
Maize	0; 40; 80; 120; 160	0; 10; 20; 30		1
Maize	0; 40; 80; 120; 160	0; 10; 20; 30		2

Table 4
Milk production data table generated by RUMINANT for groundnut residues fed to dairy cows on the wealthy farm in Murewa. Output was evaluated in terms of daily milk production per cow.

Season	Forage quality	Maize stover (kg cow^{-1} day^{-1})	Groundnut residues
Dry season	Low	20	0; 2; 4
Wet season	High		

sources available, their sources and allocation patterns (Zingore et al., 2007a).

Crop grain and residue yields were estimated from micro-plots (5 m × 5 m) staked out in farmers' fields. This information was used to crosscheck yields estimated by farmers. Information for all livestock species owned by the farmers was collected. Additional data were collected for ruminants, including productive and reproductive parameters. Information on mortality and time and price of sale of livestock and their products was captured on a monthly basis. Labour data were also collected on a monthly basis using household labour profiles designed to capture labour spent on crops, livestock and household activities by each household member. Labour data for cropping activities in each plot (e.g., weeding) were summarized on a hectare basis and compared with data from the literature to verify that estimates were within the expected ranges. Household food consumption of various commodities was translated into energy and protein intake on a monthly basis. This information was verified against World Health Organization (WHO, 1999) guidelines and general food consumption estimates for sub-Saharan Africa.

2.3.2. HROM linear programming model

HROM explicitly incorporates IMPACT data related to on-farm and off-farm nutrient resources, as well as the monthly and seasonal management of these resources. It also includes information on food security-related factors, off-farm income generation and labour constraints. Thus, HROM determines the best combination of farm resources that satisfy a set of objective functions according to both management and economic interventions. These objective functions include maximizing the net cash balance, minimizing nutrient losses or minimizing risk. For the analysis presented here, the objective was to maximize household income. HROM runs on a monthly time-step, and all activities related to crop and livestock production, household food consumption and labour, and changes in the farming system were optimized on a monthly basis. The performance of the farms is given on an annual basis after integrating the optimal combination of resources for each month. The analysis was conducted for one year (with one cropping season) and did not consider year-to-year changes in the farming systems.

Important variables within HROM include farm size and arable plot sizes; food sufficiency for households (which can be set at different levels in relation to energy and protein requirements recommended by the WHO); lower limits on consumption food commodities (depending on their cultural importance to the diet); the productivity of a particular plot under specific management; and the potential productivity of similar management on plots of different soil fertility status. HROM also incorporates restrictions on labour, cash, livestock numbers and productivity of livestock and milk. Due to the large number of equations in the model, a brief description of the objective function and constraints influencing results of scenario analysis for the case study farms in Murewa is shown below. More detailed descriptions of the generic model are presented by Waithaka et al. (2006) and González-Estrada et al. (2008). Net cash balance was maximized and the performance of the farms assessed in terms of net cash balance, labour demand and partial N and P balances.

The objective function is represented as:

$$\text{Maximize ObjFunc} = \sum_{c}^{CROP} incomeC_c + \sum_{l}^{LVSTCK} incomeL_l - \sum_{c}^{CROP} expenseC_c + \sum_{l}^{LVSTCK} \exp enseL_l \quad (1)$$

Net income was calculated on a monthly basis for the cropping and livestock activities and the annual net cash income was calculated from the monthly net income. Total net income for the cropping activities was calculated from the incomes (*incomeC*) derived from the various crops (c) and production costs (*expenseC*) for each plot. Net income for livestock was computed per livestock type (l). Income for livestock (*incomeL*) included income from sale of livestock or livestock products, while expenses included purchases of feed and labour costs (*expenseL*).

Constraints imposed on variables were selected based on characteristics for specific farms. The main constraints influencing model output were:

(i) Constraint on plot size and cropping option:

$$\forall y \in YEAR, p \in PLOT : plotsize_{y,p} \geqslant \sum_{o}^{OPTION} (LAND_{y,p,o}) \quad (2)$$

where *plotsize* is the size of the plot p in year y and LAND is the decision variable that allocates the cropping option o to plot p in year y. In the analysis of the existing land use, the options for each plot were restricted to those observed on the farms (Table 2). In the optimization of land use, the best option was assigned to a particular plot according to productivity, profitability, household dietary requirement and labour demand. All plots were assigned simultaneously. Production potential and crop yield responses to fertilizer addition were adjusted for plots differing in soil fertility on the wealthy farm based on APSIM output (Table 3). There were only small differences in productivity between the different types of plots on the poor farm, and production potential for each cropping strategy was similar on the different plots.

(ii) Constraint on energy and protein sufficiency

$$\forall y \in YEAR, m \in MONTH$$
$$: \sum_{c}^{COMMODITY} commoditynutrient_{n,c} X commodityconsumed_{y,m,c}$$
$$\geqslant nutrientrequired_{y,m,n} \qquad (3)$$

where *commoditynutrient* is the content of energy or protein *n* in commodities *c* consumed by the household. *Commodityconsumed* is the decision variable that allocates the amount of commodity *c* that should be consumed by the family in month *m* and year *y*. The variable *nutrientrequired is* the energy or protein required per year by the household. Household food requirement was taken to be 70% of the WHO recommendation for each household (FAO, 1998).

(iii) Constraint on dietary importance of commodities:

$$\forall y \in YEAR, m \in MONTH, c \in COMMODITY$$
$$: commodityconsumed_{y,m,c}$$
$$\geqslant (dietcurrent_{y,m,c} \mathrm{X}\ dietimportance_{y,m}) \qquad (4)$$

where *dietcurrent* is the diet consumed as reported by the household consisting of commodity *c* consumed in month *m* and year *y*. *Dietimportance* is the cultural importance of commodities consumed, both produced from the farm and purchased, which formed the basis of the diet selection.

The relative importance (between 0 and 1) of commodity *c* in the family's diet during month *m* indicates the extent to which consumption of commodity *c* can vary between the optimized diet and that observed: 0 was assigned if farmers considered the commodity not important, and 1 was assigned if farmers considered it important and that it could not be substituted within the diet. Values attached to important commodities were maize (0.9), groundnut (0.7), vegetables (0.7), and sweet potato (0.5). This constraint established the permitted variation in food consumption according to locally-preferred diets, allowing the substitution of certain foods in response to changes in cropping strategies (rather than having the model select only the cheapest commodities for consumption).

(iv) Constraint on labour:

$$\forall \in YEAR, m \in MONTH$$
$$: \sum_{p}^{PLOT} \sum_{o}^{OPTION} (optionlabour_{y,m,o} \times LAND_{y,p,o})$$
$$+ \sum_{i}^{LVTCK} (lvstcklabour_{y,m,l} \times ANIMAL_{y,l})$$
$$+ otherlabour_{y,m}$$
$$\leqslant HIRELABOUR_{y,m} + \sum_{w}^{WORKGROUP} (family_{w}$$
$$\times availablelabour_{w,m}) \qquad (5)$$

where *optionlabour* is labour required for different cropping options *o*, *lvstcklabour* is labour required for management of livestock type *l* multiplied by the number of animals (*ANIMAL*), and *otherlabour* is labour required for non-farming activities. The total labour required was satisfied by the amount of hired labour (as expressed by the decision variable *HIREDLABOUR*) and family labour available to work on the farm. The latter was computed for different workgroups *w*: adults working full-time on the farm (an 8-h working day) and school-attending children who were available to work for four hours a day.

2.3.3. Simulation models

HROM tested the effects of alternative nutrient management within the farm by including simulated outputs from other models. APSIM was used to simulate crop-soil management options for targeting N and P fertilizers, and animal manure to plots with different soil fertility levels. APSIM has been widely tested and validated for fertilizer and manure application strategies on crop production in Africa, including in Murewa (Delve and Probert, 2004). The APSIM maize and groundnut modules were linked to the surface residue module, soil water module, soil N module (Probert et al., 1998) and soil P module (Probert, 2004). Soil water parameters previously estimated for granitic sandy soils in Murewa were used (Chivenge et al., 2004). Soil N, C and P contents were measured in all three field types on the wealthy and poor farms and these values were used to initialise soil parameter files in APSIM with different soil fertility. The model was calibrated for the present study by simulating productivity of maize and groundnuts under the existing management. The manure used in these simulations had the following properties estimated from analysis of samples in the study area: 25% C, 1.2% N and 0.16% P.

The RUMINANT model consists of a dynamic section that estimates intake and the supply of nutrients to the animal based on Illius and Gordon's (1991) work on the fermentation kinetics and passage of feed constituents (carbohydrates and protein) through the gastrointestinal tract, and a static section that determines the animal's response (growth and milk yield) to the nutrients ingested as estimated by AFRC (2003). This generic model can simulate animals of different body weights due to the incorporation of allometric rules for scaling passage rates (Illius and Gordon, 1991). The model has been used in previous modelling studies (Herrero et al., 1999; Castelán-Ortega et al., 2003; Waithaka et al., 2006) for modelling replacement decisions in dairy herds (Vargas et al., 2001) and for studying the potential for carbon sequestration in West Africa (González-Estrada et al., 2008).

2.4. Scenario analysis

Scenarios were generated during focus group discussions with farmers following general characterization of the farms and detailed analysis of resource use strategies by resource flow mapping. The scenarios to be explored were formulated by discussing with farmers the following questions:

(i) What opportunities exist for achieving food self-sufficiency and increasing income for the food-insecure poor household and the market-oriented wealthy household by changing land use based on current cropping activities?
(ii) Is the government-recommended practice of allocating one third of the farm to grain legumes appropriate for farmers in terms of increasing farm income and returns on labour investment?
(iii) Can available nutrient resources be used more efficiently by targeted application to plots earmarked for production of the main crop (maize)?
(iv) Should nitrogen-rich legume crop residue be use for feeding cattle or incorporated into the soil to increase the N supply for crop production?

2.4.1. Current performance of the farms

Food sufficiency, household economics and farm-scale N and P balances under existing resource management were assessed using the scenario analysis tool in IMPACT. Food sufficiency was evaluated by calculating the household's annual intake of energy and protein based on information collected regarding food consumption. The total annual energy and protein required by each family was computed by summing the quantity required by each household member, which varied according to age and sex (as per the WHO standard guidelines), and multiplying it by 70%. 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 of partial N and P balances for the cropping system considered the N and P content of fertilizers and manure added to the arable fields and those of products removed. These calculations did not consider inputs from biological N_2-fixation and atmospheric deposition and outputs through leaching, erosion and gaseous losses.

2.4.2. Evaluation of resource use options by HROM

The first scenario captured the current resource management practices of the poor (Scenario Poor-1; Table 5) and wealthy (Scenario Wealthy-1; Table 6) farms. HROM was then used to maximize the net cash balance for alternative resource use scenarios under the conditions on the two farms. In all scenarios, total amounts of fertilizer and manure used were restricted to those available on the individual case study farms (Table 2), and were within the long-term range of fertilizers and manure used on similar farms (Zingore et al., 2007a). Activities for crop and animal production were based on existing management practices captured in IMPACT and alternative management practices generated by APSIM and RUMINANT.

Scenarios Poor-2 (Tables 5) and Wealthy-2 were chosen to assess the combination of crop management activities that yielded the highest net income according to the farmers' capacity to supply labour. Land use was optimized, assuming that all plots were weeded twice, the standard weeding frequency practiced by farmers. The labour force hired by the wealthy farmer (20 labour-days a month) was compared against two alternative scenarios: (i) no labour available for hiring; and (ii) an annual availability of 240 labour-days with no constraints on monthly allocation. These scenarios were designed to assess the contribution of hired labour to income on the wealthy farm, and to compare the effects of limiting monthly labour with targeting annual labour to activities that provided the highest return on labour investment. The net income generated took into account the cost of hired labour.

The impact of increasing the area for growing groundnuts and of readjusting the resource use required to maximize income under expanded groundnut production was assessed to address the perception that increasing grain legume production can improve food security, household income and soil fertility on smallholder farms (Snapp et al., 2002). In Zimbabwe, farmers are currently advised by extension agents to allocate one-third of their farms to grain legumes.

A third set of scenarios involved the direct comparison of specific alternative resource use options raised by farmers during focus group discussions. For the poor farm, the scenarios (Poor-3) focused on optimal nutrient allocation strategies relative to available labour. For simplicity, maize plots on the poor farm were combined and re-demarcated into three plots of similar area (Plots 1–3) and the scenarios were designed to manage limited nutrient resources and labour based on these plots (Table 5). For the wealthy farm, the resource use options sought to evaluate the strategic allocation of manure and mineral fertilizers to the homefield and outfield to enhance profitability. Farmers commonly grow maize on the homefields and groundnuts on the midfields and outfields. An alternative scenario was evaluated in which the groundnut crop was grown on the more fertile homefield and maize shifted to the midfield and outfield. For all management practices

Table 5
Resource use options evaluated for the poor farm in Murewa using HROM.

Scenario	Management	Description
Poor-1	Current management	Family's annual food requirement met (70% of WHO requirement) without change in land use
Poor-2	Changing land use	a. HROM selected the best land use activities based on current crop management options b. Area for groundnut crop expanded to one third of the farm and area for maize reduced concomitantly
Poor-3	Options for targeting N and P fertilizers across the plots on the farm	a. All fertilizers applied to maize in Plot 1. Plots 2 and 3 not cultivated b. Fertilizer applied at equal rates to maize in Plots 1 and 2. Both plots weeded twice c. Fertilizer inputs applied equally to three maize plots. Plot 1 weeded twice and Plots 2 and 3 weeded once

For all model runs, labour was constrained by that available on the farm.

Table 6
Resource use options evaluated for the wealthy farm in Murewa.

Scenario	Management	Description
Wealthy-1	Current management	Family's annual food requirement met (70% of WHO requirement) without change in land use
Wealthy-2	Changing land use	a. HROM selected the best land-use activities based on current crop management options and farm labour b. HROM selected the best land-use activities based on current crop management options with a maximum of 8-h labour days. Labour hired monthly c. HROM selected the best land-use activities based on current crop management options with a maximum of 240 8-h labour days. Labour hired annually d. Area for groundnuts expanded to 0.4 ha and area for maize crops reduced
Wealthy-3	Targeting maize with N, P and cattle manure across different field types	a. All fertilizers allocated to maize on the homefield. Other maize plots cultivated without added fertilizer b. All fertilizers targeted to maize and distributed evenly across all fields c. Mineral P targeted to maize on the homefield. Manure targeted to the outfield d. Mineral P targeted to maize on the outfield. Manure targeted to the homefield
Wealthy-4	Targeting groundnuts to more fertile fields with residue management	a. Groundnuts grown on the homefield. Residues fed to livestock with simulated milk production generated by RUMINANT b. Groundnuts grown on the homefield. Residues incorporated into the soil

crop productivity was also related to weeding frequency. Farmers typically weed maize twice, about three and six weeks after crop emergence. However, when labour is in short supply, farmers may weed only once. On the wealthy farm, plots were weeded twice in all scenarios, but on the labour-constrained poor farm different weeding frequencies (once or twice) were simulated.

A fourth scenario for the wealthy farm (Wealthy-4) assessed alternative uses of crop residues. Using RUMINANT, crop residues produced in APSIM simulation were used to estimate quantities of crop residues (groundnuts) fed to livestock (Table 6). This model was not used to produce manure input for APSIM, as RUMINANT only provides the quantity and quality of manure, but not the losses of manure and nutrients during storage and handling. Milk produced by lactating cows was the main product from livestock contributing to income and nutrition. On this basis, scenarios for livestock management were limited to different strategies for feeding crop residues to lactating cows. Table 6 shows the description of this scenario linking RUMINANT simulations to the productivity of groundnuts in the homefield as predicted by APSIM. The effects of feeding crop residues to cows on the farm's income and nutrient balances were compared with the effects of incorporating the residues into the soil to increase soil fertility. Groundnut residues were fed to cows for six months from the beginning of the dry season in May (after the groundnut harvest) until October, when the rains start and forage is abundant. Various amounts of groundnut residues, depending on amount of groundnut stover produced, were fed to cows as a supplement to rangeland grass that cattle typically grazed in communal areas. Maize residues were exclusively used as fodder during the dry season.

Among other factors, commodity prices drive farmers' choices on allocation and management of crops. To evaluate the capacity of the farms with contrasting characteristics to cope with price risk by modifying crop allocation, HROM optimizations were run with variable prices for each of the main crops (maize, groundnut and sweet potatoes), with the prices for other products remaining fixed to existing prices. Wide ranges of prices, from very low to very high, based on ten years' of historical price fluctuations, were simulated for each crop. Farmers have a narrow window of opportunity to market their produce with small market price variations, hence for each simulation, prices were kept constant and did not change during the simulation year.

3. Results

3.1. Current performance of the farms

The poor farm had a negative cash balance for the cropping system and a small net income from livestock (sale of eggs and chickens) and other non-farm activities (sale of labour). This led to an overall negative annual cash balance (-US$5) of the farm (Fig. 1). Monthly cash balances for the poor farm were positive only for five months: four months during the cropping season when labour was sold and one month after harvest when some of the groundnut grain was sold. The annual net revenue of the wealthy farm was positive, mainly due to income generated from the sale of maize (Fig. 1). The baseline cash balance was lower than that observed because the food consumption level estimated by the WHO was higher than actual consumption levels for the wealthy farm. On the wealthy farm, the livestock component had a negative cash balance because the farmer invested cash to purchase chemicals for treating cattle and to pay for labour for their management. The wealthy farm generated a small amount of cash from off-farm activities but spent substantial quantities of cash on children's education, health care and the purchase of food, which led to the negative revenue from other activities not directly related to farming. Monthly cash balances for the wealthy farm were highest in the two months after harvesting and the sale of crops, and were positive throughout the year.

Fig. 1. Annual cash balances of cropping, livestock and off-farm activities at the farm scale for poor and wealthy case study farms in Murewa, Zimbabwe.

Farm-scale partial N and P balances were positive but small on the poor farm due to the small quantities of produce harvested. The wealthy farm had a positive partial N balance, but the P balance was zero.

3.2. Scenario analysis

3.2.1. Scenario 1: baseline analysis of performance of the farms

Net revenue on the poor farm increased slightly when HROM maximized the net cash balance under existing resource use in the baseline analysis (Table 7). The model output agreed well with the small income observed on the poor farm. Actual food consumption of the farms was greater than the 70% of the WHO standard for food consumption for sub-Saharan Africa used in the model analysis. The increase in income in the baseline analysis was mainly due to changing in the model analysis from the actual food consumption to 70% of the WHO standard. Large discrepancies between the observed and simulated net income (US$210 and US$290 yr^{-1}) were observed for the wealthy farm (Table 8). The greater increase in income on the wealthy farm in the baseline analysis was due to a larger underestimation of the amount of food consumed and hence overestimation of the crops sold. The model simulated the differences in income between the wealthy and poor farms reasonably well.

3.2.2. Scenario 2: impact of changes in crop allocation on farm income

On the poor farm, optimal crop allocation was achieved by increasing the area for groundnut cropping from the existing 0.05–0.2 ha, and this resulted in an increase in net income from US$1 yr^{-1} to US$19 yr^{-1} (Table 7). Groundnuts grown without fertilizer inputs were more profitable than maize grown with suboptimal amounts of fertilizer; hence it was more beneficial for the poor farm to increase the area cropped with groundnuts and buy maize for consumption. Increasing the area for groundnut cropping also increased the partial N balance by 11 kg ha^{-1}, but reduced the partial P balance by 2 kg ha^{-1}. The farm area that was allocated to groundnut production was restricted by labour availability to 0.2 ha. Labour shortage is one of the factors that prevents poor farmers from allocating one third of the farm to groundnuts as recommended (Scenario Poor-1b; Table 7), even though this could be more profitable and increase partial N balance if labour is not limiting (data not shown). Analysis of the recommended practice without constraining labour increased income to US$71 yr^{-1}, but an extra 46 labour-days would be required (data not shown).

On the wealthy farm, the model suggested that expansion of the area under sweet potato cropping to 0.46 ha and elimination of maize and groundnuts was required to maximize income if no labour was hired (Scenario Wealthy-2a; Table 8). An increase in

Table 7

HROM evaluation of effects of current and optional fertilizer use and crop allocation strategies on net cash balance, labour demand and nutrient balances on the poor farm in Murewa.

Scenario		Annual net cash balance (US$)	Partial nutrient balance (kg ha^{-1})		Land use
			N	P	
Poor-1		1	6	3	Existing land use (see Tables 3 and 4)
Poor-2	(a)	19	9	5	Area for groundnuts increased to 0.2 ha and area for maize reduced to 0.66 ha
	(b)	–	–	–	Scenario not feasible due to shortage of labour. Maximum land allocated to groundnuts is 0.2 ha, as presented in Scenario 2 (a)
Poor-3	(a)	16	−4	5	Maize allocated to Plot 1
	(b)	20	−35	3	Maize allocated to Plot 1. Plot 2 limited by lack of labour to 0.17 ha
	(c)	3	−17	7	All maize plots used

See Table 5 for description of scenarios.

Table 8

HROM evaluation of current and different resource use strategies on net cash balance, labour demand and nutrient balances on the wealthy farm in Murewa.

Scenario		Net income (US$)	Partial nutrient balance (kg ha^{-1})		Land use
			N	P	
Wealthy-1	(a)	290	26	0	Current land use
Wealthy-2	(a)	450	−31	−4	Based on labour available on the farm, sweet potato allocated 0.46 ha. Groundnuts and maize excluded. Farmer sells sweet potato and buys all food for consumption
	(b)	602	−62	−6	With inclusion of 20 8-h labour days hired per year, area under sweet potato increased to 0.3 ha and maize (with fertilizer) allocated 1.2 ha. Groundnuts excluded
	(c)	1175	−48	−11	With inclusion of 240 8-h labour days hired per year, area under sweet potato increased to 1.0 ha and 0.6 ha under maize (with manure) allocated. Groundnuts excluded
	(d)	945	−39	−3	With inclusion of 240 8-h labour days hired per year. Groundnuts fixed to 0.4 ha, sweet potato increased to 0.8 ha, maize reduced to 0.4 ha
Wealthy-3	(a)	158	60	14	Current crop allocation, all fertilizers and manure applied to maize concentrated on the homefield
	(b)	169	50	13	Current crop allocation, all fertilizers and manure applied to maize distributed evenly across all fields
	(c)	221	41	12	P targeted to maize on homefield; manure targeted to the outfield
	(d)	222	43	12	P targeted to maize on outfield; manure targeted to the homefield
Wealthy-3	(a)	226	30	−1	Groundnuts grown on the homefield without nutrient inputs. Residues fed to livestock
	(b)	209	34	−1	Groundnuts grown on the homefield without nutrient inputs. Residues incorporated into the soil

See Table 6 for description of scenarios.

income by expansion of the area cropped with sweet potato resulted in a large decrease in N and P balances. Inclusion of a maximum of 20 labour-days yr^{-1} of hired labour, as observed, increased net income by US$152 yr^{-1} and allowed production of sweet potato and maize. The maize strategy selected (maize grown with fertilizer alone) was less profitable than when manure was added but was preferred as it required less labour. Manure contributes substantial amounts of N and P, and excluding it led to a large decrease in partial nutrient balances (Scenario Wealthy-2b; Table 8). Net income was increased by 400% over existing management when the labour was constrained to 240 labour-days yr^{-1} rather than 20 days month^{-1}, allowing more flexibility in allocating hired labour to the most cost-effective activities. This was achieved by increasing the area under sweet potato cropping and selecting the most profitable maize plot (maize produced with manure and N on Plot 1) (Scenario Wealthy-2c; Table 8). Allocating one third of the crop area to groundnuts (Scenario Wealthy-2d; Table 8) resulted in a decrease in net income compared with Scenario Wealthy-2c, but had a positive effect on partial N and P balances.

3.2.3. Scenario 3: evaluation of alternative resource management strategies

Weeding frequency strongly affected maize productivity when fertilizers were applied at 36 kg N ha^{-1} and 6 kg P ha^{-1}, with a reduction of 0.7 t ha^{-1} if weeding frequency was reduced from twice to once per cropping season. APSIM predicted higher aggregate farm productivity when fertilizer was applied at a moderate rate to two plots than at a lower rate to three plots. This is attributable to strong P limitation reducing N recovery at very low application rates. It is also possible that at very low N application rates, the proportion of N lost from sandy soils through leaching is large (Shamudzarira and Robertson, 2002).

The best management strategy (applying fertilizer to two plots and weeding twice) was not possible due to shortages of labour, and only half of the second plot could be cultivated (Table 7). Distributing fertilizers equally among the three plots led to the lowest returns for all labour allocation strategies, suggesting that the best maize management option for the poor farm was to concentrate the limited fertilizer and labour resources on smaller, well-managed areas.

On the wealthy farm, simulated maize yields were smaller on the outfield, particularly when no fertilizer was applied. Simulated uptake of N and P by maize was greater than by groundnuts, indicating that nutrients were used more efficiently when targeted to maize rather than groundnuts. RUMINANT simulated increased milk production when lactating cows were fed with groundnut residues to supplement rangeland grazing. Shifting groundnut production from the midfield to the homefield gave increased productivity, and concomitantly a larger amount of groundnut residues for feeding livestock. Feeding the residues to cattle led to an increase in milk production of 40 l yr^{-1} when compared with a diet based on rangeland grazing and maize residues.

Analysis by HROM showed that income was low when all nutrient resources were concentrated on the homefield or distributed equally between the homefield and outfield, strategies that involved the use of all the nutrient resources (manure, N and P fertilizers) in combination. Income was substantially increased above these scenarios when manure or basal P fertilizer were used separately, although targeted allocation to the homefield and outfield had no effect on income at the farm scale. Targeting manure to the outfield and basal P fertilizer to the homefield was more productive than the reverse, but the economic benefits of this strategy were offset by increased costs of labour for transporting manure to the outfield. Shifting production of groundnut from the midfield to the homefield and feeding the residues to lactating cattle yielded an income that was US\$17 yr^{-1} greater than if the residues were incorporated in the soil, but reduced the N balance by 4 kg N ha^{-1}.

Results produced indicate an important trade-off between income and nutrient balance on the wealthy farm. Partial N and P balances were strongly negatively correlated with net income, as removal of nutrients increased proportionally with increased productivity (Fig. 2). On the poor farm, the magnitude of changes in partial N and P balances was less than that on the wealthy farm and showed no relationship with income.

3.2.4. Impact of changes in commodity price on farm income and crop allocation

On the poor farm, net revenue responded weakly to changes in output prices for maize and groundnuts (Fig. 3), as the crops were produced mostly for subsistence. However, changes in maize and groundnut grain prices strongly affected crop allocation. A minimum of about 75% of the cropping area was allocated to maize, even at the lowest price, due to its dietary importance. The area allocated to maize was only increased substantially when the price for maize was increased above \$200 t^{-1} (>250% above the existing price). The maximum area allocated to groundnuts was the 0.2 ha achieved at existing prices, as further expansion with increases in prices was not possible due to the shortage of labour. The groundnut crop was only eliminated and replaced by maize when the price was reduced below US\$50 t^{-1} (<30% of the existing price).

The wealthy farm was affected differently by changes in prices (Fig. 3). An increase in the price of maize from US\$25 to US\$75 t^{-1} was accompanied by a decrease in income, as land was not allocated to maize within this price range and more cash was spent on purchasing maize for consumption. Producing maize for the market was viable at prices >US\$100 t^{-1} and farm income increased with increasing maize price above this threshold. Farm income and area allocated to sweet potato cropping was highly sensitive to changes in the price of sweet potato, which was the most profitable crop on the wealthy farm. The area allocated to sweet potato cropping increased sharply at US\$25 t^{-1}, but farm income was only responsive at prices >US\$37 t^{-1}.

4. Discussion

4.1. Analysis of performance of the farms and strategies for optimizing farm income

The analysis carried out by integrating different component models at the farm scale showed that income produced on smallholder farms is strongly dependent on availability of nutrient and labour resources, as well as their strategic allocation. Availability of labour, farm size, soil fertility status and livestock ownership are some of the key factors that influence decision making by the resource-constrained farmers considered in this study. Additional important factors that we did not consider include climatic risk and the ability to adapt new technologies (Jayne et al., 2006). Cropping activities contributed a large proportion of the cash generated on the wealthy farm, as land, labour and nutrient resources available were sufficient for the farm to produce crops for home consumption and sale. Optimization of resource use by the wealthy farm shows that both availability of labour and its allocation had a stronger effect on income than changing crop and fertilizer allocation strategies. Balancing investment of labour in relation to the availability of nutrient resources is required to optimize income on smallholder farms, supporting the conclusion that on farms with fertile soils, farmers should prioritize investment in labour over nutrients (Tittonell et al., 2007). An analysis by Orr et al. (2002) showed that investment in labour for weeding has a strong substituting effect on fertilizer, and smallholder farmers may obtain larger yields from weeding twice with half as much fertilizer.

The most profitable crops selected (groundnut for the poor farm and sweet potato for the wealthy farm) were more demanding in labour than maize and, as a result, less than a quarter of the arable land could be cultivated when these crops were selected. The land use strategies proposed for maximizing income require farmers to produce only one crop, which may not be attractive to farmers due to the high associated risk and farmers' preference to produce their own food.

The strong influence of labour on the selection of cropping activities to maximize income on the wealthy farm was shown in Scenario Wealthy-2c, where a less profitable maize production option was selected over a more profitable but labour-intensive option involving the use of manure (Table 8). The substantial increase in income and N balance on the wealthy farm, when improved labour management (by allocating hired labour to the most labour efficient practices rather than hiring fixed labour monthly) allowed replacement of the sole fertilizer with a combination of fertilizer with manure, demonstrated the synergy between the household, crop and animal production in increasing resource use efficiency at the farm scale. High labour availability is associated with a more resilient, diverse and profitable cropping pattern (Shaxson and Tauer, 1992).

Allocating one third of the cultivated area to groundnut production was not feasible on the poor farm due to labour constraints, whilst on the wealthy farm groundnut cropping was not attractive, as it was less profitable than sweet potato and maize. This explains why farmers typically grow groundnuts only on small areas for home consumption. Waddington and Karigwindi (2001) showed that maize grown with high rates of fertilizer was more profitable

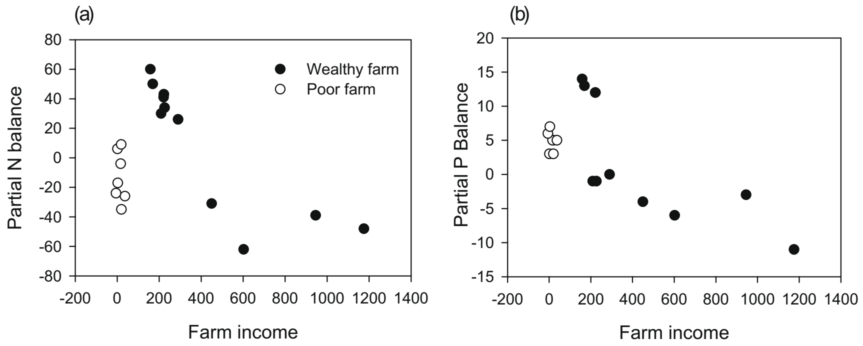

Fig. 2. Relationship between farm-level partial N and P balances and farm income for wealthy and poor farms in Murewa, Zimbabwe.

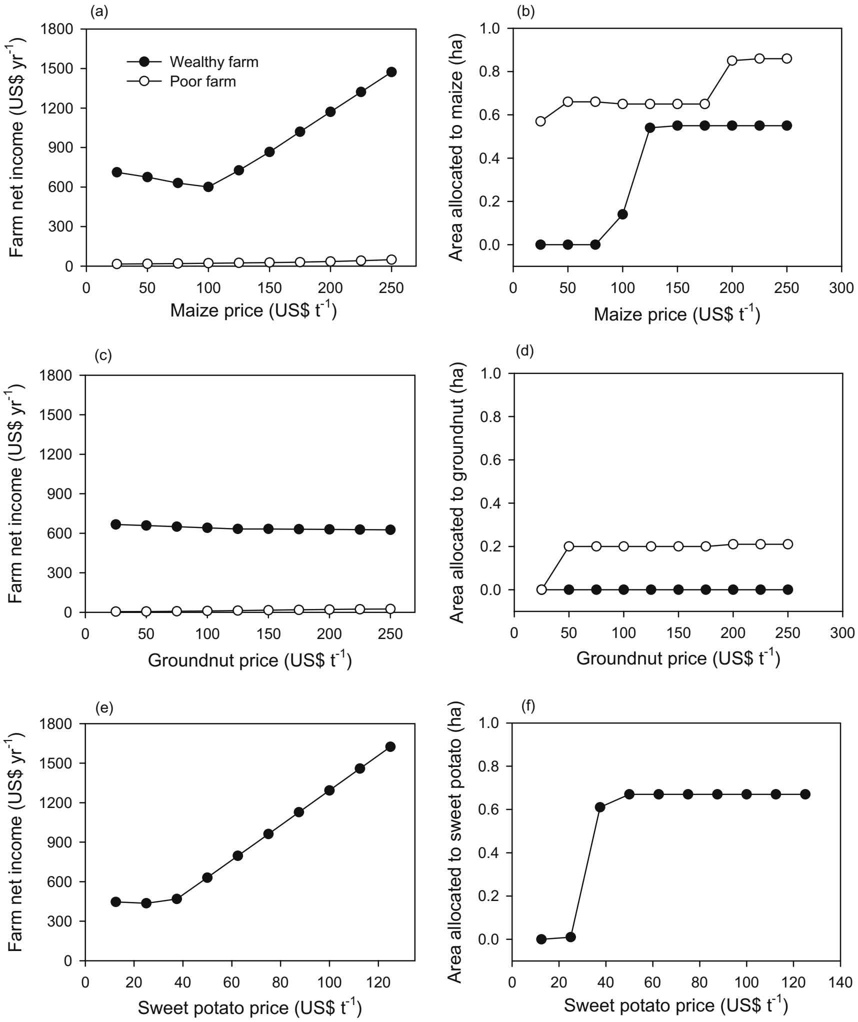

Fig. 3. Impact of changes in commodity prices on-farm income (a,c,e) and area allocated to crops (b,d,f) on wealthy and poor farms in Murewa, Zimbabwe.

than groundnuts due to low groundnut yield, marginal to zero profitability and high labour demand to manage groundnut production. However, this trend was reversed on the poor farm where soil fertility was low and maize was produced with small doses of fertilizer. Groundnut production was more profitable than maize, probably because the groundnut crop is better adapted to low soil fertility conditions and thought to be effective at extracting nutrients from unfertile soils (Ae et al., 1996). Although groundnuts were more profitable than maize, the amount of labour available limited the area allocated to groundnut production. The contrast between recommendations for groundnut allocation based on agronomic responses and farmer practice can be explained by diversity in soil fertility and labour availability.

4.2. Analysis of alternative nutrient resource management strategies

The best strategy for fertilizer allocation on the poor farm was to target fertilizers at rates that gave the highest marginal returns, but also to limit the area cultivated so that the farmer could weed twice. On the wealthy farm, changing fertilizer and crop residue management strategies without changing the area of land allocated to specific crops resulted in a substantial decrease in income, but increased N and P balances. Net income was lowest when nutrient resources were concentrated on the homefield, as this led to oversupply of nutrients in that field. Targeted application of manure and basal fertilizer to the homefield and outfield substantially increased net income above the application of manure and fertilizer in combination, suggesting that farmers' existing management strategies of applying manure and basal fertilizer separately are sensible. Although total maize production for the outfield and homefield was larger when manure was applied to the outfield and basal fertilizer to the homefield, analysis by HROM showed no overall income benefit to the farm, as the benefits accrued from increased productivity were offset by the extra costs of labour required to transport manure to the outfield.

Shifting groundnut production to the more fertile homefield was less profitable than the most productive maize strategies (Scenario Wealthy-3), unless groundnut residues were fed to lactating cows (Table 8). This disparity is due to the higher productivity and profitability of maize than groundnuts when grown in the more fertile fields. Although milk was not sold, increased milk production from feeding groundnut residues to cattle translated into an increase in net income at the farm scale, as milk substituted other commodities in the diet and reduced cash spent on food purchases. On the farms studied, milk contributed little to diet, as only small quantities were produced. The existing diet was mainly maize-based with groundnut and purchased meat as the major sources of protein. All additional milk produced was consumed and substituted for expensive protein food purchased and some maize, which could be stored or marketed. Removal of the groundnut residues from the field to feed livestock had a small negative effect on the N balance of the farm, but the decrease in the N balance on the particular groundnut plot was large (-16 kg N ha^{-1}).

4.3. Relationship between farm income and nutrient balances

Nutrient balances are determined by a complex set of biophysical and socio-economic factors (Nkonya et al., 2005). Under existing management, the high N balance on the wealthy farm was driven strongly by use of manure and mineral fertilizers. The low P balance on the wealthy farm was probably due to a disproportionate amount of N applied, resulting in removal of larger amounts of P. The large amounts of nutrient inputs were able to counteract the concomitantly larger amounts of nutrients harvested in grain and residues on the wealthy farm. The low nutrient balances and net income on the poor farm can be attributed to poor productivity and the negligible removal of nutrients due to small inputs and the small nutrient stocks in the soils. Despite the positive partial nutrient balances, estimated full N and P balances in smallholder farming systems tended to be negative mainly due to large losses from erosion, and soil nutrient stocks declined even on the wealthy farms (Zingore et al., 2007a). Since partial nutrient balances were considered in this study, the more negative balances resulted from increased productivity and larger removal of nutrients from soil nutrient stocks; hence the high net income on the wealthy farm was associated with negative nutrient balances (Fig. 2). Such negative balances can be expected on farms with more fertile soils and larger soil nutrient stocks. As a result, the increased income from expanding the area of land on which sweet potato is grown under existing management will not be sustainable unless the amounts of fertilizer and manure applied are increased. Inclusion of maize fertilized with a combination of fertilizer and manure resulted in higher income and less-negative nutrient balances than maize fertilized solely with mineral fertilizer. Organic nutrient resources have a key role in enhancing profitability and sustainability of smallholder farms and their use should be optimized in relation to available labour.

4.4. Impact of changes in commodity price on-farm income and crop allocation

Smallholder farmers are highly vulnerable to risk associated with the uncertainty of output prices, and an understanding of the flexibility of different farms to handle changes in commodity prices is required to develop resilient crop production systems (Jayne et al., 2006). On the poor farm, crops were produced for subsistence, and as a result net income was affected little by changes in output prices. For all price ranges, the minimum area of land allocated for maize production was about 0.6 ha, indicating that risk is best managed by subsistence farmers through growing the food security crop on a large proportion of the cultivated area. On the wealthy farm, output prices for sweet potato and maize exerted a great influence on both income and land use. Despite the high profitability of sweet potato cropping, the steep changes in farm income at different prices of sweet potato indicate it is also a crop with a high market risk, and this might be a key factor in discouraging the wealthy farm from allocating a large area to sweet potato production.

We recognize that adjustment of farming strategy is not solely based on price effects, as farmers' coping strategies are determined by a large number of complementary driving forces including ownership of fixed assets, climatic risk and the ability to adapt new technologies (Jayne et al., 2006). Further studies would need to consider these factors for refinement of the results based on output prices and household characteristics produced by HROM. Enhanced farm-market linkages and a good forecast of commodity prices will be important in assisting the farmers to decide on land allocation.

4.5. Implications of the results

Farm-scale analysis of resource use showed a need to fine-tune the existing technical recommendations based on agroecological conditions, to account for farm resource endowment (land, fertilizers, manure and labour) and variability in soil fertility within farms, as well as competing resource use options. Our results indicated that there is limited scope to improve productivity and income of smallholder farms with their existing fertilizer and labour resources without inducing negative nutrient balances. This is particularly evident for the poorer farms with small landholdings and no livestock (and hence no access to manure) who lack the resources to hire labour. Although cultivation of crops with little fertilizer or organic nutrient inputs by smallholder farmers is viewed as the main cause of poor crop productivity in sub-Saharan Africa, the current efforts to increase fertilizer use must also consider other complex factors driving farmers' decisions on crop and livestock management, such as labour and output prices. Attention to pricing and markets for nutrient inputs and produce, and other policies to support smallholder farms will be required to allow sustainable improvements of productivity. Such approaches will favour those farms that already have access to more land and labour. Investment in agricultural development on the poorer farms should focus on attainment of food security using technologies that require less labour, while diversification of the sources of incomes away from agriculture may offer realistic opportunities to reduce poverty in the long term.

5. Conclusions

The modelling approach used in this study of linking different existing component models through a farm-scale database was useful for integrating biophysical and socio-economic factors influencing decision making on smallholder farms and evaluating trade-offs for resource use in terms of income, nutrient balances, labour use and food sufficiency. This study underscores the need to carefully consider site-specific conditions at the farm scale when designing interventions for improving efficiency of resource use, as some options have opposing effects on income at the farm scale, especially when comparing farms of contrasting wealth. For example, expansion of the area under groundnut production was more profitable for the poor farm, but less profitable on the wealthy farm. The poor farm faced multiple constraints including poor availability of cash and labour, and lack of manure and draught power. Under these constraints, options for increasing crop production and income are limited. Resources would be used more efficiently if maize was grown on smaller, well-managed areas and mineral fertilizers applied at moderate rates rather than cultivating all fields and applying low fertilizer rates. Off-farm income from working for neighbouring farmers was an important source of income for the poor farm. On the wealthy farm, income was maximised by expansion of the cash crop, sweet potato, although high levels of risk associated with output prices may require farmers to balance its production with maize. Increasing income from improved crop, labour and nutrient allocation was mostly associated with decreasing N and P balances. Availability of nutrient resources and labour were identified as major factors determining feasibility of resource management options. Therefore, tailoring strategies for resource use to farm resource endowment is required for efficient management of smallholder farms and must be taken into account when recommending technologies.

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