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Which farmers benefit most from sustainable intensification? An ex-ante impact assessment of expanding grain legume production in Malawi

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ABSTRACT

Legume technologies are widely promoted among smallholders in southern Africa, providing an opportunity for sustainable intensification. Farms and farming strategies of smallholders differ greatly within any given locality and determine the opportunities for uptake of technologies. We provide an *ex-ante* assessment of the impact of grain legumes on different types of farms and identify niches for grain legumes in Malawi. After creation of a farm typology, detailed farm characterisations were used to describe the farming system. The characterisations provided the basis for the construction of simplified, virtual farms on which possible scenarios for expanding and intensifying grain legume production were explored using the farm-scale simulation model NUANCES-FARMSIM. Observed yields and labour inputs suggested that maize provides more edible yield per unit area with a higher calorific value and greater labour use efficiency than groundnut and soybean. Crop yields simulated by the model partly confirmed these yield trends, but at farm level maize-dominated systems often produced less food than systems with more grain legumes. Improved management practices such as addition of P-based fertiliser to grain legumes and inoculation of soybean were crucial to increase biological nitrogen fixation and grain yields of legumes and maize, and created systems with increased area of legumes that were more productive than the current farms. Improved legume management was especially a necessity for low resource endowed farmers who, due to little past use of P-based fertiliser and organic inputs, have soils with a poorer P status than wealthier farmers. Economic analyses suggested that legume cultivation was considerably more profitable than continuous maize cropping. Highest potential net benefits were achieved with tobacco, but the required financial investment made tobacco cultivation riskier. Grain legumes have excellent potential as food and cash crops particularly for medium and high resource endowed farmers, a role that could grow in importance as legume markets further develop. For low resource endowed farmers, legumes can improve food self-sufficiency of households, but only if legumes can be managed with P fertiliser and inoculation in the case of soybean. Given that low resource endowed farmers tend to be risk averse and have few resources to invest, the ability of poorer farmers to adopt legume technologies could be limited.

1. Introduction

In much of southern Africa, smallholder arable farming is dominated by maize production. Agricultural productivity in the region is poor, with annual national average grain yields varying between 0.3 and 2.2 Mg ha^{-1} in 2008–2012 in Malawi, Mozambique and Zimbabwe (FAOSTAT, 2014). In Malawi, poor crop productivity has partly been addressed by the Farm Input Subsidy Programme (FISP) (Dorward and Chirwa, 2011; Chibwana et al., 2012). The FISP has contributed to raising national maize productivity and reducing rural poverty but is not without controversy. Households participating in the FISP have been found to simplify crop rotations by allocating more land to maize and tobacco at the expense of other crops such as groundnut, soybean and bean (Chibwana et al., 2012). The over-reliance on maize has led to repeated recommendations for crop diversification using legumes.

Efforts to promote green manure legumes did not result in wide-scale adoption in Malawi, due to the land and labour investments required and the lack edible or marketable yield

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(Snapp et al., 2002; Sirrine et al., 2010). Grain legumes, such as groundnut (*Arachis hypogaea* L.), soybean (*Glycine max* (L.) Merrill), cowpea (*Vigna unguiculata* (L.) Walp.), common bean (*Phaseolus vulgaris* L.) and pigeonpea (*Cajanus cajan* (L.) Millsp.), provide more promising entry points to diversify cropping systems and enhance soil fertility management due to their multiple benefits. Grain legumes provide key components of healthy diets including essential protein and minerals, help in reducing pest and disease build-up associated with monocropping of maize, and enhance N availability for subsequent crops. Substantial yield increases of cereal crops following legumes, in comparison with monocultures of cereal, have been observed widely across sub-Saharan Africa (MacColl, 1989; Ncube et al., 2007; Franke et al., 2008; Yusuf et al., 2009; Kamanga et al., 2010a). Grain legumes can also provide income and reduce farmers' dependence on non-edible cash crops tobacco and cotton. Rural development groups and government extension agents therefore widely promote the production and processing of grain legumes among smallholders in southern Africa, often as part of wider development efforts promoting sustainable agricultural intensification (Giller et al., 2013).

Throughout Africa we find a wide diversity of farms and farming strategies, which determine the opportunities for uptake of different technologies (Giller et al., 2011). Since it is impossible to develop unique recommendations for each household, farm diversity has been categorised to define recommendation domains (Kamanga et al., 2010a; Tittonell et al., 2010b). Targeting particular groups of farmers in a development project, deliberately or unintentionally as a result of a dissemination approach, is likely to affect project impact. Some development projects, for instance, adopt a value chain approach in which agricultural innovations are promoted and directly linked to market opportunities and increased value of produce. While farmer-market linkages are of great importance to achieve sustainable adoption of new technologies and stimulate development of the agricultural sector, such approaches easily bypass the poorest farmers who are oriented towards food self-sufficiency and lack resources to produce for markets.

In this paper we provide an *ex-ante* assessment of the impact of grain legumes on different types of households and identify niches for grain legumes in smallholder farming systems in Malawi to improve targeting of grain legume technologies in development programs. The methods used in this study can be applied to a wide array of agricultural technologies potentially suitable to smallholders. After creating a farm typology, detailed farm characterisations were used to describe the current state of farming. The characterisations provided the basis for the construction of simplified, virtual farms on which the exploration of possible scenarios is based (cf.Giller et al., 2011). The farm-scale simulation model, NUANCES-FARMSIM (FARM SIMulator) (van Wijk et al., 2009) was used to explore the potential for expanding and intensifying grain legume production.

2. Materials and methods

2.1. Study location and farm typology

The study was conducted in Mchinji district, 50–80 km west of the capital Lilongwe on the Zambian border. Mchinji lies at mid-altitude area (on average 1100 m above sea level), has a mono-modal rainfall distribution with 950 mm rain annually on average, a growing period of 5–6 months starting late November and an annual mean temperature of 20 °C. Compared with other regions in sub-Saharan Africa, farmers have relatively good access to both local and urban markets due to high population densities in the district and the proximity of the capital Lilongwe (Franke et al., 2011).

To describe smallholders' farms and explore scenarios for legume technology adoption we employed the NUANCES framework (Giller et al., 2011). A survey of 77 households within a 10 km radius of Kachamba village (S13.746 E33.040) was conducted in November 2010. A structured questionnaire was used to collect information on household composition, landholding, livestock ownership, assets, housing, sources of income and production orientation. Households were selected randomly. In addition to four wealthier farmers interviewed in the random sample, another four were deliberately sampled since they were few in number. Livestock assets recorded included ruminants, pigs and poultry; household assets included farm tools, oxcart, wheelbarrow, radio, mobile phone, television, bicycle and car. Based on landholding, livestock ownership, household assets, and quality of housing, farmers were divided in three wealth classes: low resource endowment (LRE), medium resource endowment (MRE) and high resource endowment (HRE). Two other criteria for the farm typology were main source of income and production orientation. These criteria led to the manual grouping of farmers into five farm types. The approach was similar to a classification used in East Africa (Tittonell et al., 2005, 2010b), although the boundaries between farm types were different.

2.2. Detailed farm characterisations

From the larger sample, 14 farms were selected for detailed characterisation. Although the aim was to select three farms per farm type, the initial sample only contained two HRE farms with farming as a prime source of income (Type 2). A series of visits during the 2010/2011 growing season was made to each farm to assess biophysical and socio-economic variables related to crop production. Information about the household and cropping patterns were acquired and management was recorded for each crop. Moreover, information on livestock, the production and handling of animal and compost manure, and income and expenditures was collected. The area of each field was measured using a geographical positioning system (GPS), or manually if the field was too small for accurate GPS readings. The so-called gardens, small plots located in the low lying (dimba) areas next to a riverbed, were excluded because no major crops were produced here and plot sizes were very small. At the end of the growing season, farmers were visited a last time to collect grain yield data from each field. Soil samples were taken in December 2010 from fields selected based on the crop rotation and soil fertility as perceived by the farmer. This resulted in one to four fields selected per farm, depending on the size of the farm and the expected variability in soil fertility. Composite soil samples (0–20 cm depth) were taken with an auger at 10 points in each field. Samples were air-dried and sieved through a 2 mm sieve and sent to the Soil Productivity Research Laboratory (SPRL) in Zimbabwe for analysis of pH (H_2O), total N (Kjeldahl digestion), %C (Walkley-Black), available P (Olsen), cation exchange capacity (CEC) (extraction with ammonium acetate), exchangeable cations K (flame photometry), Ca and Mg (atomic absorption spectrophotometry) and particle size (Bouyoucos hydrometer). A detailed description of the methods and results of the characterisations is available (van den Brand, 2011).

2.3. Model description

Based on the results from the farm characterisations, simplified virtual farms were constructed, each representing a farm type. The farms were constructed based on data on land area, cropping pattern, soil fertility characteristics, and fertiliser and organic input use. The relative area covered by each crop was rounded to the nearest 10% of the farm area, facilitating the simulation of a crop rotation over a 20-year period. Soil available P and exchangeable

K were averaged by farm type, while other soil characteristics, not significantly affected by farm type, were averaged across farms.

The NUANCES-FARMSIM model (van Wijk et al., 2009) was used to explore the impacts of increased legume cultivation on soil fertility, yields, crop profitability and food self-sufficiency of households over a 10-year period. NUANCES-FARMSIM uses the combined crop/soil model FIELD (Tittonell et al., 2010a; Franke et al., 2014) to simulate soil fertility dynamics and yield at field level. FIELD has a seasonal time-step and two main interacting modules: (1) a soil module simulating soil carbon (C) dynamics, based on inputs and decomposition of different soil C fractions, and potential nutrient and water supply to the crop, and (2) a crop module simulating plant production based on interactions between plant available nutrients and water.

In FIELD, water availability to the crop equals the product of total rainfall in the season and a capture term, which varies as a function of soil C content. The potential supply of N to the crop from organic sources depends on C decomposition of manure, crop residues, organic amendments and labile and stable carbon pools, with the C:N ratio determining the rates of mineralisation and immobilisation. Empirical functions based on the QUEFTS model (QUantitative Evaluation of the Fertility of Tropical Soils) model (Janssen et al., 1990) are used to estimate potential P and K supply based on measured soil characteristics. Mineral fertiliser applications add to the potential supply of nutrients to the crop. The capacity to simulate residual availability of P fertiliser has been added to FIELD, which is especially relevant in crop rotations where P fertiliser is preferentially applied to certain crops. The model distinguishes between a labile and a stable phosphorus pool with P transfers between pools and uptake by the crop from the labile pool (Janssen and Wolf, 1988). The labile fraction of P of soluble superphosphate typically equals 0.8 (Wolf et al., 1987), and the fraction of P annually transferred from the labile to the stable pool is set at 0.2, while any transfer from the stable to the labile pool is neglected. These are reasonable assumptions for easily soluble P fertilisers for the first five years after fertiliser application (Janssen and Wolf, 1988).

Nutrient and water limited above-ground biomass and yield is determined by the interactions between nutrients and water available to the plant. The current model largely follows the calculations for nutrient interactions used in the QUEFTS model (Janssen et al., 1990). After calculating the potential supply of nutrients and water to the crop, the model follows Step 2–4 in the QUEFTS model. Step 2 calculates the relation between potential supply of nutrients and water, and nutrient uptake, Step 3 the possible yield ranges for a given N, P and K uptake based on maximum dilution and accumulation of these nutrients, and Step 4 combines yield ranges to one yield estimate. The interaction between water supply and nutrient uptake has been added to the original QUEFTS equations. The model calculates the potential uptake of N, P and K for a given supply of water following the equations of Step 2 (see Supplement 1). As in the original FIELD model, yield is then derived using an appropriate value for the harvest index, while belowground biomass is calculated through a root:shoot index.

The FIELD model, mostly as part of the NUANCES-FARMSIM framework, has been used in southern Africa with a range of crops including maize, sweet potato, cassava, cotton and sorghum (Tittonell et al., 2007; Zingore et al., 2007; Chikowo et al., 2008; Rufino et al., 2011; Zingore et al., 2011; De Vries et al., 2012). Also the QUEFTS model on its own has been widely used primarily in tropical cropping systems (Sattari et al., 2014). For the current study, the model was parameterised to include groundnut, soybean and tobacco in rotation with maize. Maximum and minimum nutrient concentrations in grain and residues were derived from literature (Nijhof, 1987). For groundnut, which nodulates freely with indigenous rhizobia, 80% of the N in aboveground plant parts was assumed to be derived from the air (Giller, 2001). For soybean, a more selectively nodulating legume, uninoculated plants were assumed to derive 50% of plant N from the air; inoculated plants were assumed to derive 80% from the air (Giller, 2001). The harvest index was set at 0.4 for maize, 0.33 for soybean and groundnut, and 0.8 for tobacco (Nijhof, 1987). Crop harvest indices in the field are affected by strong drought or poor plant nutrition. However, these relationships are hard to quantify for a specific situation. Given that major reduction in harvest indices usually only occurs under highly unfavourable growing conditions and the uncertainties surrounding the relationships, it was decided to keep the harvest indices fixed in the simulations. No relationship was observed between P applications and the harvest index of soybean and groundnut in the data used for model verification (Kamanga et al., 2010b). Average harvest index of groundnut in these trials equalled 0.31 and 0.32 and that of soybean 0.35 and 0.32 for fields without and with P fertiliser respectively. Crop carry-over effects were simulated through the carbon and nutrient content of crop residues (aboveground and roots) and a residue carry-over rate affected by management. C decomposition rates were calibrated against so-called 'pseudo-chronosequences' derived from soil organic carbon measurements of fields that had been under cultivation for different periods of time, using data from sandy soils in central Zimbabwe (Zingore et al., 2011).

The ability of the model to simulate groundnut and soybean yield and the crop responses to P fertiliser additions were verified against data from experimental trials testing the response of legumes to P fertiliser on a range of farms in Chisepo district, Malawi (Kamanga et al., 2010b). Maize and tobacco yields simulated by the model were verified using soil characteristics, input management and yields observed in the current farm characterisations. In addition, data on maize from similar characterisations in Salima district in Malawi were used (van den Brand, 2011).

2.4. Scenarios tested

After model verification, yields and nutrient and carbon dynamics were simulated over a period of 20 years for each of the virtual farms. Five situations were tested:

- A base case: current cropping patterns and input use;
- Scenario 1: the area of maize was reduced to 50% of the total arable area; maize and any soybean were replaced by a groundnut crop receiving no nutrient inputs;
- Scenario 2: the same cropping pattern as Scenario 1, but 20 kg P ha^{-1} applied as mineral fertiliser to groundnut;
- Scenario 3: similar to Scenario 1, but with soybean, instead of groundnut, replacing maize and any groundnut; no inputs applied to soybean;
- Scenario 4: similar to Scenario 3, but 20 kg P ha^{-1} applied as mineral fertiliser to soybean inoculated with rhizobium.

Groundnut and soybean were chosen as test legumes, since these were the main legumes grown by farmers in Mchinji according to the farm characterisations. Other legumes, such as common bean or pigeonpea, occupied less than 5% of the cropped area on any farm. Interviewed farmers exclusively grew soybean and groundnut as sole crops. The decision to reduce the maize area to 50% of the available arable land in all scenarios was based on the assumption that growing maize in a field once every second season is the maximum acceptable frequency in an agronomically-sound rotation. The differences between Scenario 1/3 and 2/4 reflected respectively farmers' current cultivation practices of groundnut and soybean in Malawi and recommended practice. In Scenarios 1–4 it was assumed that the total amount of manure applied to maize remained the same as in the base case. As the area under maize was decreased in the tested scenarios, manure application rate to maize per unit area increased proportionally. The arable area of each farm was split in 10 sections representing 10% of the cropped area, with each field in a different phase of the 10-year cropping sequence. 20 years of rainfall data (1981–2000) from Mchinji town were used as input for the model.

The farmers interviewed indicated that maize and tobacco residues were usually left in the field or burned. Moreover, free ranging ruminants fed on croplands during the dry season. Therefore, the carry-over rate of these residues from one season to the next was set at a low rate of 0.3 in the model. The farmers also indicated that 81% of the legume residues was composted, or in a few cases fed to animals, and the compost/manure returned to the land. These organic inputs are already accounted for in the model input settings and the carry-over rate of legume residues was set at 0.1. However, in scenarios where legume production was expanded, the additional legume residues are likely to be used to produce more compost/manure, giving a higher carry-over rate. Therefore, a carry-over rate of 0.5 was assumed for additional legume residues.

2.5. Data handling and cost benefit analysis

Fresh grain yields were converted to dry matter yields assuming a moisture percentage of 14%. Nutrient inputs from animal manure were calculated assuming 1.13% N and 0.19% P (Paul et al., 2009). To calculate the calorific values of grains, maize was assumed to contain 357 kcal 100 g^{-1}, groundnut 549 kcal 100 g^{-1}, and soybean 405 kcal 100 g^{-1} (FAO, 1968). The distribution of soil available P and exchangeable cations was positively skewed. Values of these variables were therefore $\log_{10}$ transformed prior to statistical analysis.

A cost benefit analysis of crop production was conducted (Table 1). Input costs were derived from the detailed farm characterisations. Hired labour costs were used to value opportunity costs of family labour, whereby child labour was assigned half the cost of adult labour. As the model did not include a labour module, labour inputs for a crop were assumed similar across farm types. Costs of post-harvest activities were excluded as they are done throughout the year, making it difficult to estimate labour demands reliably. Fertiliser prices were based on open market prices. FISP fertilisers cost about one tenth of the price of non-subsidised fertilisers in 2010–2011, but subsidised fertilisers were not available to all farmers. Prices of maize, soybean and groundnut grain were derived from monthly market surveys in Mchinji between 2001 and 2008 conducted by the Malawian Ministry of Agriculture and Food Security. Minimum and maximum benefits were based on standard deviations from means of crop yields per farm type per scenario (20 years of simulation) and the minimum price, which typically occurs just after harvest, or the maximum price, usually recorded in the first half of the growing season, averaged over 2001–2008. Tobacco leaf (burley) prices between 2001 and 2008 were obtained from the Tobacco Control Commission in Malawi, reflecting prices at the tobacco auction in Lilongwe. Prices were corrected for moisture content. All prices were compensated for inflation based on the official rates with 2010 as a base year. Values in MKw were converted to US$ at a rate of 1 US$ = 150 MKw.

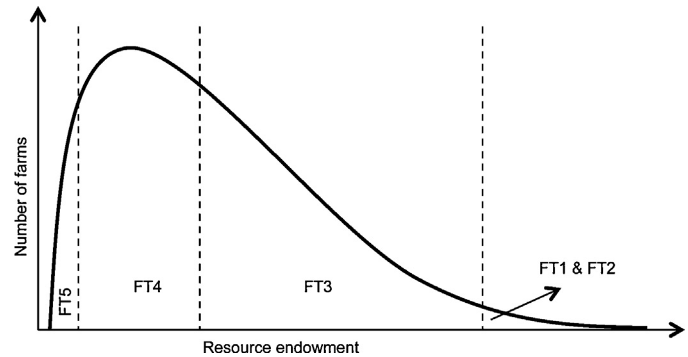

Fig. 1. Schematic overview of the frequency distribution of resource endowment among farms and the boundaries between farm types, derived from the actual frequency distribution observed in the rapid survey.

3. Results

3.1. Site and farm characteristics

The stratification of farms based on wealth and production criteria resulted in five farm types (Table 2a and b). FT5 farms were the poorest: small farms with one or more family members working casually for other farmers to generate additional income or food. Farming activities were almost entirely devoted to providing food for the household. Farmers of this type hardly owned assets like radios or bicycles nor livestock, except for some chickens and occasionally a goat. FT4 farms were less poor and did not depend on casual labour but had small temporary businesses and were sometimes able to sell a little farm produce, although they produced food primarily for the household. They also owned more livestock. FT3 farms were medium resource-endowed and income was usually generated through a combination of farm surpluses and small enterprises generating more income than those of FT4. Houses were in a better state with a larger total value of assets and more livestock. The HRE FT2 farms had large landholdings, large livestock species (e.g. cattle) and a wide range of assets including furniture and sometimes a car. FT2 farms primarily produced for markets, relied on hired labour for farming, and derived relatively large incomes from cropping. The majority of FT1 farmers were also wealthy, although on average less than FT2. Typically, one of the household members of FT1 farms worked outside the farm and earned a regular salary. Livestock contributed little to the total income of households, suggesting that intangible benefits of livestock (e.g. wealth storage) were more important than income generation from livestock (Moll, 2005). The vast majority of farms fell into FT3 and FT4 (Fig. 1).

Maize was by far the most important crop grown by all farmers (Fig. 2). Although FT3, FT4, and some FT5 farmers occasionally sold small amounts of maize, only the larger-scale FT1 and FT2 farmers considered maize also a cash crop. All farm types grew tobacco, the main cash crop, with the largest areas found in FT1 and FT2. Groundnut was grown across all farms, usually for both home consumption

Table 1
Prices used in the cost-benefit analysis.

Product	Unit	Price	
Casual labour (average)	US$ day^{-1}	1.33	
Fertiliser (unsubsidised)	US$ per 50 kg bag urea, NPK or TSP	33.50	
Inoculant	US$ ha^{-1}	10.00	
		Minimum	Maximum
Maize grain	US$ kg^{-1}	0.19	0.43
Tobacco leaves	US$ kg^{-1}	1.16	2.58
Groundnut grain (shelled)	US$ kg^{-1}	0.84	1.55
Soybean grain	US$ kg^{-1}	0.66	0.83

Table 2
(a) Description of the farm types, (b) their characteristics and (c) maize yields and labour inputs. Average cultivated area and value of livestock and assets were derived from the initial household survey; average incomes, maize yields and labour inputs from the detailed characterisations.

(a)

Farm type	Wealth class	Main sources of income
1	Mainly HRE, some MRE	A salaried job, cash crops or other farm surpluses
2	HRE	Cash crops and other farm produce
3	MRE	Some farm produce and/or slightly larger off-farm businesses
4	LRE	Little farm produce and/or small off-farm businesses
5	LRE	Casual labour

(b)

Farm type	Cultivated area[a] (ha farm^{-1})	Value of livestock (US$ farm^{-1})	Value of household assets (US$ farm^{-1})	Total income (US$ farm^{-1})	Income share from		
					Crops (%)	Livestock (%)	Off-farm (%)
1	3.3	3464	1322	2493	42	9	49
2	3.8	22,628	20,407	14,643	74	0	26
3	1.9	679	160	492	21	2	76
4	1.2	130	89	404	64	22	15
5	0.5	0	38	173	4	0	96

c)

Farm type	Maize yield (t ha^{-1})	Labour input (10^3 h ha^{-1})
1	2.85	1.76
2	3.49	2.03
3	2.23	1.51
4	4.36	1.39
5	1.67	0.91

LRE, MRE and HRE are low, medium and high resource endowed farmers.
[a] area estimated by the farmer.

and income. Soybean was cultivated only on small plots and fulfilled roles in both home consumption and income generation.

The analysis of soils from the farms showed that the upper 20 cm of soils contained on average 76% sand (range of 66–90%), 9% silt (6–16%), 15% clay (6–22%), 0.70% carbon (0.26–1.01%), 0.10% N (0.05–0.16%), 7.2 mg kg^{-1} available P (Olsen) (1.4–39) and 0.19 cmol kg^{-1} exchangeable K (0.04–1.39) with a pH(H_2O) of 6.0 (5.2–6.9). While fields within farms varied greatly in soil fertility (data not shown), no significant correlation was found between fertility parameters and distance from the homestead or with cropping pattern. Available P was the only soil parameter that differed significantly between farm types in an ANOVA test (Fpr = 0.012) (Fig. 2), and was positively and significantly correlated with livestock ownership. Soil exchangeable K was also positively correlated with available P, but did not differ significantly among farm types. Farmers applied mineral and organic fertilisers exclusively to maize and tobacco (Fig. 2). The applied mineral fertilisers were urea, calcium ammonium nitrate, NP + S blends (23:21:0 + 4S) and Compound D (8:18:15 + 6S, 0.5Zn, 0.1Bo). Organic inputs consisted of animal manure and compost, and were primarily applied by FT1 and FT2 farmers who owned most livestock.

Maize grain yields on an area basis were greater than those of groundnut or soybean (Table 3). Maize yields were smaller for FT3 and FT5 than for FT1, FT2 and FT4 farmers (Table 2c), reflecting differences in soil P and K status and input use (Fig. 2). In the 2010–2011 growing season, yields were considered relatively high due to a favourable rainfall distribution. Estimates of labour requirements by farmers (Tables 2c and 3) varied greatly among farmers, partly due to the difficulties to accurately estimate labour demands over the season, but the relative performance of the different crops was often similar. A lot of labour was required to grow tobacco seedlings in a nursery during the dry season, to apply large rates of manure, and during the long harvest period (Table 3). Groundnut was also labour intensive with approximately half the labour used in harvesting and dehulling. Soybean required least labour. The observed relative labour demand of maize and legumes concurs with results from elsewhere in sub-Saharan Africa (Van Heemst et al., 1981; Franke et al., 2010). FT5 farmers spent considerably less labour and FT1 and FT2 more labour per unit area than FT3 and FT4 (Table 2c). In terms of calorific yield, labour use efficiency and calorific returns to labour, maize outperformed groundnut and soybean, despite the higher calorific values of groundnut and soybean grain per unit weight (Table 3). The results thus suggest that, with current management, maize contributes more to food self-sufficiency of labour and land constrained households than grain legumes.

3.2. Model performance and explorations

The model simulated the variation in groundnut and soybean grain yields and their response to P fertiliser additions in experimental trials reasonably well (Pearson correlation coefficient r = 0.62 for groundnut; r = 0.51 for soybean) (Fig. 3a). Groundnut yields were not systematically over- or underestimated. Soybean yields were strongly underestimated at two sites, but not at the other five sites. Therefore, we decided not to calibrate the soybean simulations. The variation in maize yields observed in the detailed farm characterisations was predicted relatively well by the model (r = 0.82), although the model overestimated smaller maize yields and in a few cases underestimated larger yields (Fig. 3b). Poor management practices, such as lack of weeding, that lead to poor yield in the field were not included in the model explaining the model's overestimations of yield. The model overestimated tobacco yield and was poor in predicting yield variation (r = 0.40). Reasons behind this are discussed below. For further simulations, the model was calibrated by reducing predicted tobacco yields by 40%, which resulted in a better correspondence between predicted and observed yields.

The virtual farms representing the farm types differed in cropped area, soil characteristics, nutrient use, and cropping

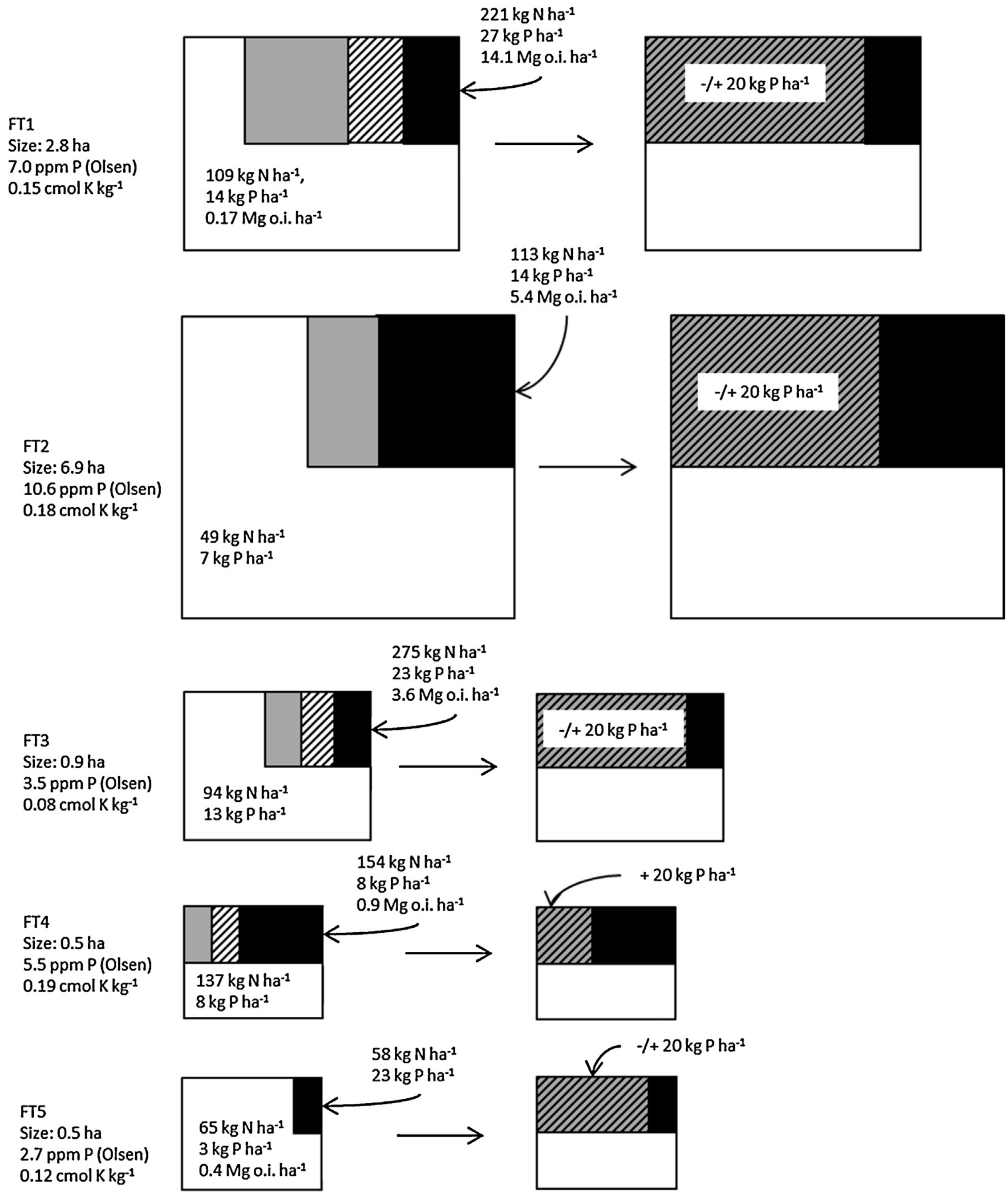

Fig. 2. Schematic presentation of the virtual farms representing farm types with maize (white), tobacco (black), groundnut (grey) and soybean (striped). At the left, the current cropping pattern is approached (base case), at the right an alternative rotation with maize covering only 50% of the farmed area and the area with groundnut or soybean (grey with stripes) expanded (o.i. = organic inputs). The relative proportion covered by each crop is rounded to the nearest 10%.

Table 3
Production and nutritional characteristics of the arable crops averaged across farm types as observed in the farm characterisations, followed by the standard error of means in parentheses.

	Maize	Groundnut	Soybean	Tobacco
Number of observations	14	7	4	10
Grain or tobacco leaf yield (t ha^{-1})	2.83 (0.44)	1.08 (0.31)	0.59 (0.09)	1.22 (0.31)
Labour (10^3 h ha^{-1})	1.31 (0.26)	1.95 (0.30)	0.87 (0.19)	3.02 (0.57)
Calorific yield (10^6 kcal ha^{-1})	10.01 (1.56)	5.93 (1.77)	2.39 (0.37)	
Labour use efficiency (kg h^{-1})	2.78 (0.54)	0.69 (0.31)	0.87 (0.29)	
Calorific returns to labour (10^3 kcal h^{-1})	7.64 (1.48)	3.04 (1.37)	2.75 (0.93)	

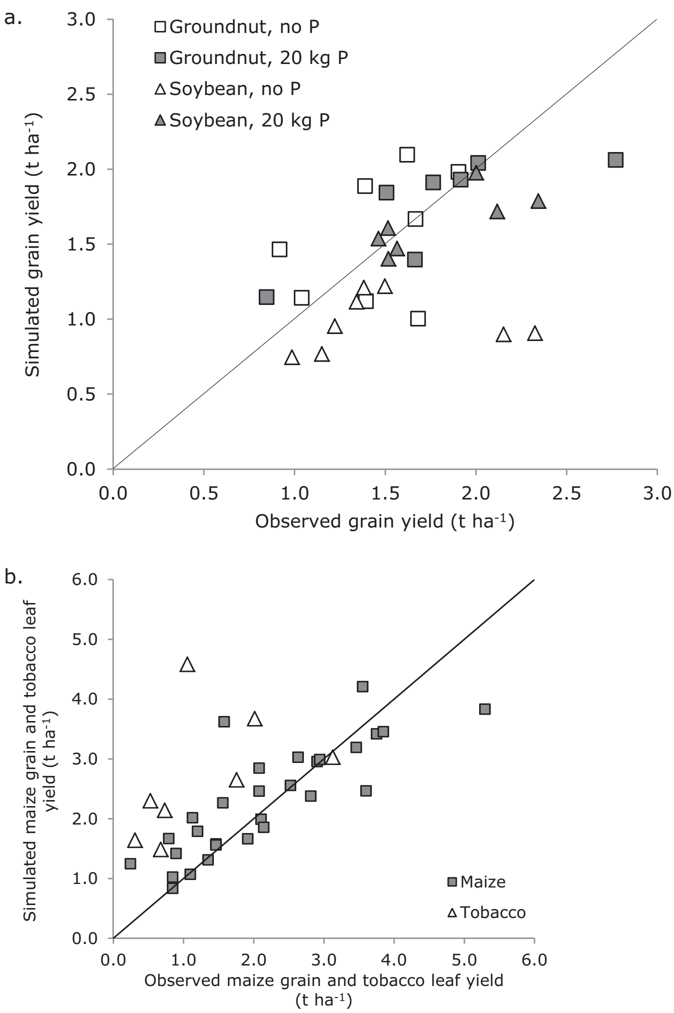

Fig. 3. (a) Observed and simulated groundnut and soybean production with and without P fertiliser. Observed data from Kamanga et al. (2010b). (b) Observed and simulated maize grain and tobacco leaf yield. Observed data from the detailed farm characterisations.

pattern (Fig. 2). The cropped area was based on the more precise measurements of fields in the sample of farms participating in the farm characterisations, which is different from the data presented in Table 2 based on farmers' estimates in the rapid household survey. FT4 farmers in the base case already cultivated on average 50% of arable land with crops other than maize and therefore, only an improved management of legumes (Scenario 2/4) was explored for this type.

In the scenarios tested, an expansion of groundnut without the use of inputs (Scenario 1) slightly improved yields of subsequent maize due to an increased plant availability of N (Table 4). However, this was partly offset by a reduced availability of P to maize, due to crop removal that was not replenished in Scenario 1 and 3. Also, the increased availability of N to maize was somewhat masked by relatively high N fertiliser application rates. Simulated soybean grain yields were less than those of groundnut because soybean had a higher P demand and without inoculation derived a lower proportion of N_2 from the air than groundnut. N residual effects of soybean were less than those of groundnut, because soybean produced less biomass and a smaller proportion of crop N remained in the fields.

An expanded cultivation of groundnut without the use of inputs (Scenario 1) had little effect on total grain yield per farm, while an expansion of soybean without the use of inputs (Scenario 3) reduced grain yield per farm (Table 4). Legume grain yields were smaller than those of maize and this was only partially compensated by the yield enhancing effects of legumes on subsequent maize crops. The calorific value of the total edible yield was increased by an expansion of the area cropped with groundnut and reduced by an expansion of soybean. This was due to the smaller soybean yields simulated, and because soybean grain has a smaller calorific value per unit mass than groundnut.

The use of P fertiliser with legumes and inoculant with soybean (Scenarios 2 and 4) improved groundnut and soybean yields, particularly on soils with a poor P status (e.g. FT5) (Table 4). The particularly large response of soybean to inputs in Scenario 4 can be explained by a simultaneously increased availability of N from N_2-fixation and P from fertiliser and the stronger P demand of soybean, compared with groundnut. P fertiliser additions to legumes improved N and P availability to maize and associated yield, due to enhanced legume growth and N_2-fixation and residual effects of P fertiliser. Tobacco benefitted less or not at all from any increase in N and P availability, because tobacco was already well fertilised, except for tobacco in FT5. For all farm types, total grain yield and calorific yield were enhanced in Scenario 2 (groundnut) relative to the base case. In Scenario 4 (soybean), total grain yield was often less than in the base case, while total calorific yield was only enhanced in FT4 and FT5. Grain production at a farm level varied greatly between farm types (Table 4), reflecting differences in size, cropping pattern, input use and yield. Domestic grain production per household member, excluding post-harvest losses, equalled 159 kg y^{-1} or 1509 kcal d^{-1} for FT4 and 133 kg y^{-1} or 1360 kcal d^{-1} for FT5 in the best scenario, which is insufficient to feed the household year round.

Differences in soil C dynamics among farm types were largely driven by the amount and frequency of organic input applications (Fig. 4). FT1 and FT2 farmers applied the largest amounts of organic inputs and had the largest soil C contents at the end of the 20-year period. The large increase in soil C contents in season 5 and 15 for FT1 was the result of an organic input application of 14.1 t ha^{-1} to tobacco once every ten years. Soil C contents in FT5 declined as soils received only 0.4 t organic inputs in nine out of ten years in the baseline scenario. Differences in soil C dynamics between scenarios were small for FT1 farmers and larger for FT5 farmers, which corresponds with a larger relative increase in yield in Scenario 1 and 2 among FT5 farmers. Legumes contributed less residual dry matter to the soil than maize, but legumes, and the associated P applications in Scenario 2, can boost C input by increasing the biomass production of a subsequent cereal or tobacco crop.

3.3. Partial budget analysis

Input costs of a crop per unit area differed between farm types (data not given), as wealthier farmers generally used more labour and nutrient inputs on maize and tobacco than poorer farmers. Average input costs in the base case were 468 US$ ha^{-1} for maize, 1104 US$ ha^{-1} for tobacco, 469 US$ ha^{-1} for groundnut and 327 US$ ha^{-1} for soybean, with the difference between groundnut and soybean caused largely by the high labour demand for groundnut. Net benefits of crops per unit area suggested that maize cultivation is barely profitable (Fig. 5). Tobacco and groundnut gave the best average net benefits, followed by soybean. Wealthier farmers tended to get higher benefits from tobacco than poorer farmers, reflecting differences in soil fertility and crop management. While average net benefits from tobacco and groundnut were comparable in most cases, except for FT5, the relatively large costs of investment for tobacco cultivation and the high output price variability, as indicated by the variability in net benefits (Fig. 5), suggested that tobacco is a riskier cash crop than groundnut. However, maximum net benefits achieved by tobacco were greater than those of groundnut in most cases. Yield variability, affecting the variability

Table 4
Simulated 20-year average grain and tobacco leaf production per ha and total grain production per farm and the associated calorific value for different farm types.

		Maize (t ha^{-1})	Groundnut (t ha^{-1})	Soybean (t ha^{-1})	Tobacco (t ha^{-1})	Total grain yield per farm (t farm^{-1} y^{-1})	Calorific yield per farm (10^6 kcal farm^{-1} y^{-1})
FT1	Base case	1.95	1.35	0.96	1.86	4.29	14.83
	Scenario 1	1.98	1.40		1.86	4.33	16.21
	Scenario 2	2.05	1.46		1.86	4.50	16.83
	Scenario 3	1.91		0.77	1.85	3.54	11.44
	Scenario 4	2.02		1.24	1.86	4.22	13.79
FT2	Base case	2.05	1.48		1.83	10.91	35.89
	Scenario 1	2.27	1.49		1.83	10.90	39.32
	Scenario 2	2.36	1.50		1.85	11.24	40.41
	Scenario 3	2.01		0.72	1.82	8.44	27.06
	Scenario 4	2.36		1.44	1.85	11.11	36.03
FT3	Base case	1.58	1.16	0.70	1.80	1.68	5.54
	Scenario 1	1.66	1.25		1.80	1.73	6.50
	Scenario 2	1.72	1.32		1.82	1.81	6.82
	Scenario 3	1.58		0.64	1.79	1.36	4.40
	Scenario 4	1.72		1.12	1.82	1.70	5.56
FT4	Base case	2.29	1.46	0.79	1.52	0.69	2.29
	Scenario 2	2.40	1.49		1.61	0.75	2.59
	Scenario 4	2.39		1.35	1.61	0.73	2.36
FT5	Base case	1.57			0.95	0.70	2.21
	Scenario 1	1.78	1.25		1.03	0.69	2.59
	Scenario 2	1.98	1.38		1.14	0.77	2.88
	Scenario 3	1.62		0.57	0.95	0.52	1.67
	Scenario 4	1.97		1.17	1.15	0.73	2.38

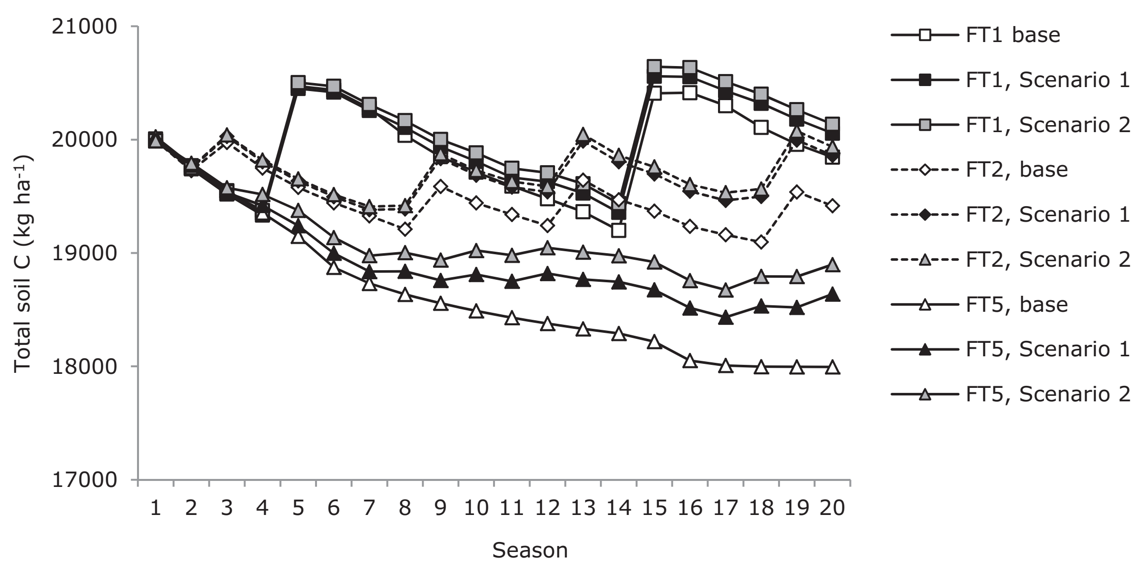

Fig. 4. Simulated soil carbon dynamics of a single field over twenty seasons for FT1, FT2 and FT5.

in net benefits, over seasons was relatively high for soybean and low for maize, while tobacco had a lower yield variability among FT5 and FT4 farmers than other crops. Yield variability caused by differences in susceptibility to biotic factors was not assessed by the model. At farm level, expansion of groundnut cultivation (Scenario 1) increased net benefits for all farm types (assuming all produce is sold and none is kept for home consumption) (Table 5). Although soybean cultivation was more profitable than maize, Scenario 3 did not always lead to increased net benefits relative to the base case, as soybean sometimes replaced more profitable groundnut. The use of inputs in groundnut or soybean (Scenario 2 and 4) always increased net benefits relative to the Scenarios 1 and 3.

Table 5
Net benefits of cropping systems per farm (US$ farm^{-1} y^{-1}), calculated through a partial budgeting study.

	FT1	FT2	FT3	FT4	FT5
Base case	1101	3377	233	237	16
Scenario 1	1584	5041	335		238
Scenario 2	1689	5182	377	300	277
Scenario 3	744	2987	147		69
Scenario 4	1099	4315	259	253	181

4. Discussion

Apart from the wide diversity among smallholders in the study area, which is commonly observed in sub-Saharan Africa (Giller et al., 2011), the distribution of resource endowments was highly skewed (Fig. 1). The vast majority of farmers were classified as FT3 or FT4 – with less than 1 ha of land and little livestock (Table 2) supporting a household of 5–6 people on average. Only 4% of the farmers belonged to the relatively wealthy FT1 or FT2 classes.

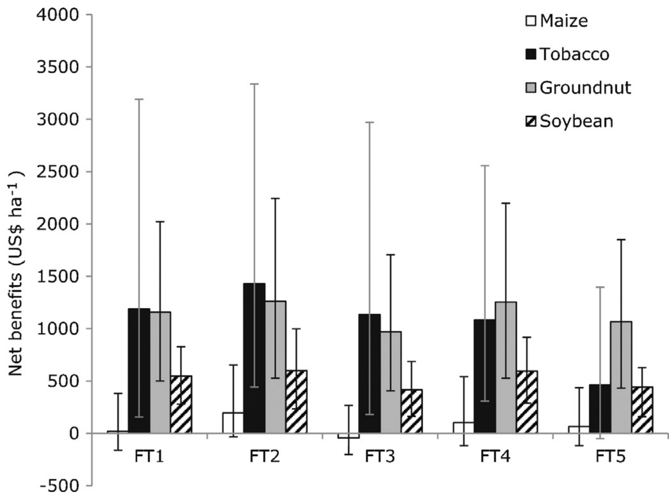

Fig. 5. Net benefits of crop cultivation, averaged over a 20-year period across scenarios. Error bars give minimum and maximum net benefits based on the standard deviation of the mean simulated yield and the minimum and maximum prices of outputs.

The wide range in farm sizes and resource endowments observed highlights the need to recognise farmer diversity when exploring strategies for rural development. Resource endowment, sources of income and labour, and production orientation were useful indicators to derive a functional farm typology, as found earlier in western Kenya and Uganda (Tittonell et al., 2010b). Farm typologies can be constructed in various ways, based on resource endowment alone (Kamanga et al., 2010a), livelihood strategies (Brown et al., 2007; Dorward, 2009) or a range of socio-economic indicators (Bidogeza et al., 2009). An advantage of typologies based on more than resource endowment alone is that these better distinguish farmers with comparable wealth but contrasting livelihood strategies, which is relevant when considering possible uptake of agricultural innovations.

While the model produced realistic estimations of yields and soil C dynamics, the rotational benefits of grain legumes on maize were small compared with reports from southern Africa (Snapp et al., 2002; Zingore et al., 2008). This is most likely because rotational benefits other than provision of N are not captured in the model. Furthermore, the relatively large rates of fertiliser N applied to maize masked the crop's dependence on N_2 fixed by preceding legumes. Before calibration, the model clearly over-estimated tobacco yields, relative to actual yields. Despite high nutrient application rates, observed tobacco yields were relatively low. This could be due to poor crop husbandry or the reaping of tobacco leaves in cycles during the growing season, resulting in the crop not being able to achieve its potential yield.

Our partial budgeting analysis took variability of output market prices over time into account, but not the fact that farmers differ widely in market access. This is especially relevant for tobacco as wealthier farmers generally sold their tobacco at the tobacco auction in the capital Lilongwe, whereas poorer farmers sold to village middlemen for 20–30% less. Maize and groundnut had better developed local markets accessible for most farmers. Maize, groundnut and soybean prices, obtained from monthly market surveys conducted by the Malawian Ministry of Agriculture and Food Security, were high compared for instance with world market prices. We do not know to what extent these market prices reflect farm gate prices.

Soil analyses indicated that 86% of the fields had available P values less than 10 mg kg^{-1} and 76% of the fields had less than 0.2 cmol kg^{-1} exchangeable K (values considered critical for maize and legumes). The occurrence of soils with a critically low P or K status was much higher than that observed in a large soil survey in Malawi in 1993 (Snapp, 1998). While soil sampling in our study cannot be compared in scale and geographic width with the 1993 survey, this difference may be the result of continued cropping over the last 20 years, the emphasis on N-based fertilisers in the FISP and the absence of K in the fertiliser blend (23:21:0 + 4S) commonly used for maize.

To target technologies, appropriate niches need to be identified. Such technology niches have multiple agro-ecological, socio-economic and cultural dimensions (Ojiem et al., 2006). The importance of these dimensions is dynamic, as for instance soil fertility characteristics, prices and cultural values change over time. However, certain boundaries could be rather rigid, even across agro-ecologies, as they reflect primary constraints. For instance, an LRE and food insecure rural household is likely to be constrained in its abilities to adopt innovations by labour and/or land availability in many parts of sub-Saharan Africa. In relatively densely populated areas such as most parts of Malawi, such households often own too little land to be food self-sufficient, and earn food or income by working on other peoples' farms (known as ganyu labour) during times of peak labour demands. Therefore, poor farmers are unlikely to diversify unless alternative crops offer large benefits. For more market-oriented farmers, a key aspect determining the adoption of an agricultural innovation is likely to be the relative profitability and financial risks of the new technology.

We found that grain legume production was considerably more profitable than maize (Table 5; Fig. 5). Legume grain fetched two to four times the price of maize from 2001 to 2008 which easily compensated for smaller grain legume yields. While tobacco cultivation potentially provided higher net benefits than grain legumes, tobacco is a relatively risky crop with high investment costs and large output price variability. Legumes have more diverse markets with significant local consumption. The demand for soybean has rapidly grown in Malawi and elsewhere in Africa in recent years due to its multiple uses in the food and feed industries. Between 2005 and 2012, the production area of soybean in Malawi grew from 69,000 to 102,000 ha, and total production from 40,000 to 107,000 t grain (FAOSTAT, 2014). Primarily the MRE and HRE farmers can take advantage from the opportunities offered by legumes as cash crops. As HRE farmers are a small fraction of the total number of farmers in the study area (Fig. 1), MRE farmers (FT3) are likely to constitute the main group of farmers (in terms both of numbers of farmers and area farmed) that can expand the area with legumes as cash crops. LRE farmers in FT4 also cultivated legumes and other typical cash crops, though their small farm sizes limit their possibilities to expand legume production. Given the low profitability of maize, one may wonder why HRE farmers nevertheless cropped large proportions of their land with maize, of which they sold substantial amounts. Anecdotal evidence suggested this is related to cultural preferences and the status associated with growing maize, which is also used to hire ganyu labour. Also tobacco, a typical man's crop, was favoured by male household heads as a status improving crop.

Field studies from Malawi give a mixed picture regarding the impact of legumes on overall crop productivity with maize monocultures in some cases giving more total edible yield than legume-maize systems (Kamanga et al., 2010a) or the reverse (Snapp et al., 2010). Our field observations indicated that maize provides more edible yield and a larger grain return to labour than legumes, making maize an attractive food security crop for the poorest farmers who are severely land and labour constrained. The FARMSIM analyses however suggested that increased groundnut and soybean cultivation along with improved management can improve overall productivity of farms (Table 4). Also previous field research (Snapp et al., 1998; Zingore et al., 2008; Kamanga et al., 2010b) highlighted the yield enhancing effect of P fertiliser with grain legumes, and of rhizobial inoculants with soybean, benefitting also subsequent crops through residual effects of P fertiliser and an enhanced N supply from legume residues. Legumes also benefit from the strong residual effects of P fertiliser applied to preceding crops. LRE farmers tend to have soils with a relatively poor P status and these farmers would need to apply more P inputs, occasionally in combination with other nutrients, to make grain legumes more productive and competitive with maize in terms of contributing to food self-sufficiency. Regrettably, LRE farmers are also those who can least afford investments in inputs. Rhizobial inoculants are cheap in comparison with fertiliser, but are not widely available to farmers. Overall, the results suggest that grain legumes do not easily compete with maize as a food security crop, and only with proper management–if feasible for LRE farmers – can legumes improve food self-sufficiency of the poorest households. The multiple uses of grain legumes as food security and cash crop are likely to add to the attractiveness of grain legumes for poorer farmers.

5. Conclusions

The *ex-ante* impact analyses, using a combination of field observations and modelling, proved useful for identifying likely niches for legume technologies among farmers differing in resource endowment. Observed yields and labour inputs suggested that maize provides more edible yield per unit area with a higher calorific value and labour use efficiency than groundnut and soybean. The NUANCES-FARMSIM analyses partly confirmed these trends, but at farm level over multiple years maize-dominated systems often produced less edible food than when the area cropped with grain legumes was expanded. Improved management practices including use of P fertiliser and inoculation of soybean were required to increase grain yields of both legumes and maize. Partial budgeting analyses suggested that legume cultivation is considerably more profitable than maize. We conclude that grain legumes have a good potential as cash crops particularly for medium and high resource-endowed farmers. With proper management, legumes can also improve food self-sufficiency for the poorest households, although these face the strongest constraints to invest in new technologies.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.eja.2014.04.002.

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