Supplementary material

File S1

The following procedure was used to classify farmers based on maize production with varying fertilizer application intensity:

We matched the whole dataset by crop production and their associated level of fertilizer used. We then grouped the farms cultivating maize with zero, low, medium and high fertilizer levels based on percentiles.

All land area, crop types, applied fertilizers declared as zero or blank were removed. This means that the land was either not cultivated or no fertilizer was applied.

Fertilizer rate per hectare was calculated for each plot with the formula

$$qty_{fert} = \frac{Weight\ of\ a\ bag}{Declared\ area} \quad \text{(S1)}$$

Where;

$qty_{fert} = Quantity\ of\ applied\ fertlizers\ in\ bag$

Nitrogen proportion was set to 15% unless the percentage is indicated or the fertilizer product applied is urea

Nitrogen rate per hectare is calculated with:

$$N_{rate} = \frac{F_{rate} \times N_{prop}}{100} \quad \text{(S2)}$$

Where;

$N_{rate} = Nitrogen\ rate\ in\ kg\ per\ hectare$

$F_{rate} = Fertlizer\ rate\ in\ kg\ per\ hectare$

$N_{prop} = Nitrogen\ proportion\ in\ percentage$

Grain yield from bags is calculated as:

$$Gn_y = \frac{Gn_a \times Grain_{weight}}{a} \quad \text{(S3)}$$

Where;

$Gn_y = Grain\ yield\ from\ bag\ in\ kg\ per\ hectare$

$Gn_a = Grain\ amount\ harvested\ on\ land\ in\ bags$

$a = area$

Rows with zero grain yields per hectare were removed

Maize was then categorized into three groups based on the nitrogen rate per hectare and the categories include maize-low: 0-10, maize-medium-medium 10-30, maize-high greater than 30

File S2

- CLEM model assumptions

a. All farm types are modelled based on the farmers' current management practices as observed in the data.

b. All 100% of crop produce are sold, which is the main source of income in the model.

c. Other sources of fixed income are income from remittance, off-farm income, and fixed income from livestock sales (i.e. poultry)

d. Ruminant mortality and fatality are not accounted for in the model.

e. The livestock are fed with residues for 7 months, which is typically the planting season in the study area and grassland for 5 months, which is typically the dry season period in the area. The grassland is infinite i.e. the quantities available are enough to feed all the animals for 5 months and there is no need to purchase other food sources during this period.

f. Farmers can obtain loans whenever their income is not enough to perform any activity. The size of the loan is limited based on data obtained for each farm type.

g. If the farmers' income falls to the negative and they obtain loans to carry out their production activities, there is an interest rate that has to be paid.

h. Farmers sell livestock only if they do not have enough money to cover their household living expenses.

i. Labour activities are carried out by the household members and hired labour is used if the available labour is not enough. The costs of hiring labour are accounted for wage rate is obtained from the data.

File S3

- Farm optimization model assumptions

The main assumptions adopted in parameterizing the optimization model include the following:

1. The crop yields are sold (100% sales as nutrition is not considered in the model. Only household feeding cost is included)

2. The biomass from crop production (obtained from the crop model), which is based on the land size and the crop type are fed to the ruminant livestock, in addition to grassland and additional feed supplements that may be bought based on the feed requirements of the animals and availability. The available residue quantity comes from the crop model and are updated each year

3. These residues are fed to the livestock for 7 months and the animals graze on grasslands for the remaining 5 months of the year (during the rainy seasons- May to October). The feeds obtained from grassland are assumed to be sufficient for the animals and they have certain associated labour costs.

4. Each farming operation, including crop production and livestock production requires certain amount of labour (total man days) and their costs (i.e. wage rate per day) were included as total labour cost.

5. Cash at hand are also included as part of the cash constraint. This was modelled in such a way that all income (excluding income from crop revenues as this should come at the end of the year) plus cash at hand and obtainable amount of loan must be greater than all expenditure.

6. If the farmers take loans, they have to pay it back at the end of the year with interests. The interest rates and the maximum loan the farmers can take were obtained from the data

7. The total revenue on the farm include: revenue from crop production, off farm income (fixed), income from remittances, income from poultry sales (this was obtained as from the data and the amount was modelled as a form of fixed income)

8. Livestock are held and not sold because farmers' perceive them as a form of wealth preservation. We therefore, fixed the numbers of animals, accounting for all associated costs to keep them.

9. We represented the household food requirements by their cost equivalents, taken from the household revenue

File S4

- Optimization model constraints

In the following section, the production constraints as parameterized in the farm decision model are discussed in detail.

- *Crop production*

The crop production activities in the region comprise maize (with varying degree of fertilizer application intensity), rice, soybeans, upland rice and groundnut, which are planted on the farmers' plots.

$$\sum_{c=1}^{C} X_{plot,c,typ} \leq land\_size_{plot,typ} \quad (S4)$$

Equation (S4), shows that the sum of the cultivated crops per production plots must be less than or equal to the available land area per plot.

$$\sum_{i=1}^{mz} X_{plot.mz} * y_{mz,plot,typ} \geq total\_con_{typ} \quad (A5)$$

Equation (S5) shows that maize yield must be at least equal or greater than the household consumption requirement.

- *Animal production*

The animals are fed with the crop residues produced after harvesting the crops. To ensure that enough residues are produced or bought, a constraint was added stating that the total residue produced from own crop production and the possible amount that may be purchased is enough to feed the animals for 7 months and then the animals can graze on grasslands for the remaining 5 months of the year.

$$\sum_{i=1}^{plot,c,rc}(((X_{plot,c,typ} * f_{rc,c,typ}) * 0.583[1]) + \Sigma_{i=1}^{rc} rstd_{rc,typ}))) \geq \sum_{i=1}^{a}(foda_{a,fod} * hs_{a,typ} * 0.583) \quad (S6i)$$

Equation (S6) ensured that the total residue produced on the farm in 7 months plus the amount bought in kg is greater than or equal to the feed required by the total herd in the same period.

$$rsc_{typ} = \Sigma_{i=1}^{rc} rstd_{rc,typ} * res\_cost_{rc} \quad (S7)$$

Equations (S7) show the cost of residues bought.

- *Labour constraints*

Labour is obtained from the household and hired labour. A labour constraint was introduced into the model to ensure that the crop production activity is

[1] Obtained by dividing 7 by 12 to represent 7 months of available forage in a year

restricted by the available household labour and a possible number of hired labour that the farmers are able to hire based on the cash available to them. All adults in the household are able to provide 30 man-days of labour per month, while young children mostly in their teens can provide 15 man-days of labour per month. Any additional labour required provided by hired labour at the daily wage rate.

Equation (S8) shows that the adults in the households are available for 30 days, while young adults are available for 15 days in a month. The combination of these and hired labour sums up the total man-days of labour. Equation (S9) shows the cost of hired labour

$$\Sigma_{i=1}^{mandays,plot,c}\left(lab_{mandays,plot,c,typ}\right) * \left(X_{plot,c,typ}\right) \ \leq \ \Sigma\left(\left(HH\_ad_{typ} * 30\right) + \left(HH\_y_{tpy} * 15\right)\right) + Hl_{typ} \quad (S8)$$

$$Labcost_{typ} = \ Hl_{typ} * \ w_{day} \quad (S9)$$

- *Cash constraints*

Cash constraint was introduced to limit farmers' production activities based on the available cash and a possible amount of loan they can obtain at a particular time. The sum of the cash at hand, income from off-farm employment, income from poultry sales and the obtained loan must be equal to the total costs on the farm including the labour cost, and miscellaneous costs in equation (S10). Equation (S11) ensures that the farmers cannot obtain loans more than the amount they have already declared during the data collection process.

$$cash\_at\_hand_{typ} + \ off_{farm_{typ}} + loan_{typ} \geq \ Labcost_{typ} + \ total\_con_{typ} + tot\_exp_{typ} + all\_herd\_cost_{typ} + \ rental_{typ} + \ rsc_{typ} + tc_{typ} \quad (S10)$$

$$loan_{typ} \leq \ \Sigma_{i=1}^{l}(l_{typ}) \quad (S11)$$

Revenue

The revenue included in the model is mainly from crop production as animals are not sold in the model. Other possible sources of revenue considered in the model are income from remittances and income from off-farm employment.

Equation (S12) shows that the revenues obtained from each plot should be equal to the yield per plot multiplied by the price per kg of the crop

$$cpr_{typ} = \Sigma_{i=1}^{plot,c} X_{plot,c,typ} * y_{c,plot,typ} * p_c \quad (S12)$$

Table S1. Description of mathematical symbols used in the optimization model

Symbol	Description	Units
plot	Total area of cultivated plot	ha
land_size	Total available land area	ha
c	cultivated crop (the choice include: maize zero, maize low, maize medium, maize high, soybeans, rice and groundnut	
mz	Maize crop	
total_con	Total consumption	
f	available forage	
rs_{bgt}	Total residue bought by the farmers	kg
$foda$	feed requirements by the animals in kg	kg
hs	The herd size of the farmer (including sheep, cattle and goat)	
rsc	Total cost of residue bought	GH₵
res_cost	Price of residue per kg	GH₵
$mandays$	Total man-days of labour required	man-day
HH_ad	Adults in the household	
HH_y	Young adults in the household	
Hl	Total hired labour	
w_{day}	Wage rate per day	GH₵
cash_at_hand	Cash at hand	GH₵
off_{farm}	Income from off-farm employment	GH₵
l	Loan obtained by the farmers	GH₵
$labcost$	Total labour cost	GH₵
mc_c	Total miscellaneous cost	GH₵
ahd_c	Total herd production cost	GH₵
cpr	Revenue from crop production	GH₵
y	Yield per plot	GH₵
p	Price of crop per kg	GH₵/kg

Table S2. Scenario analysis of cropping activity under changing risk aversion coefficient

Weather	Farm type	Risk aversion coefficient	Land proportion allocated to crops						Land area
			Maize low	Maize medium	Maize high	soybean	Upland rice	Groundnut	
Bad weather	LRE	0	4.6%	0.0%	0.0%	0.0%	85.4%	9.8%	0.9ha
		0.0001	4.7%	0.0%	0.0%	0.0%	85.4%	9.8%	0.9ha
		0.001	4.7%	0.0%	0.0%	0.0%	75.8%	19.6%	0.9ha
		0.01	4.6%	0.0%	0.0%	5.33%	39.3%	50.8%	0.92ha
		0.1	17.4%	5.8%	1.7%	38.8%	21.3%	15%	0.92ha
		1	18.2%	1.3%	0.7%	9.1%	63.5%	7.1%	0.55ha
	MRE	0	0.0%	0.0%	0.0%	0.0%	26.9%	73.1%	0.89ha

		0.0001	0.0%	0.0%	0.0%	0.0%	73.1%	26.9%	0.89ha
		0.001	0.0%	0.0%	0.0%	0.0%	80.1%	19.9%	0.91ha
		0.01	1.1%	0.0%	0.0%	24%	10.3%	64.6%	1ha
		0.1	21.6%	0.0%	0.0%	39.9%	4.1%	39.9%	0.73ha
		1	5%	0.0%	0.0%	8.3%	0.9%	85.9%	0.27ha
	HRE	0	0.0%	0.0%	0.0%	0.0%	58.2%	41.8%	1.65ha
		0.0001	0.0%	0.0%	0.0%	0.0%	58.2%	41.8%	1.65ha
		0.001	0.0%	0.0%	0.0%	0.0%	40.6%	59.4%	1.92ha
		0.01	9.1%	0.0%	0.0%	55%	10.2%	25.7%	2.28ha
		0.1	11.3%	6.6%	3.0%	60.7%	3.6%	14.8%	1.09ha
		1	5%	2.9%	1.3%	31.1%	2%	57.5%	0.08ha
		0	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.92ha
		0.0001	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.92ha
		0.001	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.92ha
	LRE	0.01	0.0%	0.0%	0.0%	0.0%	100%	0.0%	0.92ha
		0.1	0.0%	19.9%	11.5%	24.5%	24.1%	20.1%	0.92ha
		1	23.8%	17.7%	13.2%	30.1%	6.7%	8.5%	0.61ha
		0	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	3.36ha
		0.0001	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	3.36ha
Good weather	MRE	0.001	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	3.36ha
		0.01	0.0%	0.0%	0.0%	10.9%	52%	3.1%	3.11ha
		0.1	19.0%	16.6%	9.7%	30.7%	12.4%	11.6%	2ha
		1	23.2%	17.6%	13.1%	30.7%	6.8%	8.6%	0.58ha
		0	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	5.13ha
		0.0001	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	5.13ha
		0.001	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	5.13ha
	HRE	0.01	9.8%	1.1%	0.0%	21.7%	38.3%	29.2%	4.38ha
		0.1	19.0%	16.8%	10.9%	32.6%	10.3%	10.4%	2.63ha
		1	19.1%	17.1%	12.7%	35%	7.4%	8.8%	0.47ha