Supplementary Material

Appendix A. Equations used in the farm model

Arable land was split over a series of land types, *i.e.* homogenous zones in terms of performance and impact of the different cropping systems: 1) irrigated lowland, 2) Low-irrigated lowland (irrigation channels but frequent lack of water), 3) flat/ moderately sloping non-irrigated land with clay loam soil, 4) slopping non-irrigated land with clay loam soil, 5) flat/ moderately sloping non-irrigated land with sandy soil, 6) slopping non-irrigated land with sandy soil, 7) flat/ moderately sloping non-irrigated land with fertile clay loam soils, 8) sloping non-irrigated land with fertile clay loam soils. Maize (CMS and AMS), pasture and rice-fallow system (Past-CS) were cultivable only on non-irrigated land, paddy rice only on irrigated or low-irrigated lowland and dry season crops only on irrigated lowland. Hand sowing of maize was possible on every non-irrigated land types and motorized sowing was only feasible on flat and moderately sloping non-irrigated land types.

The seasonality of cash and labour constraints of agricultural activities in the model was accounted for by dividing the year in time periods over which the balances of stocks, cash, and labour must be positive (see equations “food stock balance”, “Labour” and “cash balance”, Table S1). We considered the five following periods: 1) maize ploughing/sowing (from mid-April to end-May) and rice nursery, 2) rice transplanting and first weeding (from end-May to mid-July), 3) weeding of rice and maize fields (mid-July to mid-September), 4) maize and rice harvests (mid-September to end-November), 5) dry season crops (End-November to mid-April). The different periods did not have the same duration. Periods from 1 to 5 lasted respectively 45, 45, 60, 75 and 140 days.

The five constraints to income maximization were set for each period t (Table S1).

Table S1: Equations expressing constraints to income maximization used in the farm model

Constraints to income maximization	**Equations**
Available arable land per land type	For each land type Z, $$\sum_{c} X(c,z) < AREA(z)$$ X(c,z): area under crop c in a land type z AREA(z): area of land type z on the farm
Constraints for each period t	
Food security to satisfy the energy needs of the family	CONSORice(t)*valEnerRice≥$\sum_{h}^{H} HEnerNeed(t,h)$*Nh(h) CONSORice(t): household rice consumption for period t (kg DM) valEnerRice: the digestible energy content of rice (cal/kg) HEnerNeed(t): human energy need (in cal) of one person of type h according to age and gender categories over period t Nh(h): number of persons of type h on the farm
Food stock balance	INI_STOCK(p,t)+PURCH(p,t)+PROD(p,t)=FARM_CONSO(p,t)+SALES(p,t)+FINAL_STOCK(p,t) INI_STOCK(p,t): initial stock of product p at the beginning of period t (kg), PURCH(p,t): the amount of product p purchased (only rice in the model) during period t (kg) PROD (p,t): amount of product p produced on farm during period t (kg), FARM_CONSO(p,t): the consumption of product p (kg) by household members (only rice in the model) during period t, SALES(p,t): amount of product p sold during period t (kg), FINAL_STOCK(p,t): stock of product p available at the end of period t.
Labour	$$\sum_{c,z} Req_{Work\ (c,z,t)} * X(c,z) + \sum_{a} Req_{Wani\ (a,t)} * Xani(a) + \sum W\_Out(t) \leq \sum W_{In(t)} + \sum_{g} dispoW(g,t)$$ X(c,z): area under a crop c in land type z, Reqwork(c,z,t): amount of work (in days) required during period t for a crop c in a land type z, Xani(a): number of an animal unit of type a, ReqWani(a,t): amount of work (in days) required during period t for an animal unit of type a, W_out(t): number of days in a period t during which household members work off-farm, W_in(t): number of days in a period t during which household members work in-farm, dispoW(g,t): labor supply in days of men, women and others (children, elders) in each period.
Cash balance	*INI_CASH (t) +* $\sum incomes(t)$ *+ loan(t1) = FINAL_CASH (t) +* $\sum expenses(t)$ INI_CASH (t): initial cash available at the beginning of a period t, Incomes (t): incomes from sales or off-farm in period t, Loan(t1): amount of the loan (only for first period), FINAL_CASH(t): cash available at the end of a period t, Expenses(t): expenses in period t for inputs, hired labour, rice purchases, household expenses for food and education.
Livestock feed satisfaction	$$ConsoC(t) \geq EN(t).Xcows$$ With for all periods t of the year where forage is needed (t2, t3 and t4), consoC(t): amount in kg of dry matter of forages consumed by cow units in kg of dry matter, EN: quantity of forage needed in kg of dry matter by a cow unit, Xcows : number of cow units on the simulated farm

Calibration procedure of the farm model:

Half of the farms belonging to each Maize Farming System types (MFS) were used to calibrate the model. We used the transaction costs for rice purchases and hired labour to calibrate each MFS (see Sadoulet et al. (1998) for a definition). After calibration, the consistency between simulated and observed farm plan was assessed on the 16 farms, following the approach used by Affholder *et al.* (2010) as derived from Norton and Hazell (1986), using two indicators on cultivated areas: mean absolute deviation (MAD) which quantifies the absolute deviations of predictions, and model efficiency which quantifies the ability of the model to predict land allocation compared to the mean of observations.

MAD= $\frac{1}{N}\sum_{i=1}^{N} |XP_i - XOBS_i|$

Model efficiency= 1- $\frac{\sum_{i=1}^{N} (XP_i - XOBS_i)^2}{\sum_{i=1}^{N} (XP_i - \widehat{Xobs})^2}$

With XP_i the predicted area of a cropping activity, $XOBS_i$ the observed area of a cropping activity, N is the number of pairs of cropping activity compared (N=80), $\widehat{Xobs}$ is the mean value of the N observed areas. The closer MAD index to zero the better and the closer the model efficiency is to one the better.

Appendix B: criteria and indicators of farm sustainability

Table S2: Criteria and indicators of farm sustainability quantified by the farm model, units in brackets.

Sustainability indicators	Description	Source of data to compute the indicator
Farm income and diversity		
Total farm income (USD)	Gross value from livestock and crop total sales plus income generated from off-farm activities minus the sum of all expenses for crop, livestock, hired labour, buying food (rice), fixed costs and loan interests (in case the farmer contracted a loan in period 1)	Farm model
Per capita Farm income (USD/capita/ day)	Total daily farm income per household Member (poverty line is assumed to be 1.9 USD/ capita/ day)	Farm model
Income diversity (score)	score = number of activities generating income (from 2 to 6)	Farm model
Cash inflow regularity (score)	score = number of periods of the year during which income is generated (from 1 to 5)	Farm model
Agricultural Productivity		
Product from farm activities per hectare (USD/ha)	Product from livestock and crop total sales plus the value of rice produced and consumed per hectare of land cultivated	Farm model
Labour productivity from farming activities (USD/man-day)	Total farm income + gross margin of rice produced and consumed -income generated from off-farm activities)/ total labour used by farm activities	Farm model
Cash and maize price dependency		
Income dependency on maize price fluctuation (%)	Estimated by decreasing by 20% maize selling price and by calculating, with a fixed farm plan, the ratio: ([product from maize selling with current price]-[product from maize selling with price decreased])/total farm income	Farm model
Cash outflow needed at the beginning of the cropping season (USD/ha)	Total expenses needed in first period for crop, livestock, hired labour, rice bought and fixed costs.	Farm model
Farm future viability [(1)]		
Farm equipment/heir (equipment/heir)	Farm equipment are the following: seed drill, milling machine, threshing machine, shelling machine, rototiller, truck, motorbikes, and cars	Light survey +farm model
Cattle unit/heir (cattle unit/heir)	Total cattle owned by the household per heir	Farm model
Land/heir (ha/heir)	Total land cultivated per heir	Farm model
Number of affordable additional dependants	Number of additional dependant that the farm could feed and pay for education provided the farm does not fall below the $1.9/day poverty line. The needs considered are those of the children	Farm model
Rice production self-sufficiency		
Rice production self-sufficiency (-)	-If Rice produced - total rice needs for household consumption>0, indicator score=100 -If Rice produced - total rice needs for household consumption<0, this indicator is calculated with the ratio Rice produced/total rice needs for household consumption	Farm model
Work and ease of work		
Workload (%)	Total work required for farm and off-farm activities over total labour force available	Farm model
Frequency of workload peak (% period with peak)	A peak is reached when workload in a period is>70%	Farm model

<table>
<tr><td>Ease of work (score 10-100)</td><td>Score aggregating 2 variables: Tool used for sowing (hand/motorized), Amount of work spent on manual weeding (days ha-1)
The scores were assigned with a decision rule model built with DEXi software (see Lairez et al., 2023):
<table>
<tr><th>Sowing tool</th><th>Work for weeding (days/ha)</th><th>Ease of work score</th></tr>
<tr><td>Hand</td><td>>10</td><td>10</td></tr>
<tr><td>Hand</td><td>4-10</td><td>32</td></tr>
<tr><td>Hand</td><td>0-4</td><td>54</td></tr>
<tr><td>Motorized</td><td>>10</td><td>54</td></tr>
<tr><td>Motorized</td><td>4-10</td><td>76</td></tr>
<tr><td>Motorized</td><td>0-4</td><td>100</td></tr>
</table></td><td>Indicator assessed only for maize
Field monitoring network (lairez et al., 2023)</td></tr>
<tr><td colspan="2">Farmer autonomy and constraints</td><td></td></tr>
<tr><td>Percentage of rice bought (%)</td><td>As expressed by the name of the indicator</td><td>Farm model</td></tr>
<tr><td>Selling constraints (USD)</td><td>Cash available at the end of period 3 (before harvest) minus the expenses in period 4 (after harvest)</td><td>Farm model</td></tr>
<tr><td>Lowland constraint to higher income (USD/ha of lowland)</td><td>Marginal increase of income per additional unit (hectare) of lowland area, calculated by GAMS software</td><td>Farm model</td></tr>
<tr><td>Non-irrigated land constraint to higher income (USD/ha)</td><td>Marginal increase of income per additional unit (hectare) of non-irrigated area</td><td>Farm model</td></tr>
<tr><td>Labour constraint to higher income (USD/day)</td><td>Marginal increase of income per additional labour unit (man.day) available during labour peak periods</td><td>Farm model</td></tr>
<tr><td>Indebtedness (%)</td><td>Loan/total income (%)</td><td>Farm model</td></tr>
<tr><td colspan="2">Control of Herbicide leaching</td><td></td></tr>
<tr><td>Score (10-100)</td><td>Score aggregating 3 variables: Herbicide treatment risk (product and doses), Leaching risk due to heavy rainfall (Risk of occurrence of heavy rainfall (>45 mm) in the 2 days following herbicide application), and Leaching risk due to soil type (%OM)
The scores were assigned with a decision rule model built with DEXi software (see Lairez et al., 2023):
<table>
<tr><th>Herbicide treatment risk</th><th>Leaching risk due to percolation</th><th>Leaching risk due to soil type (%OM)</th><th>Control of herbicide leaching</th></tr>
<tr><td>>21.5</td><td>1</td><td>>2</td><td>10</td></tr>
<tr><td>>21.5</td><td>1</td><td><2</td><td>10</td></tr>
<tr><td>>21.5</td><td>0</td><td>>2</td><td>10</td></tr>
<tr><td>>21.5</td><td>0</td><td><2</td><td>25</td></tr>
<tr><td>]5.9;21.5]</td><td>1</td><td>All</td><td>25</td></tr>
<tr><td>]5.9;21.5]</td><td>All</td><td>>2.6</td><td>25</td></tr>
<tr><td>]5.9;21.5]</td><td>0</td><td><2</td><td>50</td></tr>
<tr><td>]0;5.9]</td><td>1</td><td>All</td><td>50</td></tr>
<tr><td>]0;5.9]</td><td>0</td><td>All</td><td>75</td></tr>
<tr><td>0</td><td>-</td><td>-</td><td>100</td></tr>
</table></td><td>Indicator assessed only for maize
Field monitoring network (lairez et al., 2023)</td></tr>
<tr><td colspan="2">Maintenance of soil buffer capacity</td><td></td></tr>
<tr><td>Score (10-100)</td><td>Score aggregating 3 variables: Soil pH, Soil cation exchange capacity and Biomass left on soil surface
The scores (10: low maintenance of soil buffer capacity, 100: high maintenance of soil buffer capacity) were assigned with a decision rule model built with DEXi software (see Lairez et al., 2023):
<table>
<tr><th>pH</th><th>CEC</th><th>Biomass left on</th><th>Score maintenance</th></tr>
</table></td><td>Indicator assessed only for maize
Field monitoring network (lairez et al., 2023)</td></tr>
</table>

		soil (t/ha)	of soil buffer capacity
<6	<14	<2.9	10
6-7	<8	<2.9	10
<6	<8	[2.9;5.3[	10
<6	>14	<2.9	32
6-7	8-14	<2.9	32
>7	<8	<2.9	32
<6	8-14	[2.9;5.3[	32
6-7	<8	[2.9;5.3[	32
<6	<8	>=5.3	32
6-7	>14	<2.9	54
>7	8-14	<2.9	54
<6	>14	[2.9;5.3[	54
6-7	8-14	[2.9;5.3[	54
>7	<8	[2.9;5.3[	54
<6	8-14	>=5.3	54
6-7	<8	>=5.3	54
>7	>14	<2.9	76
6-7	>14	[2.9;5.3[	76
>7	8-14	[2.9;5.3[	76
<6	>14	>=5.3	76
6-7	8-14	>=5.3	76
>7	<8	>=5.3	76
>7	>14	>2.9	100
6-7	>14	[2.9;5.3[	100
>7	>8	[2.9;5.3[	100

Control of erosion

Score (10-100)

Score aggregating 4 variables: Number of days between ploughing and sowing, Runoff risk (% of water runoff on total rainfall during the crop cycle) and Slope (1: flat, 2: medium, 3: steep)

The scores were assigned with a decision rule model built with DEXi software (see Lairez et al., 2023):

Number of days between ploughing and sowing	Runoff (%)	Slope	Erosion control score
>30	>6.7	Steep or moderate	10
>30	<6.7	Flat or moderate	25
20-30	>6.7	Steep	25
20-30	>6.7	Moderate or flat	50
20-30	<6.7	All	50

Indicator assessed only for maize
Field monitoring network (lairez et al., 2023)

<table>
<tr><td></td><td><table>
<tr><td><20</td><td>All</td><td>Steep</td><td>50</td></tr>
<tr><td><20</td><td>>6.7</td><td>Moderate or flat</td><td>75</td></tr>
<tr><td><20</td><td><6.7</td><td>Moderate or flat</td><td>100</td></tr>
</table></td><td></td></tr>
<tr><td colspan="2">Nitrogen Balance</td><td></td></tr>
<tr><td>Score (10-100)</td><td>Nmin + Nfert − Nuptake
With
Nmin= α*fn*Norg (Sattari et al., 2014 ; Janssen et al., 1990)
- α = 68,
- fn=0.25*(pH-3) if $4.3<pH<7$
- fn=1 if $pH>7$
- Norg in kg N ha^{-1}, 20 cm depth
Nuptake= Ya*21 (21 is N (kg) taken up per ton of maize grain at 12% humidity</td><td>Indicator assessed only for maize fields
Field monitoring network (Lairez et al., 2023)</td></tr>
</table>

(1) Heir are the direct descendants of the household. They were taken as the average number of descendants per family using the sample of 16 farms.

Appendix C: Procedures applied to sustainability indicators

- **Normalization of individual indicators**

Internal normalization was used (Pollesch and Dale, 2016), normalizing indicators according to distribution of indicators performances of the 16 farms modelled in the baseline and the SCEN1.This normalization followed equation 1 below for the case of an indicator i whose increase means an increase [Eq. 1a] or a decrease [Eq. 1b] in sustainability:

Equation 1:

Eq. 1a:

$$\text{Normalized Indicator Score i } = \frac{\text{Indicator value i} - \{\text{Min}_j\}}{\{\text{Max}_j\} - \{\text{Min}_j\}}$$

Eq. 1b:

$$\text{Normalized Indicator Score i} = 1 - \frac{\text{Indicator value i} - \{\text{Min}_j\}}{\{\text{Max}_j\} - \{\text{Min}_j\}}$$

Where $\{\text{Min}_j\}$ and $\{\text{Max}_j\}$ are respectively the minimum and maximum values of the indicator over the j=32 simulations corresponding to 16 farms under scenario baseline and SCEN1.This normalization resulted in dimensionless values ranging from 0 to 1.

- **Aggregation of indicators to criteria level**

Radar graphs were used to compare performances of farms on the 11 sustainability criteria. To build the graphs, normalized indicators previously obtained were aggregated to the criteria level. For each criterion j, all normalized indicators i quantifying it, were aggregated on a 100 grades scale using a geometric mean following equation 2 below:

Equation 2:

$$\text{Criterion score j} = 100 * \sqrt[n]{\prod_i^n \left(1 + Normalized\ indicator\ score\ i\right)} - 100$$

Contrarily to a classic arithmetic mean approach usually used for indicators' aggregation, the geometric mean avoids low indicator scores to be compensated by high scores on other indicators composing a criterion (Lairez et al., 2016; Pollesch and Dale, 2016). This sustainability assessment was applied only to the main scenarios (baseline and SCEN1). Radar diagrams were displayed for representative farms of each MFS, selected to cover all soil types encountered in a MFS.

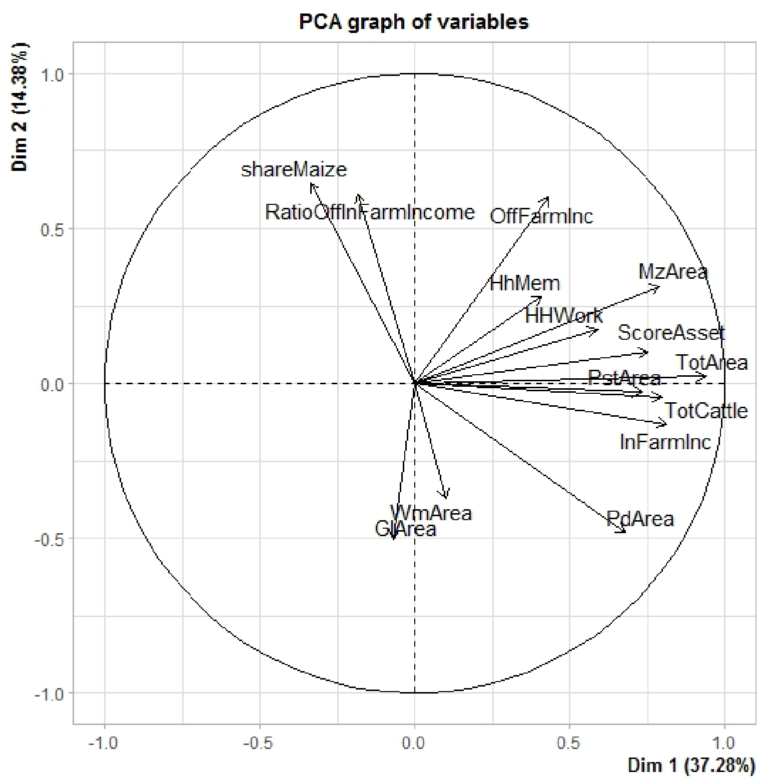
Appendix D: Principal Component analysis and hierarchical clustering results on farm land allocation variables, family size and workforce, farm equipment and income.

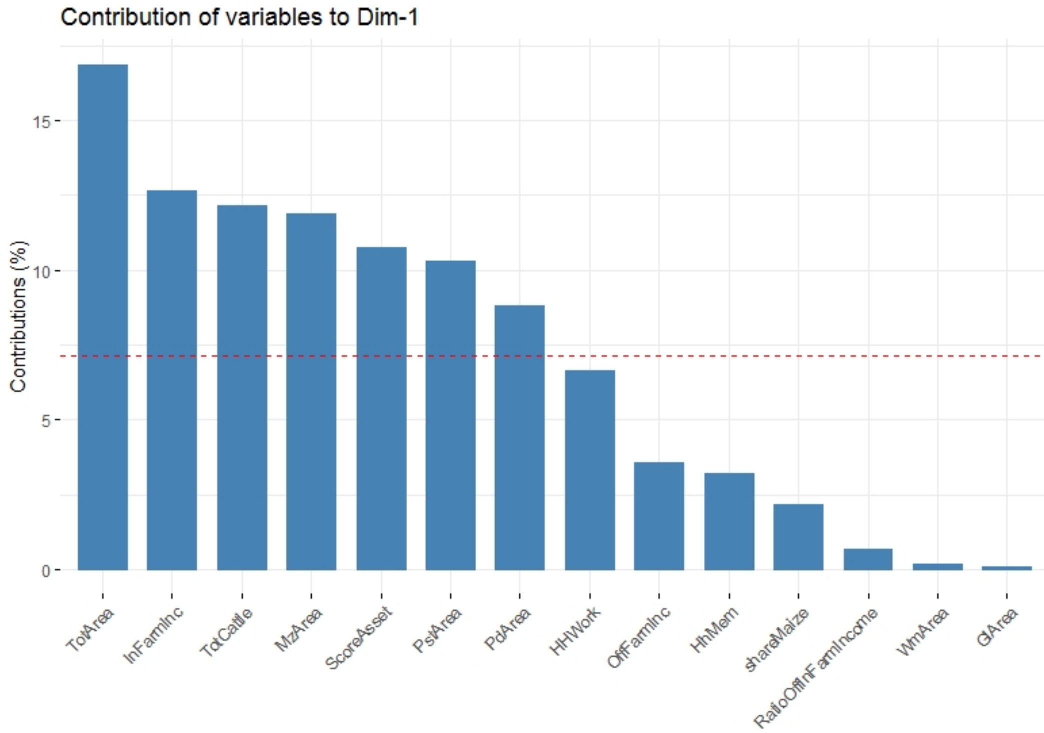
From the initial sample of 120 farms, eight farms were removed due to no maize cultivation (abandonment the year of survey).

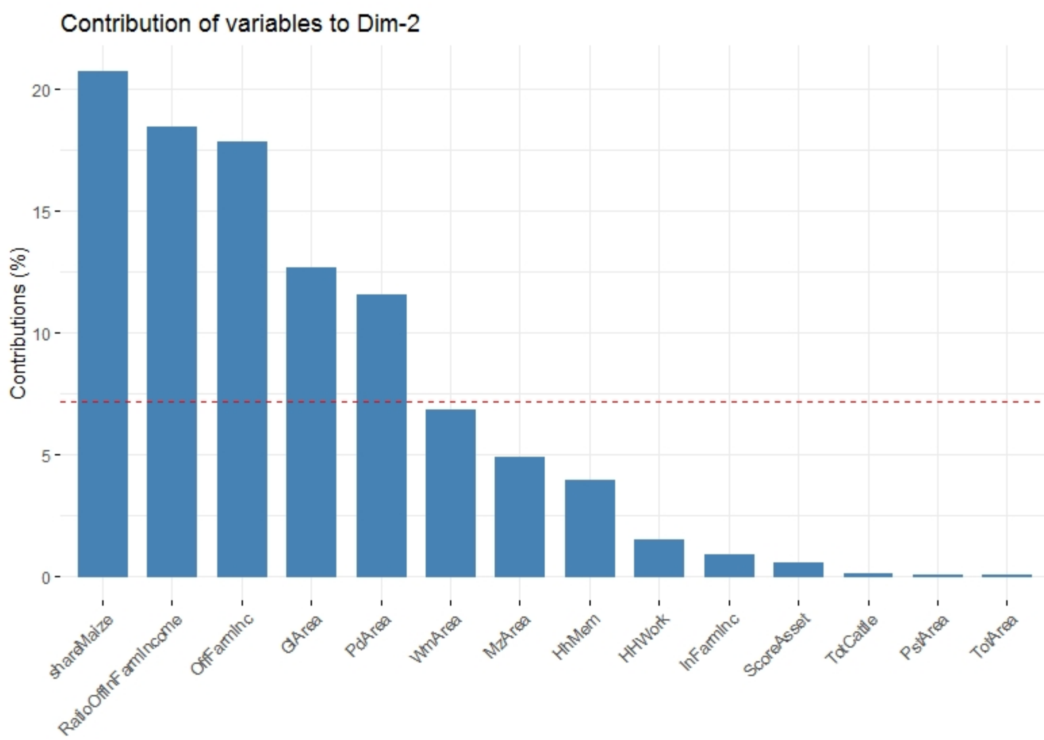
Table S3: Eigen values of the Principal component analysis

	eigenvalue	variance.percent	cumulative.variance.percent
Dim.1	4.988986	31.181165	31.18116
Dim.2	1.881228	11.757672	42.93884
Dim.3	1.554822	9.717638	52.65648
Dim.4	1.262621	7.891384	60.54786
Dim.5	1.121991	7.012445	67.56030

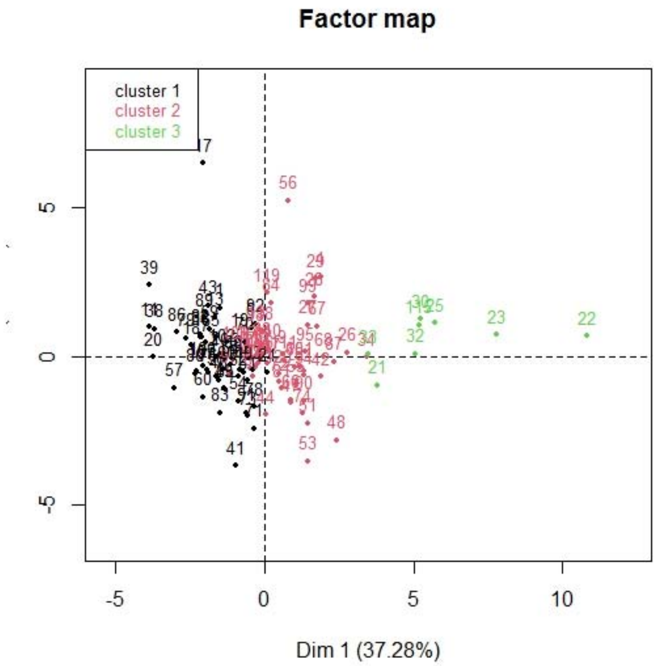
PCA graph




Contribution of variables to Dim-1
Contributions (%)
0
5
10
15
TotArea
lnFarmInc
TotCattle
MzArea
ScoreAsset
PstArea
PdArea
HHWork
OffFarmInc
HhMem
shareMaize
RatioOffInFarmIncome
WmArea
GlArea


Contribution of variables to Dim-2
Contributions (%)
0
5
10
15
20
shareMaize
RatioOffInFarmIncome
OffFarmInc
GlArea
PdArea
WmArea
MzArea
HhMem
HHWork
lnFarmInc
ScoreAsset
TotCattle
PstArea
TotArea

Hierarchical clustering



Cluster 1 (47% of farms). Small farms constrained on rice production (2.6 ha in total on average). Small area of paddy land (0.8 ha) and maize (1.6 ha). Small family (4.2 household members) with low workforce (0.56 workers per household member to feed). 1 cattle unit on average and few farm equipment (score: 3.4).

Cluster 2 (47% of farms). Medium maize/rice farm. Medium area of paddy rice (1.4 ha) and medium area of maize (2.6 ha). Large family (6.4 household members) with low workforce (0.6 workers per household member to feed). 2.7 cattle units on average and more farm equipment (score: 5).

Cluster 3 (7% of farms). Large maize farm with cattle. Large paddy rice area (2.2 ha) and maize (4.6 ha). Large family (6 household members) with more workforce available than for cluster 2 and 1 (0.73 workers per house member to feed). 6.7 cattle units and more farm equipment than cluster 2 and 1 (score: 7.5).

Appendix E: model calibration and prediction quality

Table S4: Calibration parameters per farm type: transaction costs for rice purchases and hired labor. The model was calibrated on 8 farms

	Farm type 1	Farm type 2	Farm type 3
Transaction cost for rice purchase	0.17	0.11	0.11
Transaction cost for hired labor	0.05	0.05	0.05

Table S5: Assessment of the quality of the land allocation predictions by the model for the 16 farms

	Distinction on maize cropping system type (observed manual/motorized maize should be simulated in manual/motorized maize respectively)
MAD *	0.28 ha
Model efficiency**	0.63

*: The closer to zero the better the prediction quality is, **: the closer to 1 the better the prediction quality is.

Table S6: Maize areas and cattle units simulated and observed for the 16 farms modelled in the baseline and comparison to observed values of the total sample of 120 farms

Farm Type 1-LRE		
Simulated	**Observed 16 farms**	**Observed 120 farms**
Average maize area per farm in the 16 farms (ha)		Average maize area
1.2	1.1	1.6
Cattle units cut for carry system in the 16 farms		Average cattle units for cut and carry system
3.7	1.9	1
Cattle units for pasture grazing system in the 16 farms		Average cattle units for pasture grazing system
0	0	0
Farm Type 2-MRE		
Simulated	**Observed**	**Observed**
Average maize area per farm in the 16 farms (ha)		Average maize area
2	1.9	2.6
Cattle units cut for carry system in the 16 farms		Average cattle units for cut and carry system
5	6	6
Cattle units for pasture grazing system in the 16 farms		Average cattle units for pasture grazing system
0	0	0
Farm Type 3-HRE		
Simulated	**Observed**	**Observed**
Average maize area per farm in the 16 farms (ha)		Average maize area
3.3	3.6	4.6
Cattle units cut for carry system in the 16 farms		Average cattle units for cut and carry system
0	0	4.5
Cattle units for pasture grazing system in the 16 farms		Average cattle units for pasture grazing system
12	8	12