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Abstract

Context

Typologies are widely used to tailor management practices to structural farm households, and to identify recommendation domains. However, it has often been shown that the recommendations are not followed by farmers, especially in the agricultural context of sub-Saharan Africa.

Objective

We aimed to identify links between a typology based on the structure of farm households and a typology based on farmers' management practices adopted by farmers in the Sudano-Sahelian zone of Burkina Faso.

Methods

We co-developed socio-economic and technical survey with agronomists and socio-economists and collected data on 291 smallholder farming households. We used principal component analysis, followed by hierarchical clustering to build two typologies: a farm household typology and a farm management typology and analyzed the link between the two.

Results and Conclusions

Our typologies distinguished 4 types of farm households and 3 types of farm management. Although we expected to find a dominant farm management type for each type of farm household, we show that the use of the typology is not sufficient to disentangle the intra-diversity of farm household types, as, except for large-scale cotton producers, of whom 94% fall in the mineral input user category, all the farmers do not use the same set of management practices. For instance, 29.5% of medium-scale cotton-based farm types do not match the "mineral input users" type, but are characterized by their use of mulch and cereal-legume crop rotation. Based on our empirical data, we show that promoting a basket of options (a set of management practices) based on a typology of farm household structure may not always be appropriate. Moving from theory (i.e. use of typology to define 'best fit') to practice (i.e. collecting data on actual agricultural practices), we show that using a combined typology approach will reveal matches and mismatches when practices are tailored to a given farm type.

Significance

In addition to using a farm household typology to tailor practices, we also define a limited set of locally relevant variables that are representative of the diversity of farmers' practices.

Keywords: systems agronomy; agricultural practices; sustainable intensification; typologies; West Africa

1 Introduction

The expressions "no silver bullet", "no one size fits all", "tailored approach", are commonly used by the scientific community to avoid blanket approaches when encouraging sustainable intensification practices (integrated soil fertility management, agroforestry, conservation agriculture) in sub-Saharan Africa (SSA) (Descheemaeker et al., 2019; Nelson et al., 2019). Even so, it is challenging to design and promote sustainable intensification practices that take the complexity of farming systems into consideration, i.e., that find the right balance between a detailed description of farming systems and broad recommendations based on specific socio-ecological characteristics. The challenge is particularly acute in sub-Saharan Africa (SSA), where farming systems are very diverse as a consequence of (i) contrasted livelihood strategies and socio-economic situations and (ii) heterogeneous biophysical contexts (Vanlauwe et al., 2019). The livelihood diversification of households in SSA is wide ranging (Alobo Loison, 2015), as is their land use and labor availability (Kuivanen et al., 2016), and their land tenure status (Lentz, 2005), all of which are reflected in their household strategies to improve their living conditions (Berre et al., 2017; Van Dijk et al., 2017).

Salient differences in rainfall regimes and temperature help distinguish two of the main systems: sorghum and millet-based systems in the north of Burkina Faso, and maize and cotton-based systems in the south. The socio-economic context also differs across Burkina Faso and reflects the history of farming systems in each region. For instance, farming systems in the cotton basin are impacted by the local cotton company's credit scheme, which gives farmers access to mineral fertilizer at the beginning of the cropping season, and which is also used for the other crops (mostly maize) grown in rotation with cotton (Gray, 2005; Ripoche et al., 2015 for similar case in Mali; Traoré, 2020).

Taking this diversity into account is therefore essential to avoid recommending sustainable intensification practices that do not match household needs and context. Typologies built on resource endowment and production goals (i.e. structural typologies) are analytical tools that can cope with such diversity by explicitly highlighting the potential and the limitations of farms in adopting innovative technologies (Jain et al., 2009; Giller, 2013; Riveiro et al., 2013). Typologies have long been used in agriculture-related studies (Jollivet, 1965) to identify groups of farmers with shared characteristics, and to design agricultural policies, support programs (Landais, 1998), and to identify recommendation domains (Descheemaeker et al., 2019). More recently, Alvarez et al. (2018) argued for their usefulness in capturing farm diversity specifically to target ad-hoc technologies for groups of farmers. To reach its objective of identifying "best fits" between a "basket of options" and farmers' resources (labor, land, cash, etc.), systems agronomy has developed typologies based on resource endowment and farmers' production orientation. These typologies are used to tailor a set of management practices or a basket of options, and to increase their adoption rate (Giller et al., 2015).

Even though the usefulness of typologies to tailor recommendations is undeniable, Giller et al. (2009) also argued that for appropriate adoption of conservation agriculture, not only resource endowment, but also ecological constraints such as competing uses for crop residues, or weed pressure, have to be taken into account.

The objective of the present study was to investigate whether there is a link between a farm household typology (based on resource endowment and production goals) and farmers' actual practices captured in a typology. We hypothesize that the farm household types are disconnected from types of management practices. First, we present the methodology used to collect data on households and their agricultural practices (section 2). We then present our results (section 3) (i) by presenting the farm household and farm management typologies, and (ii) by analyzing the link between the two typologies. Lastly, we draw conclusions from our empirical evidence and discuss more globally sustainable intensification in the region (section 4).

2 Material and methods

2.1 Study area

The study was carried out in the province of Tuy in the region of Haut-Bassins in western Burkina Faso. The main activity in the province is smallholder rain-fed agriculture, especially cotton and maize. Cotton plays a key role in the farming systems in the region, not only in terms of land use but also in terms of input use, as farmers obtain fertilizers from the local cotton company at the beginning of the cropping season. The growing season lasts from April to November, with most annual rainfall (about 1,000 mm) falling between July and September. Thanks to this high rainfall, other crops, notably legumes (groundnuts, soya beans, cowpeas), can also be grown in the rainy season. Rain-fed crops are harvested between October and January, while horticultural crops (vegetables, mango) are cultivated and harvested in the dry season from January to May. Most agricultural plots include trees, some species of which can provide food, and most farms raise animals (cattle and small ruminants). Many households also pursue off-farm activities including trade, service jobs or crafts. The presence of gold in the area offers jobs either through the industrial gold mining site in Houndé (the capital city of Tuy) or at numerous clandestine sites.

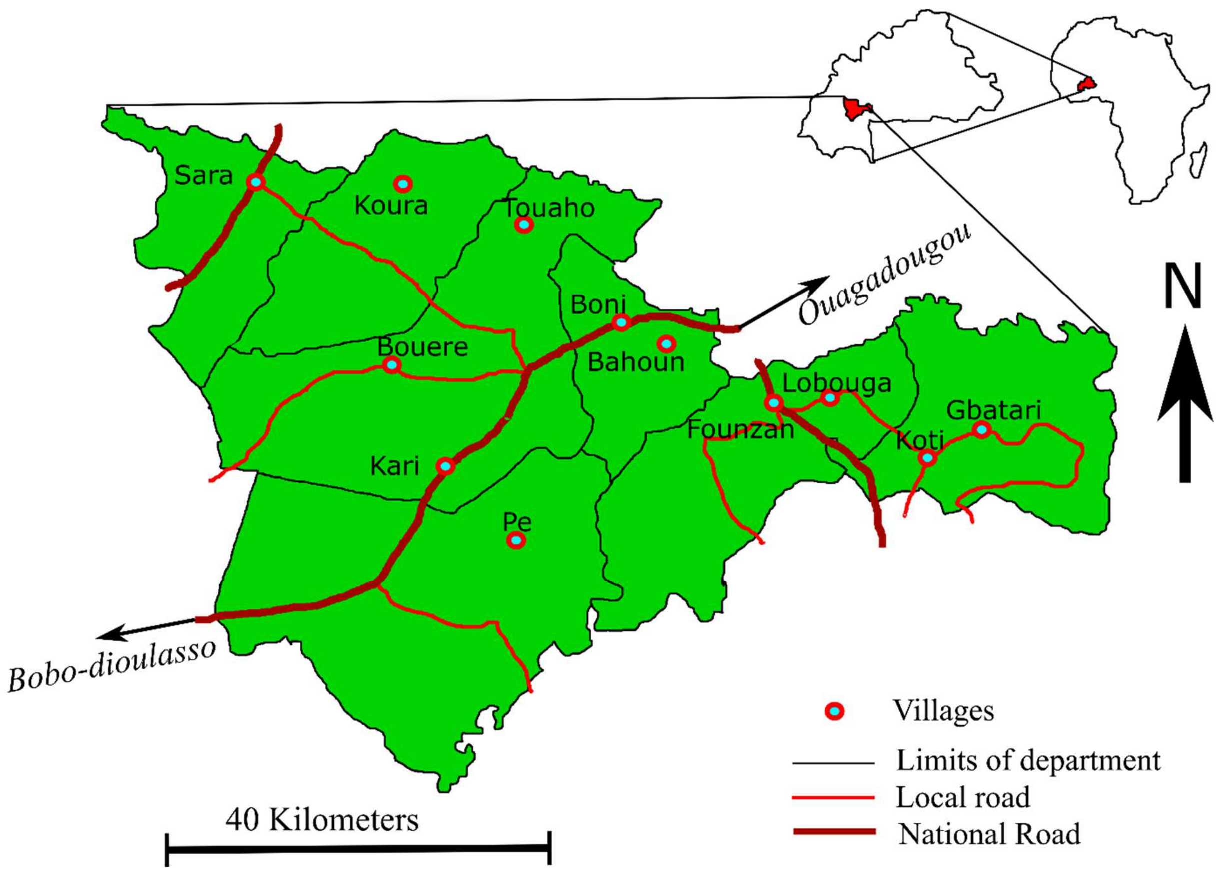

Figure 1: Map of Tuy province (main roads in red) in Burkina Faso and villages surveyed in the province

2.2 Data collection

The heads of 300 smallholder households were interviewed to collect information on farm household resource endowment (total cropped area and area under the different crops, household composition, the number of animals owned) and agricultural practices. These data were collected in two different surveys of the same sample of households, one to collect information on the household resource endowment, and the other information on the management practices used by the same household.

Household data were retrieved in a survey carried out in the framework of a longitudinal nutritional survey that started in October 2017 and ended in September 2018 so as to include a whole agricultural season, i.e., from grain harvest in 2017 to grain harvest in 2018. All the participants gave their informed consent to take part in the study. Participants were selected using a three-stage sampling method. First, 12 villages in Tuy province were selected randomly (Figure 1). Second, in each village, three households were randomly selected as "departure points" for walking itineraries. Third, from these starting points, we applied a random-route method to select the households to be surveyed (25 per village, giving a total of 300).

As data on agricultural practices were not collected during this survey, we conducted a specific survey (available with the data) on this topic. The same 300 households were surveyed in October-November 2018. Data were collected by a team of nine trained enumerators who were managed by three field supervisors and by the field coordinator. As we had to discard nine surveys due to lacking or inconsistent data, we finally analyzed data collected from 291 smallholder households.

2.3 Dataset and methodology used to build the typologies

We built a household typology using nine variables derived from the household survey (table 1). We included variables such as adult equivalent per cultivated area or tropical livestock unit (TLU) per cultivated area to avoid a typology only driven by farm size. We also used some functional variables (i.e. crop yield, crop allocation) to briefly describe each type.

Table 1: Variables used for the farm household typology

Variables	Description	Units
Land cultivated	Total cultivated area	ha
Land allocated to cotton	Land allocated to cotton	%
Land allocated to legume	Land allocated to legume	%
AE	Adult equivalent*	Unit
Ox	Number of oxen	Unit
AE per land cultivated	Adult equivalent per ha	$AE.ha^{-1}$
Income per AE	Income per adult equivalent	$FCFA.AE^{-1}$**
TLU per land cultivated	Tropical livestock unit	$TLU.ha^{-1}$
Simpson Index ***	Indicator based on crop diversity	-

** calculated according to the Oxford scale (OECD, 1982);*
***FCFA: Francs of the Financial Community of Africa;*
**** calculated according to (Simpson, 1949)*

To account for the diversity of actual farmers' practices, we first defined variables according to four main pillars: input management, agroforestry, crop-livestock integration, and soil management. Relying on four pillars enabled us to account for the specificities of the Sudano-Sahelien context, where the use of inputs is still an important factor in allowing smallholder farmers to escape poverty trap (Tittonell and Giller, 2013). Also, because all the farmers in the study area grow trees on their farm (Koffi et al., 2017) it was important to include tree density and diversity in our analysis. Crop-livestock integration is an integral part of the mixed farming systems we were studying in the study area (Vall et al., 2006). The fourth pillar (soil management) represents soil and water conservation management practices, measures that are promoted in Burkina Faso to support the rehabilitation of degraded land (Nyamekye et al., 2018).

For each household, we calculated 12 variables (Table 2) according to the framework based on the four pillars described above. Plot level variables were calculated using survey data (Table 2). We first drew up an inventory of all the plots on the farm and the farmers gave us an estimate of their surface area. Using the inventory of the plots, we aggregated the data at farm level, determining the percentage of farmland allocated to a specific practice.

For the crop-livestock integration component, we estimated the manure application rate per ha. Total organic fertilizer applied on crops ($\sum_{i=1}^{n} Norg_i$) is based on both manure applied by farmers (manure purchased or collected from their own stalls), and on manure deposited directly by animals during free grazing. The total quantity of manure applied by the farmers was calculated by multiplying the number of local units (cartloads) given to us by the farmers during the survey by the mean quantity per cartload based on local expertise. The total quantity of manure applied directly by animals was based on a daily excretion rate of 2.5 kg of dry matter divided by the proportion of time the animal spent feeding in the stall versus free grazing. The daily excretion rate is based on a potential ingestion of 6.25 kg of dry matter per livestock unit multiplied by a mean digestibility of local feeding resources of 40% (Guérin et al., 1986). The N content of the different types of organic fertilizer was based on the literature (Snijders et al., 2009; Audouin et al., 2015). From this information, we calculated the proportion of land on which animal manure was applied ($\%Land\_Norg, Equation$ 1), the maximum rate of animal manure applied ($MaxNorg, Equation$ 2) and the proportion of N applied as animal manure ($\%Norg$, Equation 3, we also explored the indicator 'Total N organic applied on farm land', but it was highly correlated with the proportion of N applied as animal manure so we decided to remove it from the analysis):

$$\%Land\_Norg = \sum_{i=1}^{n} plot\_size\_OrgN_i \Big/ Land\_cultivated \qquad \text{(equation 1)}$$

where, for a given household, $plot\_size\_OrgN_i$ is the surface area of field i where manure is applied, n is the number of plots where manure is applied, and $Land\_cultivated$ is the sum of all plots cultivated with and without manure applied.

$$MaxNorg = \max(Norg\_rate_1, \ldots, Norg\_rate_n) \qquad \text{(equation 2)}$$

where, for a given household, $Norg\_rate_1$ is the manure application rate for plot 1, and n is the total number of plots.

$$\%Norg = \frac{\sum_{i=1}^{n} Norg_i}{\sum_{i=1}^{n}(Nmin_i + Norg_i)} \qquad \text{(equation 3)}$$

where, for a given household, n is the number of plots on the farm, $Norg_i$ is the total organic fertilizer applied on plot i, and $Nmin_i$ is the total mineral fertilizer applied on plot i.

For the agroforestry pillar, we noted the tree species ($Tree\_species_i$), and number of trees per plot (n) on each farm. From this information, we derived the density of trees on the farmed land (excluding orchards, such as mango orchards) ($Tree\_density$, equation 4) and the number of tree species on the farm ($N_{Tree\_species}$, equation 5).

$$Tree\_density = \sum_{i=1}^{n} tree_i / Land\_cultivated \qquad \text{(equation 4)}$$

where, for a given household, $tree_i$ is the number of trees in plot i, n is the total number of plots, and $Land\_cultivated$ is the surface area of all plots with or without trees.

$$N_{Tree\_species} = \sum_{i=1}^{n} Tree\_species_i \qquad \text{(equation 5)}$$

where, for a given household, $tree\_species_i$ is the number of tree species in plot i, and n is the total number of plots.

For variables related to the management of inputs at the farm level, we collected information on plots where a legume crop (cowpea, groundnut, soybean) was cultivated (either intercropped or in rotation), the number of plots that were fertilized (and amount and type of fertilizers) and that were treated with herbicide. The following variables were derived (equations 6-9):

$$\%Land\_Nmin = \sum_{i=1}^{n} plot\_size\_MinN_i / Land\_cultivated \qquad \text{(equation 6)}$$

where, for a given household, $plot\_size\_MinN_i$ refers to the size of plot i where mineral fertilizer was applied, n is the total number of plots where mineral fertilizer was applied, and $Land\_cultivated$ is the surface area of all plots with or without mineral fertilization.

$$Max\_Nmin = max(Nmin_{rate_1}, \dots, Nmin_{rate_n}) \qquad \text{(equation 7)}$$

where, for a given household, $Nmin_{rate_1}$ refers to mineral fertilization rate (kg.ha^{-1}) in plot 1, and n is the total number of plots.

$$\%Land\_Herb = \sum_{i=1}^{n} plot\_size\_herb_i / Land\_cultivated \qquad \text{(equation 8)}$$

where, for a given household, $plot\_size\_herb_i$ refers to the size of plot i where herbicide was applied, n is the number of plots where herbicide was applied, and $Land\_cultivated$ is the surface area of all the plots with or without herbicide application.

$$\%Land\_Leg = \sum_{i=1}^{n} plot\_size\_leg_i / Land\_cultivated \qquad \text{(equation 9)}$$

Where, for a given household, $plot\_size\_leg_i$ refers to the size of plot i planted with legume, n is the number of plots planted with a legume, and $Land\_cultivated$ is the surface area of all the plots with or without legumes.

Finally, for soil management practices, we calculated the percentage of plots where soil and water conservation practices (i.e. zaï- a farming technique consisting in digging pits in the soil during the preseason to catch water and concentrate compost, stone bunds, grass strips, living hedges) were applied, where mulch was left on the ground, and where no tillage was practiced, according to the following variables (equations 10-12):

$$\%Land\_till = \sum_{i=1}^{n} plot\_size\_till_i / Land\ cultivated \qquad \text{(equation 10)}$$

where, for a given household, $plot\_size\_till_i$ refers to the size of plot i where tillage is implemented, n is the number of tilled plots, and $Land\ cultivated$ is the surface area of all the plots with or without tillage.

$$\%Land\_watman = \sum_{i=1}^{n} \mathrm{plot\_size\_watman}_i / Land\ cultivated \qquad \text{(equation 11)}$$

where, for a given household, $plot\_size\_watman_i$ refers to land size of plot i where water management practices are implemented, n is the number of plots where water management practices are implemented, and $Land\ cultivated$ is the surface area of all the plots with or without water management practices.

$$\%Land\_mulch = \sum_{i=1}^{n} plot\_size\_mulch_i / Land\ cultivated \qquad \text{(equation 12)}$$

where, for a given household, $plot\_size\_mulch_i$ refers to the size of plot i where mulch is implemented, n is the number of plots where mulch is implemented and $Land\ cultivated$ is the surface area of all the plots with or without mulching.

Table 2: Variables used for the farm management typology

Pillar	Variables	Description	Unit
Crop-livestock integration	Land receiving organic fertilizer	Proportion of land where animal manure was applied	%
	Max. organic input rate	Maximum rate of animal manure applied (irrespective of the crop)	kg.ha-1
	N applied as organic fertilizer	Proportion of N applied as animal manure (versus mineral)	%
Agro-forestry	Tree density on land	Tree density on land (excluding orchards)	N° of tree.ha-1
	Number of tree species	Number of tree species	
Input management	Land receiving mineral fertilizer	Proportion of land where mineral fertilizer was applied	%
	Max. mineral input rate	Maximum rate of mineral input applied (irrespective of the crop)	kg.ha-1
	Land receiving selective herbicide	Proportion of land treated with selective herbicide	%
	Land under legume crop	Proportion of land with a legume crop (soybean, cowpea, groundnut)	%
Soil management	Land under no till	Proportion of land under no till	%
	Land SWCM	Proportion of land with Soil and Water Conservation Management (SWCM) practices	%
	Land receiving mulch	Proportion of land with mulch	%

2.4. Analytical framework

We built two typologies, one using farm household structure variables (Table 1) and the other using variables representative of management practices (Table 2). For both datasets, we used a two-step statistical approach to build our typologies. First, a principal component analysis (PCA) identified the most discriminant variables to summarize the diversity of the sample in a few first principal components (data- or dimension-reduction process). Second, we performed a hierarchical clustering (HC) analysis on these components to divide our samples into statistically distinguishable types (Alvarez et al., 2018; Berre et al., 2019). We used the Ward algorithm to find compact, spherical clusters. The number of clusters was defined using the dendrogram showing the decrease in the dissimilarity index according to the number of clusters. Both PCA and HC were implemented in R (3.0.0, R Development Core Team, 2005) using the ade4 package (Thioulouse et al., 1997).

Next, we analyzed links between a given household and its associated practices. We first linked the two typologies with an alluvial diagram (R package ggalluvial) (Brunson, 2018), which made it possible to see the proportion of each farm household type that applied a certain set of practices, defined according to our farm management typology. We then analyzed Pearson's correlation among the farm household variables and the farm management variables (R package ggcorrplot, (Kassambara, 2016). Finally, to check for the potential prevalence of some practices or sets of practices among specific farm types, we tested the significant differences using a non-parametric Kruskal Wallis test for each farm management variable according to the type of farm household.

3 Results

3.1 Farm household typology

Figure 2 a, c, and e show the discriminant variables that distinguished the four types of farm households shown in Figure 2b and d. The three first components of the analysis explained 61% of the overall diversity of the household sample. The first component was related to land availability and distinguished farm households with more cultivated land from farm households subject to high land pressure (high adult equivalent per hectare). The second principal component revealed a gradient based on livestock density i.e., farm households with a high livestock density and larger number of oxen (Figure 2a and 2e). The third gradient was linked to crop diversity and contributed information supported by principal component three (Figure 2e). In Figure 2c, the gradient is characterized by farm households with a high Simpson index, a large proportion of land allocated to legumes in the lower part of the graph, and farm households that allocated a large proportion of their cultivated land to cotton in the upper part.

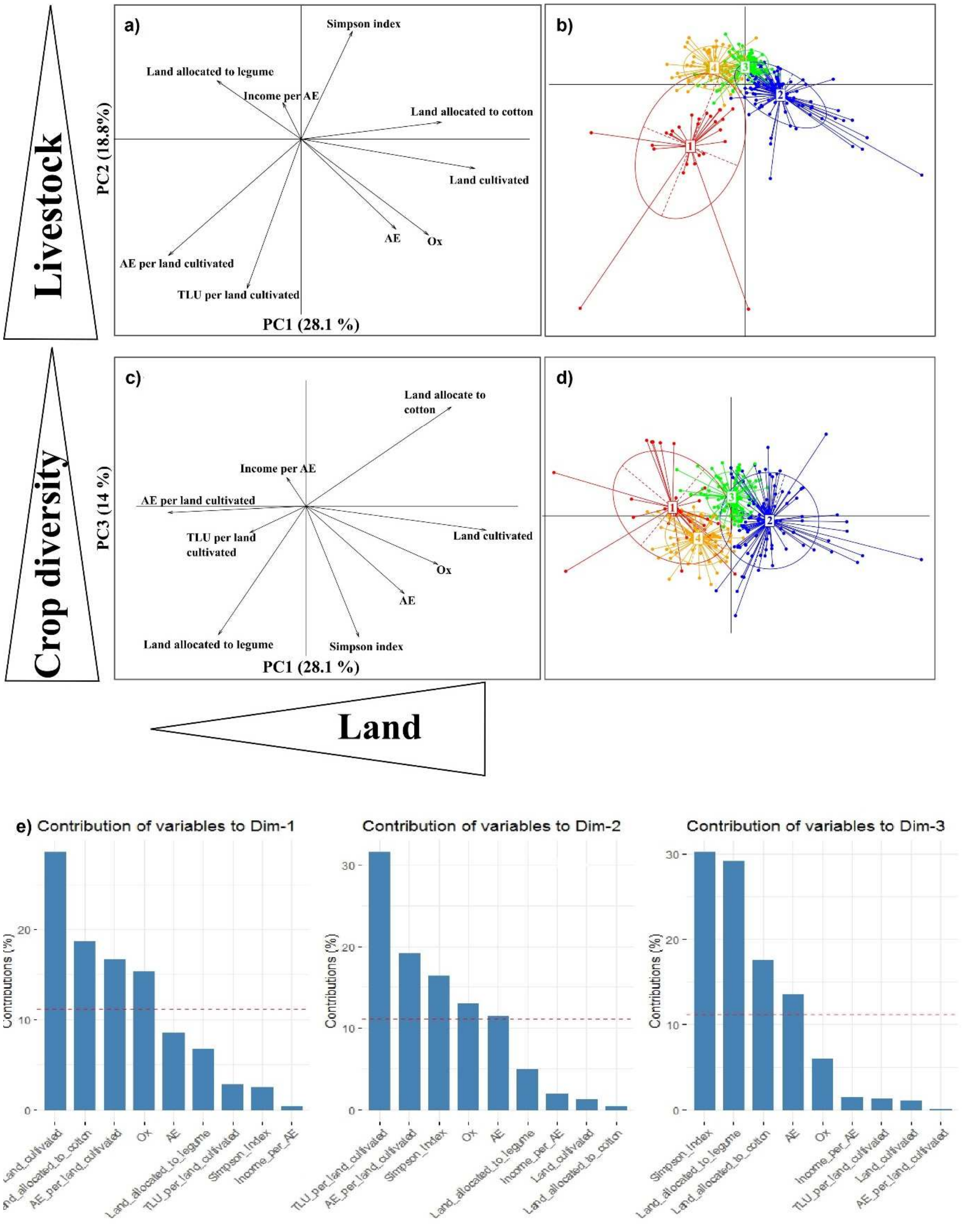

Figure 2: Representation of the farm household types based on principal component analysis and hierarchical clustering. The arrows on the left represent the most influential variables for PC1 (horizontally) and PC2 and PC3 (vertically), and the circles and dots on the right represent the projection of farms according to their type. The PCA1-2-3 loadings are presented. The red dashed line indicates the expected average contribution if all variables

contribute equally to the component : 100% contribution divided by the total number of variables available in the dataset, here 100/9=11.11%.

By combining the information in table 3 with the typology, it is possible to briefly describe four types of farm households distinguished by the PCA and hierarchical clustering:

- **Smallholder farmers under land pressure (type 1, n=28)**: With 2.1 ha and 7.5 adult equivalents in the household, this type of farmer is under land pressure (4.5 adult equivalents per hectare) and allocates a small share of cultivated land to cotton and legumes. The number of oxen and tropical livestock units per hectare is high compared to the other farm types, pointing to a higher organic input potential. Variables not used in the typology (listed in table 3) reveal that this type includes the smallest number of farmers who grow groundnuts, and that 75% of the groundnuts they produce are self-consumed. The maize yield is lower than in the other farm types.
- **Large households with a cotton-based farming system (type 2, n=100):** Type 2 is characterized by large cultivated area and a large household, respectively 15.3 ha and 11.3 adult equivalents. They allocate 45% of their cropland to cotton, the highest proportion among the four types of farm households. Finally, Type 2 farmers obtain the highest yield of maize with 1,414 kg ha^{-1} compared to other farm household types. Livestock density is low, but these farmers nevertheless own more than five oxen and thus benefit from animal traction.
- **Medium-size cotton-based farming system (type 3, n=95):** Type 3 is also characterized by cotton-based farming systems (like farm type 2) with 40% of land allocated to cotton. But, compared with farm type 2, type 3 households are smaller with only 6.6 ha and 4.3 adult equivalents. Livestock density is low (0.5 total livestock unit per hectare) and these farmers own fewer than two oxen.
- **Legume producers under land pressure (type 4, n=68):** Type 4 is characterized by 22.4% of cultivated land allocated to legumes (i.e. cowpea, groundnut, soybean). This farm type had the highest proportion of groundnut producers (87%), but the lowest self-consumption of groundnuts, indicating a strategy to sell this crop. Livestock density is low and these farmers own fewer than two oxen.

Table 3: Main characteristics of the four farm types identified in the farm household typology. +/- indicates standard error

		1 (n=28)		2 (n=100)		3 (n=95)		4 (n=68)	
Variables used for the typology	Land allocated to cotton (%)	5.5	±12.4	44.9	±19.5	40.2	±17.7	7.3	±13.1
	Land allocated to legume (%)	7.2	±19.3	7.5	±8.1	6.5	±5.8	22.4	±12.0
	Land cultivated (ha)	2.1	±1.5	15.3	±9.6	6.6	±3.2	4.1	±2.6
	Adult equivalent	7.5	±4.9	11.3	±6.1	4.3	±1.6	5.3	±2.3
	N° of oxen	2.9	±5.7	5.4	±3.6	1.8	±1.4	1.9	±1.9
	Adult equivalent per ha	4.5	±2.9	0.9	±0.6	0.8	±0.5	1.6	±0.9
	TLU per ha	4.9	±5.6	0.9	±0.9	0.5	±0.4	1.0	±0.7

	Income per adult equivalent	1545 ±2316	1999 ±7140	3425 ±5783	4351 ±6674
	Simpson Index	0.4 ±0.2	0.6 ±0.1	0.6 ±0.1	0.7 ±0.1
Other variables of interest*	Age	48.1	46.2	40.2	42.8
	Groundnuts self-consumed (%)	75 (43%)	64.5 (79%)	55.4 (68%)	54.2 (87%)
	Yield of maize (kg.ha^{-1})	808 (85%)	1414 (100%)	1122 (97%)	1149 (88%)
	Yield of cotton (kg.ha^{-1})	694 (18%)	706(92%)	654 (83%)	703 (29%)

**In parentheses, percentage of farm households that cultivate the crop*

3.2 Farm management typology

Figure 3 shows the three types of farm management distinguished by principal components 1 and 2, which together explain 34% of total diversity (component 3 was explored but did not contribute any additional information).

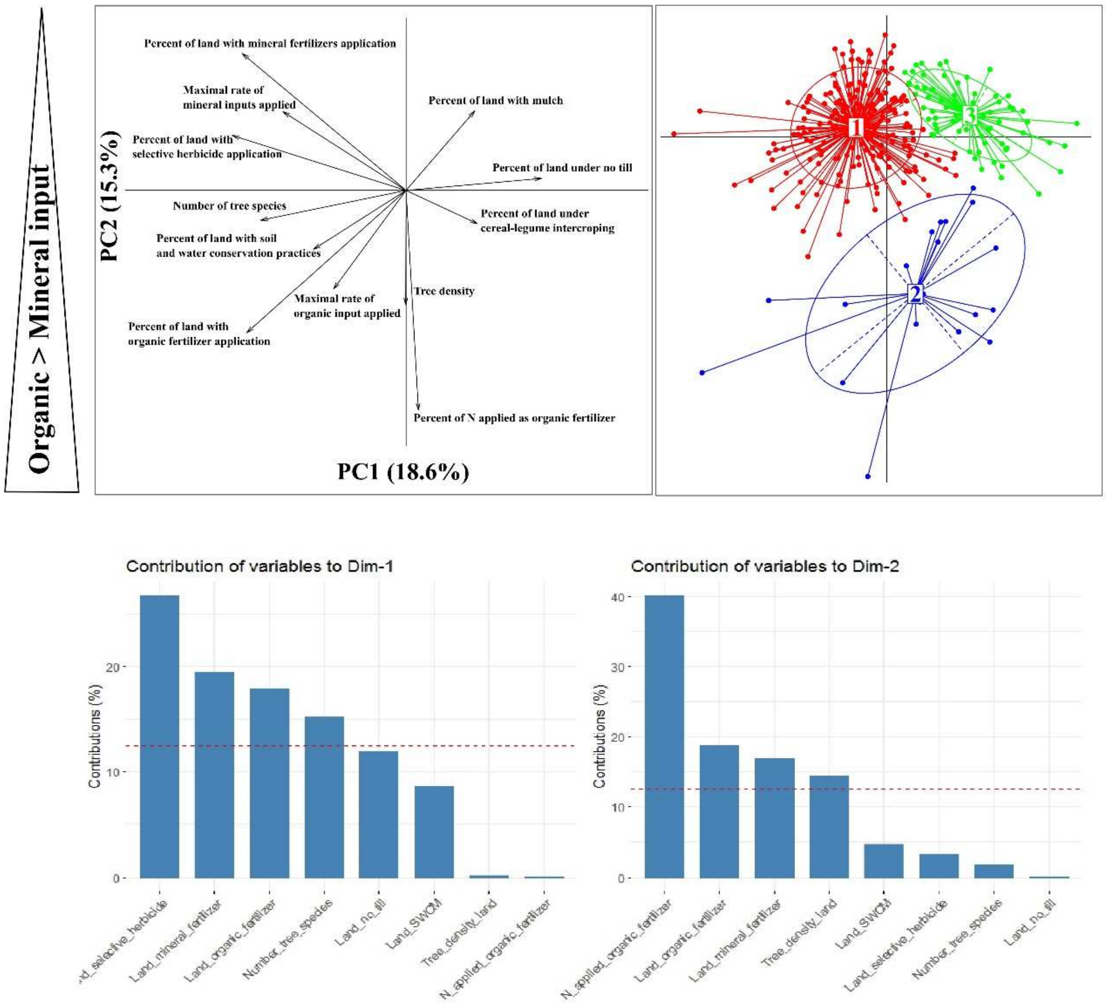

Figure 3: Representation of the farm management types based on principal component analysis and hierarchical clustering. The arrows on the left represent the most influential variables for PC1 (horizontally) and PC2 (top and bottom circle, respectively), and the circles and dots on the right represent the projection of farms according to their type of practice. The PCA1-2 loadings are

presented. The red dashed line indicates the expected average contribution if all variables contribute equally to the component.

Table 4 summarizes the main variables from the agricultural management survey according to each set of practices. Combining this information with the typology made it possible to briefly describe three farm management types distinguished by the PCA and hierarchical clustering:

- **Mineral input users (type 1, n = 202):** Type 1 is characterized by the input management pillar of our framework, with the highest proportion of land where herbicide and mineral fertilizer are used (at an average maximum rate of 161 kg.N ha^{-1}) and the smallest proportion of land allocated to legume crops. This type groups farmers with a relatively high proportion of land under mulch (41%) or who apply soil and water conservation practices on 20% of their land.
- **Manure users and high tree density (type 2, n=21)**: This farm management type is associated with two main pillars of our framework: crop-livestock integration, and agroforestry. Farmers belonging to this farm management type can be defined as having a high proportion of their land receiving organic fertilizer and plots with a high tree density. Despite the high tree density, no-till practices are only used in 10% of their plots. In terms of inputs, they use mineral fertilizers on only 14% of their land at an average maximum rate of 49 kg.N ha^{-1}. They leave mulch on 29% of their land and grow a legume crop (either inter-cropped or in rotation) on 17% on their land.
- **Cereal-legume rotation and mulch users (type 3; n=68)**: Type 3 is characterized by a soil management pillar with more than half their land under mulch and 39% of their land is no till. They apply mineral fertilizer to 40% of their plots at an average maximum rate of 92 kgN.ha^{-1}. Their land has the lowest tree density, and they apply little organic fertilizer on their land, but have the highest proportion of plots allocated to legume crops.

Table 4: Main characteristics of the three farm management types identified in the farm management typology. +/- indicates standard error (SWCM : Soil and Water Conservation Measures)

SI pillars	Variables	Unit	1 (n=202)	2 (n=21)	3 (n=68)
Crop-livestock integration	N applied as organic fertilizer	%	7 ±7	64 ±35	3 ±5
	Land receiving organic fertilizer	%	29 ±26	47 ±32	4 ±9
	Max. organic input rate	kg.ha^{-1}	10 ±19	53 ±136	2 ±5
Agroforestry	Tree density	tree/ha	8 ±7	14 ±13	6 ±4
	N° of tree species	unit	3 ±2	3 ±2	2 ±1
Input management	Land receiving mineral fertilizer	%	70 ±26	14 ±22	40 ±31
	Max. mineral input rate	kgN.ha^{-1}	161 ±103	49 ±68	92 ±61
	Land receiving selective herbicide	%	75 ±31	41 ±46	35 ±36
	Land under legume crop	%	11 ±16	17 ±24	22 ±28
Soil management	Land under no till	%	6 ±16	10 ±26	39 ±40
	Land under SWCM	%	20 ±28	17 ±33	4 ±15

Land under mulch	%	41	±32	29	±28	62	±35

3.3 Link between farm household types and farm management types

Figure 4 shows the connection between farm household types and the farm management types. There is a link between large households with cotton-based farming systems and the farm management types, as 94% of this group belong to the mineral input users type. The medium-size cotton-based farming system type is also characterized by a large proportion of households who use mineral inputs (67.4%) and a significant share of cereal-legume rotation and mulch users (29.5%). Less than 50% of the two other farm household types belong to the farm management type mineral input users (45.6% and 46.4% respectively, for legume producers and smallholder farmers). We found a positive correlation between land receiving mineral fertilizer and land allocated to cotton (0.68, figure S1). Figure 5 shows similar trends, i.e., the two cotton-based farming systems (types 2-3) have similar levels of variables representative of the input management pillar (high level of input use), and the crop-livestock integration pillar (low level). However, 29.5% of medium-size cotton-based farming systems also leave some mulch on their fields and implement cereal-legume rotation. Medium-size cotton-based farming system used soil management practices in the form of no-till and use mulch on a higher proportion of their land than large households with a cotton-based farming system.

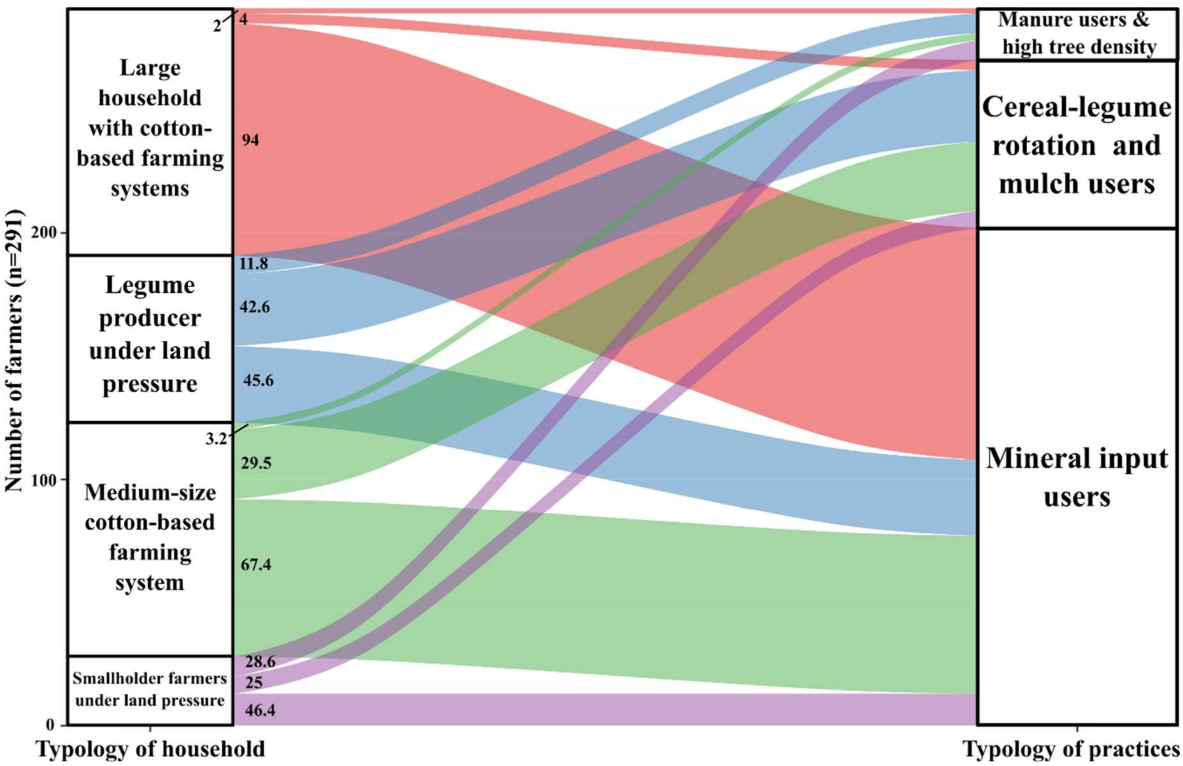

Figure 4: Link between farm household and farm management types

Smallholder farmers and legumes producers under land pressure used a more balanced share of practices. Respectively, 25.0%, 28.6%, and 46.4% of farmers belonging to the “smallholders under land pressure” type, corresponded to the farm management types cereal-legume rotation, manure user, and user of mineral inputs. In comparison, 42.6%, 11.8%, and 45.6% of the farmers belonging to the “legume producers” type correspond to the farm management types cereal-legume rotation, manure user, and mineral input users, respectively. Hence, almost half the smallholders under land pressure, and legume producers use mineral inputs. Figure 5 also shows that "smallholder farmers under land pressure" have a higher tree density and apply N in the form of organic fertilizer. Smallholder farmers under land pressure used significantly less selective herbicide as confirmed by the negative correlation between adult equivalent per hectare and percentage of land with selective herbicide (-0.3, figure S1). Figure 5 shows that 'legume producers' have proportionally more land under cereal-legume rotation and use less inputs (selective herbicides and mineral fertilizer).

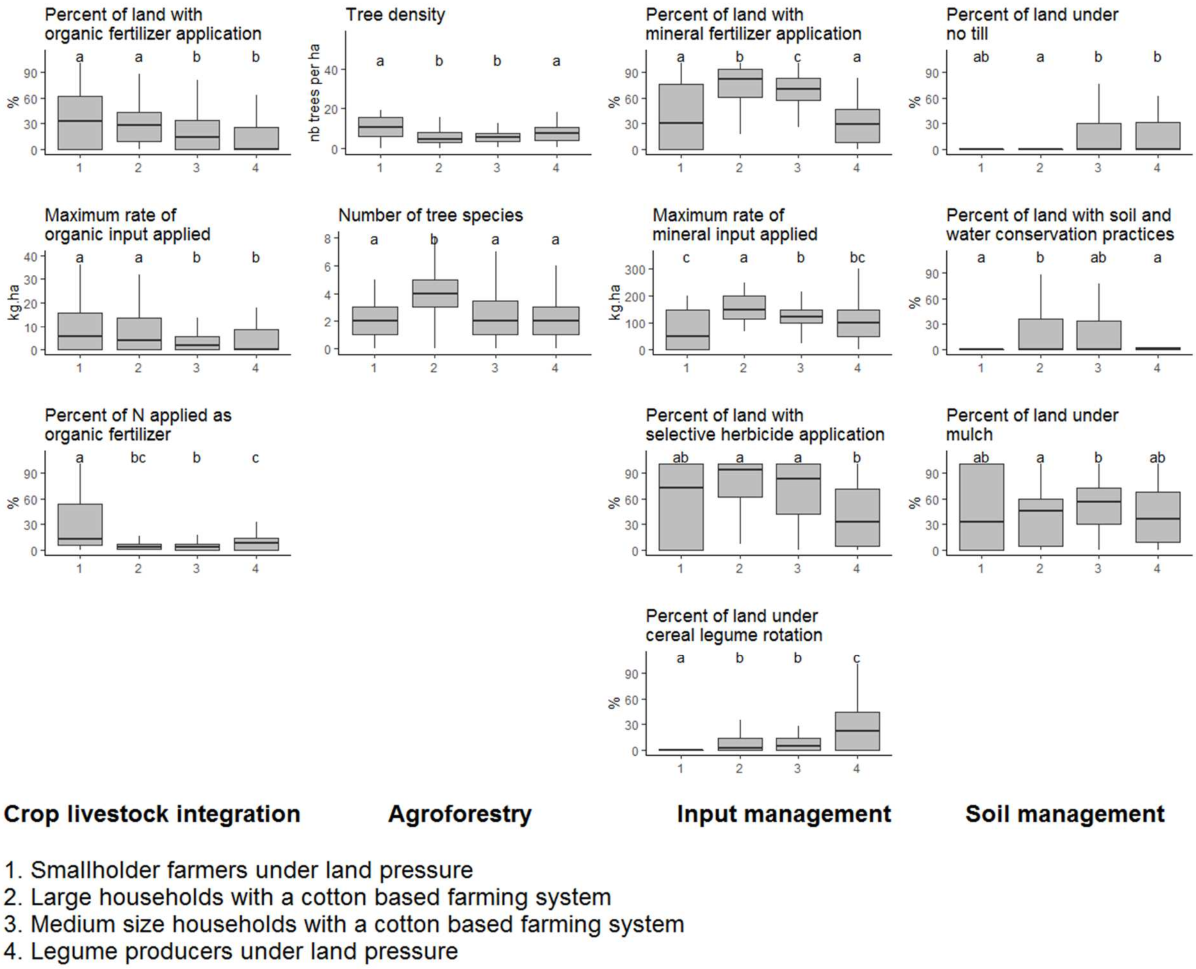

Figure 5: Boxplot for each sustainable intensification practice indicator (see table 2 for units) according to our four pillars for the four farm household types. The upper and lower edges of the boxes indicate the 75^{th} and 25^{th} percentiles, the horizontal line in each box indicates the median, whiskers below and above the box indicate the 10^{th} and 90^{th} percentiles. Within each sustainable intensification practice indicator, means of boxes with the same letter are not significantly different at $P < 0.05$ in pairwise comparisons (Kruskal Wallis and Dunn's test).

4 Discussion

4.1 Prudence in tailoring management practices to farm household types

The typologies revealed drivers of diversity in household types and their agriculture practices. The farm household typology revealed the main structural variables that influence farming system diversity in the region, i.e. land use and the proportion of land under cotton, and the contrasted level of crop-livestock interaction (Figure 2), in agreement with results reported in the literature (Vall et al., 2006; Diarisso et al., 2015). The farm management typology revealed contrasted agricultural practices used to improve soil fertility with legume, manure, or mineral inputs. We aimed to connect the two typologies to reveal the strength of the link between a given farm type and its associated sustainable intensification practices. In doing so, we revealed that cotton production and its mineral input supply system, along with the gradient of crop-livestock integration, are key variables to understand the strength of the link between the type of household and its agricultural practices.

Cotton is the main cropping system in the region, with 70% of the households growing cotton. Farmers in the region are often cash-constrained and the credit scheme offered by cotton companies means they have access to fertilizer (Ripoche et al. 2015). Hence, the two farm household types with cotton-based farming systems have the highest proportion of farmers belonging to the farm management type 'mineral input users' (Figure 4), and they apply fertilizer to more land than farmers belonging to other types of farming systems (Figure 5). However, the farm management typology also revealed the widespread use of mineral inputs with 70% of the households using mineral inputs independently of the farm household type, showing that management strategies are partially dissociated from household types, as some practices are the result of wider scale drivers that affect all types of smallholder farmers. Indeed, it has been shown that, in sub-Saharan Africa, sustainable intensification of the systems depends on the use of fertilizer to increase smallholder farmers' crop productivity (Adam et al., 2020; Vanlauwe et al., 2014).

Regarding crop-livestock integration, the farm household typology also reveals varying degrees of crop-livestock integration in the region as a strategy to cope with land pressure and difficult access to a supply of animal feed (Vall et al 2006). Livestock density ranged from 0.9 to 4.9 $TLU.ha^{-1}$ between types. Farmers with a rather low $TLU.ha^{-1}$ compared to all the other farmers, seem to compensate for their limited supply of manure for use as fertilizer by implementing crop-legume rotation. In addition, their reduced need for feed for their small herd allows them to increase soil fertility by leaving mulch on a larger proportion of their land. Further, we showed that the households under land pressure (smallholder farmers and legume producers under land pressure) did have a smaller proportion of mineral input users, due to their smaller share of land allocated to cotton production. We can thus assume that smallholder farmers with limited land favor the allocation of land to subsistence crops (e.g. maize, legume, sorghum) to the detriment of cotton. Indeed, the volatility of cash crop market is too hazardous for these risk-averse households which may prefer to ensure the basic nutritional need of the household with subsistence crops.

Farm household typologies are a widely used tool to help extension services, NGOs, government, and researchers to better target recommendation domains (Descheemaeker et al., 2019). Nonetheless, our two-typology approach identified problems concerning tailoring practices based on farm household types. Thanks to the farm household typology, we identified key discriminant variables of the farming systems. Some management practices were implemented by all household types (i.e. mineral inputs), because of the global need to intensify these systems already underlined by Adam et al. (2020) and Vanlauwe et al. (2014). Further, we identified a diversification of agricultural practices (more balanced distribution between the three types of farm management practices) by smallholders under land pressure. Our combined approach involving both data on household structure and basic agricultural practices indicators revealed matches and mismatches. Hence, rather than using a farm household typology, we suggest defining locally relevant key indicators to be used by extension services or NGOs to catalyze dialogue on tailored practices during national surveys in the agricultural sector, or research and development projects.

4.2 Combined typologies based on expert-based variables to reveal farm management drivers

Our study illustrates how difficult it is to connect a given household type to a given management type. Our demonstration of this difficulty reinforces the importance of the ‘options by context’ concept (Descheemaeker et al., 2019) which calls for tailoring management practices to the real-world heterogeneity of farmers’ circumstances. Developing farmer research networks (i.e. large-scale participatory research) to capture the diversity of farmers’ conditions could be a useful alternative strategy (Nelson et al., 2019). It would help gather information from a large number of farmers, and enable rigorous, democratized, and useful knowledge creation (Richardson et al., 2021). Farmer research networks offer an alternative solution between blanket recommendation based on household typology on the one hand (Berre et al., 2019), and qualitative studies focusing on singular case studies on the other hand (Ryschawy et al., 2019). These networks should encourage collaboration among different actors (i.e. farmers, extensionists, farmers, representative of local institutions) and help farmers to make informed choice on agroecological practices that they can adapt to their contexts (Richardson et al., 2021). As farmer research networks bring groups of farmers to the center of the research, it would facilitate an integration process that would help define locally relevant indicators to guide the recommendations of management practices that fit their particular contexts.

Using farmer research networks, we propose to combine farm household typologies with the use of locally relevant variables. The definition of these locally relevant variables appeared to be essential in our study by adding information on crop-livestock integration and legume production. Even if different methodologies are available to assess agro-ecological practices (Wezel et al., 2020; Chopin et al., 2021), the choice to conduct our analysis based on four locally-relevant pillars (crop-livestock integration, agroforestry, input management and soil management) was crucial to reveal this set of locally-relevant variables that focused on the key practices observed in the region.

4.3 Limits of the approach

Developing typologies using statistical analysis depends to a great extent on selecting the right variables for the analysis of the collected data (Berre et al., 2019). Principal component analysis (PCA) aims to reduce the dataset by combining multiple variables into a smaller number of `factors' or `principal components' (Alvarez et al., 2018). Ideally, variables to use as inputs in a PCA should be independent to avoid noise in the analysis and to better capture the variability in the dataset. However, in our study, we decided to rely on the definition of a framework based on four main pillars to define the farm management typology. Each variable was chosen to represent each pillar of our framework, and hence some variables are inter-related (e.g. the percent of N applied as organic fertilizer in the "crop-livestock integration" pillar is obviously correlated with the maximum rate of mineral input applied in the 'input management" pillar).

Further, we decided to focus our typology on the plot, hence variables that are important from a perspective beyond the plot scale were not included. For instance, in our study area, free grazing, a traditional practice allowing livestock owners to graze their animals on crop residues after harvest, has a major effect on practices such as leaving mulch on the ground in the field and on biomass flow at a larger scale than the farm scale (Berre et al., 2021). Other important farm level aspects also left out of our study were labor and off-farm activities (Falconnier et al., 2018). Including these components was beyond the scope of this study.

Another limitation of our study is the absence of a historic dimension, as we failed to capture farmers' strategies we would have captured using a more longitudinal dataset. We relied on a household survey that only provides a "snapshot" taken at a given point in time, whereas tailoring practices to a given farm type involves a moving target (Valbuena et al., 2015). Framing this in our local context, we can state that a more longitudinal approach could have explained the increase in crop-livestock integration in the region, e.g. cattle owners investing in crop production in reaction to severe drought in the region (Ayantunde et al., 2020). As a complement to the use of typology, we recommend collecting robust data over time to monitor and analyze changes over time.

5 Conclusion

We built one typology based on the structure of farm households and another based on farmers' practices that represent the diversity of agricultural practices used by farmers in the Sudano-Sahelian zone of Burkina Faso. By analyzing the links between these two typologies, we revealed the complexity of tailoring management practices to a specific farm household type. Even if farmers belonging to the 'cotton-based farming systems' type were significantly represented in the farm management type "mineral input users", mineral inputs were also widely used by the other farm household types. Further, we showed that the farm household types under land pressure applied more diversified management strategies, and that it was consequently difficult to use the farm household type to tailor management practices. Rather than using a farm household typology, we suggest that extension officers use farmer research networks to define locally relevant indicators that will help to better tailor practices to fit farmers' needs. Our study aimed to contribute to the theoretical debate in systems agronomy on the promotion of tailored technologies in a context of highly diverse farming systems in Sudano-Sahelian Burkina Faso. Beyond concepts and theoretical assumptions, the mismatch between household type and farm management type call for more research on the drivers of - and barriers to - sustainable intensification practices.

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This article is dedicated to the memory of Michel Havard.

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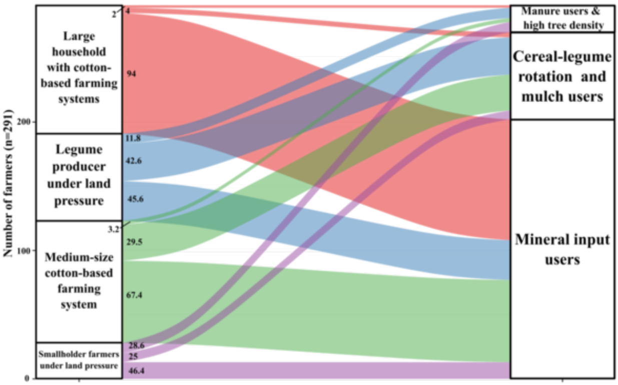
Socio-economic and technical dataset on 291 smallholders household

- Farm household data
- Locally-relevant indicators to decribe sustainable intensification practices (SIP)
- Connection between household type and SIP type is assessed

Typology of household

Typology of practices



Match...
Cotton producers were mainly input users due to the credit scheme of cotton cmopanies to

... and mismatch
29.5% of mid-size cotton producers used crop-legume rotation and minimize farm labor, while using less mineral inputs