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Integrated production functions for main crop fields in Pontieba, south-western Burkina Faso: Empirical estimations for efficiency assessment and further integrated modelling

Food security and better livelihoods for rural dryland communities

Integrated production functions for main crop fields in Pontieba, south-western Burkina Faso: Empirical estimations for efficiency assessment and further integrated modelling

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Abstract

Understanding efficiencies of the uses of major inputs for smallholder cropping systems such as labour and fertilizer under heterogeneous site conditions are important for sustainable intensification management and policy. The present study aims at estimating crop production in response to farming inputs and natural conditions of the cropping locations, and assess resource use efficiency based on the estimated production functions. The study was conducted in the village of Pontieba which presents all major agricultural livelihood typologies in the Ioba province of South-Western Burkina Faso. The Cob-Douglas production function was modified to couple variables reflecting soil-water condition of the cropping locations (GIS data) with data on crop management acquired through interviewing households, and then used for estimating elasticity coefficients of factors affecting yields. Besides main usual crop management-related drivers of crop yield (plot area (-), family labour (+) and mineral nutrient (+)) the results of the estimations showed that livestock endowment (+) and upslope contributing area of the cropping location (-) were the main drivers influencing crop yield response in smallholder farming systems of Pontieba. The estimated crop production functions showed that the labour and nutrient use efficiency are very low over fields of all crop types, implying that efforts to increase crop yield by intensifying inputs would not increase but may even decrease farmers' agricultural profits and net incomes. This suggests that solutions for solving the problem are converging to measures improving fertilizer use efficiency and return to labour before making more investment on increasing inputs. We also suggest directions and measures for increasing fertilizer and labour use efficiency in specific to major crop types.

Keywords: Sustainable Agricultural livelihoods, divers of agricultural yield response, decision making, semi-arid areas, integrated systems modelling, Burkina Faso

1. Introduction

Food security remains an important issue for many countries in the African dryland areas. The number of people suffering from undernourishment continues to increase in these countries (FAO, 2015). Most people in the drylands areas rely mainly on agriculture for their livelihood. In Burkina Faso for instance more than 80% of the population rely on agriculture for their food and their income. Up to 37% of rural households were food insecure in 2013 (SPCPSA, 2013) and 25% of the total population in the country was undernourished in 2011 - 2013 (FAO, 2013). The improvement of food security in particular and of livelihood in general depends mainly on the improvement of agricultural productivity.

Previous studies highlighted the need for sustainable intensification (Robinson et al., 2015; Thiombiano and Le, 2015b) as a way of ensuring sustainable food production. Garnett et al. (2013) stressed that sustainable intensification should ensure an improvement in crop productivity with attention on environmental sustainability. Farmers and policy makers need to be guided for identifying intensification pathways that improve productivity while ensuring environmental sustainability. This requires not only analysing for farming systems the underlying drivers of sustainable land management but also analysing factors influencing crop choice because of the linkage between crop choice and nutrient management practices. This process should be completed by identifying affecting factors of crop yield response for efficient use of production resources and for maximizing farmer crop productivity. Few studies exist in Sub Saharan African that conducted crop specific (and for several crops) analysis of management and biophysical factors influencing the yield response of in smallholder farms. There is a need to assess and better understand the current underlying drivers of yield response for informing policy decision making and for guiding farm design studies. The main objective of this study is therefore to identify and discuss drivers of agricultural yield response in the village of Pontieba.

2. Methods and materials

2.1. Study site

The present study was performed in the south-western Burkina Faso in the village of Pontieba located 11° 7' 0" North and 3° 7' 0" W. The village was chosen for this study because its farming community contains all fives typical smallholder livelihood types in

Ioba province identified by Thiombiano and Le (submitted). The village is situated in Ioba province close to Dano, the capital town of the province (see Fig.1). The south-western region belongs to the South-Sudanian climatic zone and is one the regions receiving more rains in Burkina Faso. However the rainfall is declining. From above 1,000 mm per year in the past, the region and the Ioba Province in specific has nowadays an average annual rainfall of 900-965 mm according to records from the provincial direction of the ministry of agriculture.

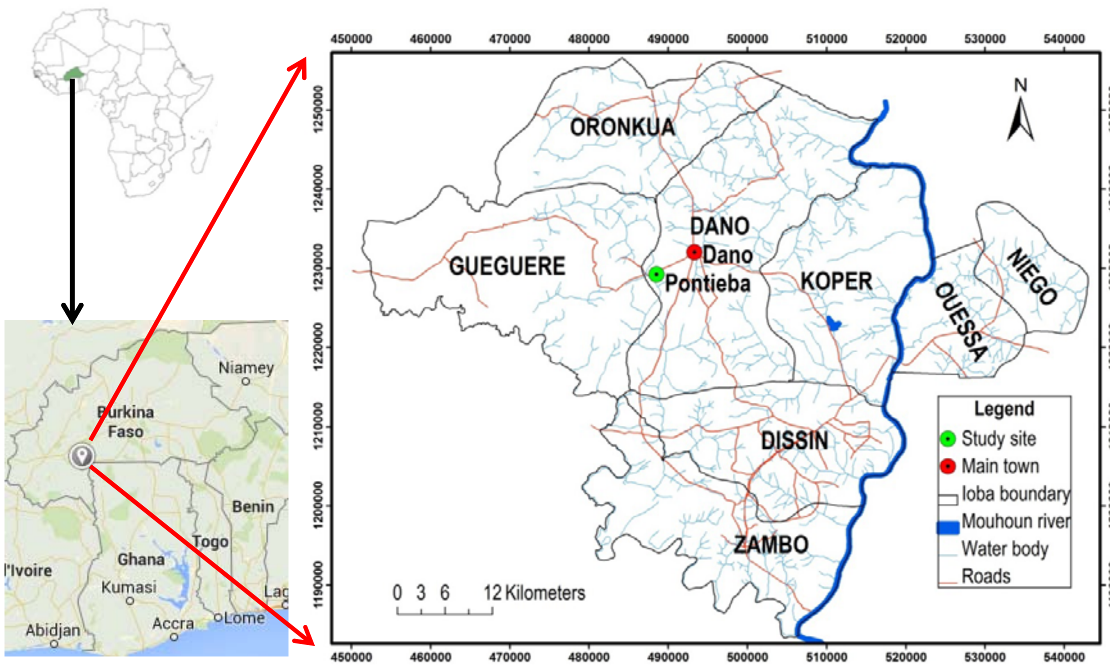

Fig. 1. Location of the study site - Pontieba village. Source: Thiombiano and Le (submitted). Notes: Text labels with capital and normal characters are for communes and villages, respectively. Dano is the main town of Ioba province.

The vegetation cover is savannah and is declining as well. The main soil type encountered in Ioba province and in the village of Pontieba is leached ferruginous tropical soils, hardened in some locations (Thiombiano, 2015). Subsistence agricultural activities are the main source of livelihood in the village. However, land pressure due to population growth (2.5%) (INSD, 2009), land degradation, and rainfall decrease and variability are increasing threat to population livelihood. Cereals and cotton are the main cultivated crops in the village.

2.2. *Study design*

This study is part of a research aiming at regionally adapting the LUDAS model (Le, 2005; Le et al. 2008, 2010, 2012a, 2012b) to West African smallholder agricultural livelihood systems in a drylands area of Burkina Faso. The first step of the research consisted in formulating an agro ecological livelihood system (ALS) typology in the research area, the village of Pontieba in Ioba province, South-western Burkina Faso (see Thiombiano and Le, 2015a). The identified typology will serve to define different human agent types in the modelling part. The present study, as illustrated by the box with red text in Fig.2, estimates crop yield production functions in response to main farming inputs, site conditions and household's livestock resource. Resource use efficiency will be assessed based on the estimated yield response functions.

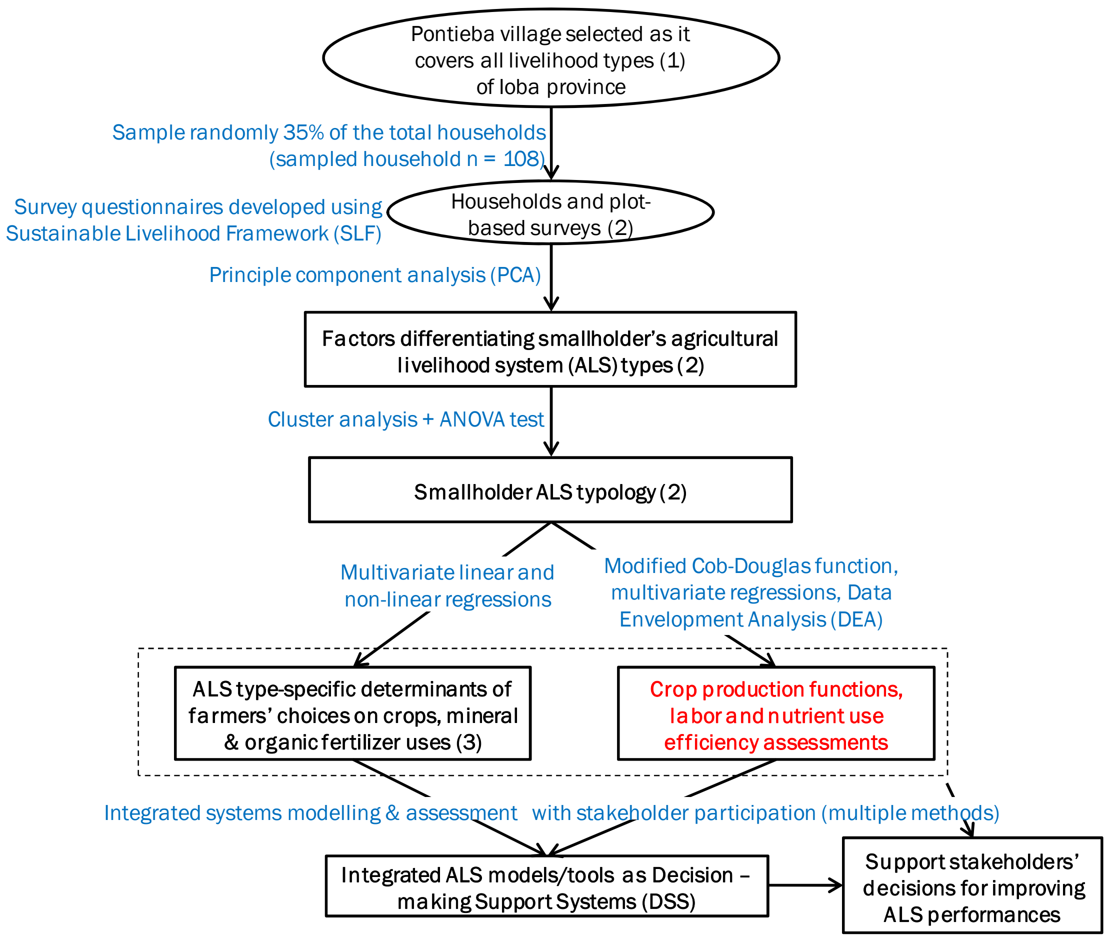

Fig.2. Corresponding step of the current study (box with red text) in the analytical flow towards integrated ALS models/tools as decision support systems (DSS) for improving ALS outcomes. Sources/references: This figure is adapted from Le (in prep.); (1) Thiombiano and Le (submitted), (2) Thiombinano and Le (2015a), (3) Thiombiano and Le (2016).

2.3. Method for modeling crop yield response toward resource use efficiency assessment

Crop yield is tributary to environmental conditions and to management practices implemented by the farmer. In modelling crop yield, two main approaches reviewed by Le (2005) are often used. On one side, the empirical production function approach which makes use of statistical analyses such regression and correlation analyses that take little account of biological and ecological processes underlying crop growth and development. On the other side, the process based approach which estimates crop yields based on agro-ecological, physiological and biochemical theories (Park et al., 2005). This approach has relatively high power of extrapolation over space and time but requires extremely intensive calibration-verification procedure. In practice and in the case of our study the empirical approach is best suited as (i) our main modeling objective is to anticipate agricultural yield response rather than to understand plant growth processes of crop growth, (ii) with plot-specific data, empirical models even offer a more reliable yield response than poorly calibrated process-based growth models, (iii) the careful choice of explanatory variables across a wide range of potential yield drivers may help formulating ecologically realistic yield functions and thereby overcome the limitations of the empirical approach (Le, 2005).

2.4. Empirical models for estimating yield responses

Yield response variables

The yield response variables are yield of main crop types corresponding to the five main crops in the study region: These crops are: sorghum + millet, groundnuts, rice, maize and cotton (Thiombiano and Le, 2016). The yield of each crop equals to the physical production in kilogram per land unit per year (Kg ha^{-1} $year^{-1}$).

Selection of variables determining crop yields

The agricultural yield of a plot (P_{Y_crop}) can be conceptualized as a function of genetic factors (G), natural environment conditions (E) and human management (M): Yield = G x E x M. In this study, we focus on how relevant E and M variables determine crop yields. Given the relatively small size (less than 50 km^2) of our study site (the village of Pontieba), the climatic condition can reasonably be assumed to vary very little within the village boundary, and therefore considered as uniform for all farms. The soil-water conditions of the plots can be approximated by upslope contributing area (P_{UPS}) and topographical wetness index (P_{WET}), and slope length factor (P_{LS}). Upslope contributing area of the plot position reflects nutrient accumulation that would have a positive effect on crop yields. Topographical wetness index (= ln (P_{UPS} / P_{UPS})) measure the potential of water saturation shaped by the topography that would favor crop growth in dry areas. The slope length (P_{LS}) of the plot indicates the soil erosion potential on its position, thus is expected to affect negatively the crop yield.

Table 1: Description of variables used for agricultural production function estimation

Variable	Definition	Data source
Dependent variables		
$P_{Y\_SORGMIL}$	Yield of sorghum or millet (kg ha^{-1} year^{-1})	On-farm interview
P_{Y_GNUTS}	Yield of groundnuts (kg ha^{-1} year^{-1})	On-farm interview
P_{Y_RICE}	Yield of paddy rice (kg ha^{-1} year^{-1})	On-farm interview
P_{Y_MAIZE}	Yield of maize (kg ha^{-1} year^{-1})	On-farm interview
P_{Y_COTTON}	Yield of cotton (kg ha^{-1} year^{-1})	On-farm interview
Management variables (M)		
P_{AREA}	Plot size (ha)	GIS-based measurement
P_{FLAB}	Family Man days used for production activities on the plot (Man day year^{-1})	On-farm interview
$P_{LABCOST}$	Monetary value of hired labor for production activities on the plot (F CFA year^{-1})	On-farm interview
P_{MINE}	Quantity of mineral nutrient input on the plot (Kg year^{-1})	On-farm interview
P_{CPEST}	Monetary value of pesticides for production activities on the plot (F CFA year^{-1})	On-farm interview
P_{TLUHA}	Tropical Livestock Units per land unit (TLU ha^{-1})	On-farm interview
Site condition variables (E)		
P_{UPS}	The upslope contributing area (m^2) at the plot location, indicating sedimentation accumulation potential	Terrain analysis from DEM
P_{WET}	Topographical wetness index (= *ln* ($P_{UPSLOPE}$/surface slope)), indicating potential water saturation	Terrain analysis from DEM
P_{LS}	The slope length (LS) factor at the plot location, indicating soil erosion potential.	Terrain analysis from DEM
P_{DHouse}	Plot distance from household homestead (m)	On-farm interview

Land management variables such as Family labor input (P_{FLAB}), Cost of hired labor ($P_{LABCOST}$), Mineral nutrient used (P_{MINE}) and pesticides (P_{CPEST}) are factors directly used by farmers for improving crop productivity. However, crop yield responsiveness to an increment of agrochemical and labor inputs may vary according to the crop choice, natural conditions {Le, 2005) and also the farmer know-how in the use of these technologies. Livestock endowment (H_{TLU}) indirectly influences crop yield through manure provision (collected by farmers or left on plot during livestock roaming). The effect of an increment of livestock per land unit depends on the farmer decision making which defines livestock management mode and organic manure use. The level of use of labor (P_{FLAB}) and of chemicals (P_{MINE} and P_{CPEST}) are also determined by the farmer decision making and is affected by policy factor as well (Le, 2005). As for Plot distance from household homestead (P_{DHOUSE}) it is a proxy of soil fertility given the fertility gradient in most smallholder farms with closest plots to homestead being likely more fertile (Tittonell et al., 2005). We then expect plot remoteness from homestead (high value of P_{DHOUSE}) to negatively affect crop yield.

Variables selected for agricultural yield modelling are briefly defined in Table 1. By using these variables, the yield function can be written as:

$$Y_{P\_Crop} = f(P_{AREA,} P_{LAB}, P_{LABCOST,} P_{MINE}, P_{CPEST}, P_{TLUHA}, P_{DHOUSE}, P_{UPS}, P_{WET}, P_{LS}) \quad (1)$$

Selection of yield function form

We used the power function (Cob-Douglas) which is one of the most commonly used production functions. The power function can be written as follow:

$$Y = \alpha X^{\beta}, (\alpha > 0) \quad (2)$$

where Y is the yield response, X is the explanatory variables, α and β are the coefficients. The coefficient β indicates the direction of the yield change, and the acceleration behavior of the yield increment in response to the increasing of X. The β measures directly the elasticity of agricultural yield Y to the change in the predictors X: β = %ΔY / %ΔX (Le, 2005). If X is a resource input, the β is the partial factor efficiency of X resource use. The simple power function (2) can be extended to a multivariable power function and transformed into a log-linear function: ln*Y* = ln α + *β*ln*X*. Yield function (1) can then be written as follow:

$$\begin{aligned} \ln(Y_{P\_Crop}) = {} & \ln\alpha + \beta_1 \ln P_{AREA} + \beta_2 \ln P_{FLAB} + \beta_3 \ln P_{MINE} + \beta_4(\ln P_{MINE} * \ln P_{FLAB}) + \\ & \beta_5(\ln P_{MINE} * \ln P_{LABCOST}) + \beta_6 \ln P_{CPEST} + \beta_7 \ln P_{TLUHA} + \beta_8 \ln P_{DHOUSE} + \\ & \beta_9 \ln P_{UPS} + \beta_{10} \ln P_{WET} + \beta_{11} \ln P_{LS} \end{aligned} \quad (3)$$

Evaluation of the performance of models

The global performance of models was evaluated using the F-statistic test. As for the explanatory performance of each independent variable, the T-statistic tests were used. The goodness-of-fit of the regression models was measured by the standard error of the estimates and the coefficient of the determination (R^2). The higher the value of R^2, the better the fit of data (Le, 2005).

2.5. *Data source*

The data sources for the considered variables are indicated in the last column if Table 1. Data of plot-based crop yield and management factors were taken from Thiombiano and Le (2016). They conducted surveys in year 2014 in the village of Pontieba. Using the Sustainable Livelihood framework (SLF) they collected a multidimensional dataset from 108 households selected randomly. All farming plots (N = 479) of these households were mapped by field visits with GPS units. Crop yields and management factors of these plots (e.g. labor spent, mineral and organic fertilizers used) were carefully interviewed on the farm and cross checked.

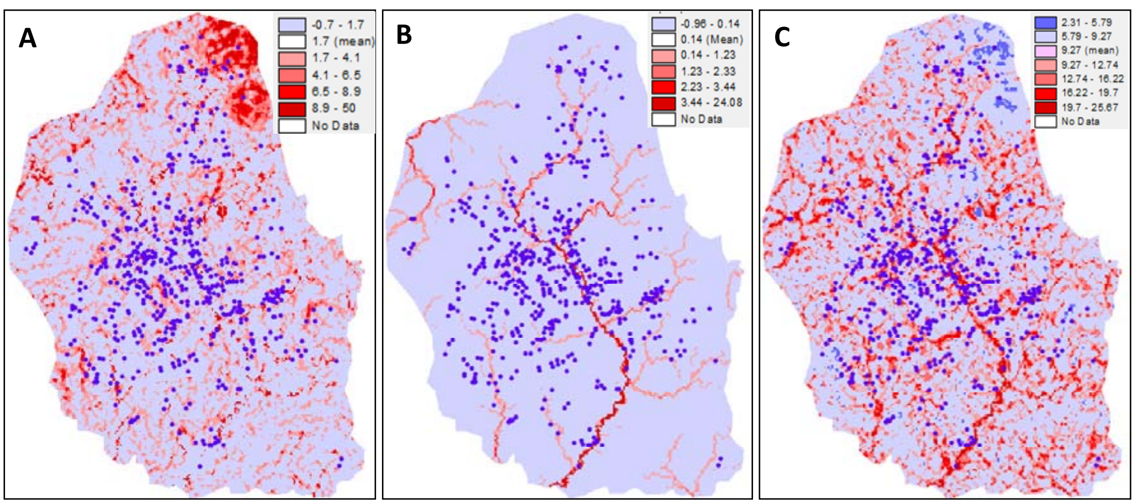

Fig.2. Spatial distribution of surveyed plots (N = 479, blue dots) on GIS maps of (**A**) slope length factor (P_{LS}), (**B**) upslope contributing area (km^2) (P_{UPS}) and (**C**) topographical wetness index (P_{WET}). Note: Map projection: UTM 30N, WGS84, resolution: 10 m.

Given that the plots were mapped, site condition variables were extracted from GIS data layers that were generated by terrain and buffer analyses. Terrain analyses were done based on a Digital Elevation Model (DEM) with a 30m resolution, for calculating slope length factor (P_{LS}), upslope contributing area ($P_{UPSLOPE}$), and topographical wetness index

(P_{WET}). Proximity to main towns was done by buffering analysis using Burkina Faso topographical map. Figure 3 shows locations of surveyed plots on GIS maps of slope length factor (P_{LS}), upslope contributing area ($P_{UPSLOPE}$) and topographical wetness index (P_{WET}).

3. Results

3.1. Descriptive statistics of variables used for agricultural year models

The summary of descriptive statistics for variables used for estimating agricultural yield functions is shown in Table 2a,b,c,d, and e. These statistics show that crop yields in the study zone are generally low as highlighted by Thiombiano (2015). Sorghum/millet and maize which are the main staple foods recorded average yield of 412 kg ha^{-1} year^{-1}, and 1,441 kg ha^{-1} year^{-1}, respectively. The largest plots are allocated to sorghum and millet (0.78 ha) productions and in second position to cotton (0.66 ha), the main cash crop of the region.

Table 2a. Descriptive statistics of variables for sorghum + millet production function in the agricultural year 2013/14

	Number of plots	Mean	Standard deviation (SD)	95% Conf. Interval
Sorghum/millet yield *($P_{y\_SORGMIL}$) (Kg ha^{-1} year^{-1})*	148	412	290	47
Plot area *(P_{AREA}) (ha)*	148	0.78	0.54	0.09
Family labour *(P_{FLAB}) (Man-day ha^{-1} year^{-1})*	148	32	32	5
Labour cost *($P_{LABCOST}$) (F CFA ha^{-1} year^{-1})*	148	1,910	6,457	1,052
Mineral nutrient *(P_{MINE}) (Kg ha^{-1} year-1)*	148	5	53	9
Pesticides cost *(LnP_{CPEST}) (F CFA ha^{-1} year^{-1})*	148	238	2,398	390
Tropical livestock *(H_{TLUHA}) (TLU ha^{-1})*	148	0.43	0.62	0.10
Plot Upslope *(P_{UPS}) (m^{2})*	148	56,577	257,843	41,885
Wetness index *(Ln($P_{UPSLOPE}$/Surface slope))*	148	9	3	1
Slope length *(P_{LS}) (m)*	148	1.42	1.56	0.25
Plot distance from homestead *(P_{DHOUSE}) (m)*	148	1,246	1,013	165

The small land area allocated to marketable food crops such as groundnuts (0.39 ha) and rice (0.16 ha) indicates on one hand the subsistence character of the agriculture of the area. Remotest plots (bush field) were allocated to sorghum (1,246 m from homestead) and cotton (940 m from homestead) production while maize (253 m from homestead) was cropped around homestead. This confirms the crop allocation strategy along the soil fertility gradient. Less nutrient demanding crops (Sorghum/millet) are allocated to remoted and likely less fertile plots, while more nutrient demanding crops (Maize) are allocated to fertile plots closest to homesteads and for which it is easy carrying nutrient to it. Cotton crops are allocated to plots situated at reasonable distance from homestead and for which it relatively easy to carry nutrient and other inputs. Rice was the most labor intensive crop for both families (187 Man-day ha^{-1} $year^{-1}$) and hired labour (42,206 F CFA ha^{-1} $year^{-1}$) followed by groundnuts (69 Man-day ha^{-1} $year^{-1}$) and maize (68 Man-day ha^{-1} $year^{-1}$) for family labour. In terms of nutrient use, cotton was the most mineral nutrient intensive (205 *Kg* ha^{-1} *year-1*) followed by rice (181 *Kg* ha^{-1} *year-1*). The average mineral nutrient use intensity (205 *Kg* ha^{-1} $year^{-1}$) for cotton is nearly the recommended use intensity (200 *Kg* ha^{-1} $year^{-1}$). It illustrates the close technical assistance offered by cotton companies contrary to others crops for which not at all or very less assistance is available.

Table 2b. Descriptive statistics of variables for groundnut production function in the agricultural year 2013/14

	Number of plots	Mean	Standard deviation (SD)	95% Conf. Interval
Groundnuts yield *(P_{y_GNUTS}) (Kg ha^{-1} $year^{-1}$)*	55	445	432	117
Plot area *(P_{AREA}) (ha)*	55	0.39	0.32	0.09
Family labour *(P_{FLAB}) (Man-day ha^{-1} $year^{-1}$)*	55	69	95	26
Labour cost *($P_{LABCOST}$) (F CFA ha^{-1} $year^{-1}$)*	55	4,584	13,028	3,522
Mineral nutrient *(P_{MINE}) (Kg ha^{-1} year-1)*	55	2	15	4
Pesticides cost *(LnP_{CPEST}) (F CFA ha^{-1} $year^{-1}$)*	55	0	0	0
Tropical livestock *(H_{TLUHA}) (TLU ha^{-1})*	55	0.42	0.56	0.15
Plot Upslope *(P_{UPS}) (m^2)*	55	31,381	82,612	22,333
Wetness index *(Ln($P_{UPSLOPE}$/Surface slope))*	55	10	3	1
Slope length *(P_{LS}) (m)*	55	1.27	1.41	0.38
Plot Distance from homestead *(P_{DHOUSE}) (m)*	55	815	691	187

Table 2c. Descriptive statistics of variables for rice production function in the agricultural year 2013/14

	Number of plots	Mean	Standard deviation (SD)	95% Conf. Interval
Rice yield *(P_{y_RICE}) (Kg ha^{-1} year^{-1})*	58	1,732	1,424	374
Plot area *(P_{AREA}) (ha)*	58	0.16	0.09	0.02
Family labour *(P_{FLAB}) (Man-day ha^{-1} year^{-1})*	58	187	258	68
Labour cost *($P_{LABCOST}$) (F CFA ha^{-1} year^{-1})*	58	42,206	105,425	27,720
Mineral nutrient *(P_{MINE}) (Kg ha^{-1} year-1)*	58	181	300	79
Pesticides cost *(LnP_{CPEST}) (F CFA ha^{-1} year^{-1})*	58	1,081	6,706	1,763
Tropical livestock *(H_{TLUHA}) (TLU ha^{-1})*	58	0.48	0.56	0.15
Plot Upslope *(P_{UPS}) (m^2)*	58	969,130	2,005,498	527,319
Wetness index *(Ln($P_{UPSLOPE}$/Surface slope))*	58	13	5	1
Slope length *(P_{LS}) (m)*	58	1.07	1.75	0.46
Plot Distance from homestead *(P_{DHOUSE}) (m)*	58	779	525	138

Table 2d. Descriptive statistics of variables for maize production function in the agricultural year 2013/14

	Number of plots	Mean	Standard deviation (SD)	95% Conf. Interval
Maize yield *(P_{y_MAIZE}) (Kg ha^{-1} year^{-1})*	128	1,441	1,664	291
Plot area *(P_{AREA}) (ha)*	128	0.31	0.21	0.04
Family labour *(P_{FLAB}) (Man-day ha^{-1} year^{-1})*	128	68	81	14
Labour cost *($P_{LABCOST}$) (F CFA ha^{-1} year^{-1})*	128	4,635	14,081	2,463
Mineral nutrient *(P_{MINE}) (Kg ha^{-1} year-1)*	128	88	183	32
Pesticides cost *(LnP_{CPEST}) (F CFA ha^{-1} year^{-1})*	128	1,114	6,076	1,063
Tropical livestock *(H_{TLUHA}) (TLU ha^{-1})*	128	0.43	0.53	0.09
Plot Upslope *(P_{UPS}) (m^2)*	128	94,184	456,525	79,848
Wetness index *(Ln($P_{UPSLOPE}$/Surface slope))*	128	10	4	1
Slope length *(P_{LS}) (m)*	128	1.05	1.11	0.19
Plot Distance from homestead *(P_{DHOUSE}) (m)*	128	253	589	103
Slope length *(P_{LS}) (m)*	77	1.17	1.45	0.33
Plot Distance from homestead *(P_{DHOUSE}) (m)*	77	940	897	204

Table 2e. Descriptive statistics of variables for cotton production function in the agricultural year 2013/14

	Number of plots	Mean	Standard deviation (SD)	95% Conf. Interval
cotton yield *(P_{y_COTTON}) (Kg ha^{-1} $year^{-1}$)*	77	615	441	100
Plot area *(P_{AREA}) (ha)*	77	0.66	0.39	0.09
Family labour *(P_{FLAB}) (Man-day ha^{-1} $year^{-1}$)*	77	44	61	14
Labour cost *($P_{LABCOST}$) (F CFA ha^{-1} $year^{-1}$)*	77	14,237	29,636	6,727
Mineral nutrient *(P_{MINE}) (Kg ha^{-1} year-1)*	77	205	163	37
Pesticides cost *(LnP_{CPEST}) (F CFA ha^{-1} $year^{-1}$)*	77	20,783	24,217	5,497
Tropical livestock *(H_{TLUHA}) (TLU ha^{-1})*	77	0.48	0.53	0.12
Plot Upslope *(P_{UPS}) (m^2)*	77	250,968	1,198,787	272,091
Wetness index *(Ln($P_{UPSLOPE}$/Surface slope))*	77	10	4	1
Slope length *(P_{LS}) (m)*	77	1.17	1.45	0.33
Plot Distance from homestead *(P_{DHOUSE}) (m)*	77	940	897	204

3.2. Estimated crop production functions

3.2.1. Estimated production function of sorghum + millet plots

The regression results in Table 3 show that the model is significant (F-statistic $p < 0.01$) in explaining the change in sorghum and millet yield. The value of R^2 (0.25) indicates that 25% of the variation in the observed sorghum or millet yield is explained by the model. This shows an acceptable fit of the model to the observed data.

Three variables were found to be significantly affecting the yield of sorghum or millet: Plot area (P_{AREA}),Livestock per land unit (P_{TLUHA}) and Plot upslope area (P_{UPS}). The plot area and its upslope contributing area had a negative effect on the yield of sorghum or millet. It means that large plots of these cereals are less productive likely due to the crop management capacity of the farmers. It was observed during fieldwork that many fields were weedy. The negative effect of upslope contributing area can be explained by the resulting depositional potential that may favor faster growing weeds compared to the crops. Associated to low crop management capacity, weeds contribute to reduce crop yield. As for livestock it positively affects the yield of sorghum or millet. This indicates that the more the farm is endowed in livestock per unit of cultivated land the highest the yield of sorghum and millet. The results illustrate the important role of livestock in smallholder farms where livestock is most of the time roaming.

The amplitude of the β (elasticity) indicates the marginal effects of the significant explanatory variables. The β values for P_{AREA} and P_{TLUHA} show values of more than 1, indicating that the two variables have meaningful marginal effect on the yield of sorghum or millet. The elasticity value of - 0.294 for P_{AREA} reveals that doubling the area of sorghum or millet plot will induce a decrease by 0.294*100= 29% of crop yield. However, an improvement of livestock/land ratio by double (100%) will improve sorghum or millet yield by 0.141 * 100 =14%. Plot upslope contributing area shows an elasticity of -0.137, indicating that 100% increase of this variable reduces sorghum or millet yield by 0.137*100=13.7%.

Table 3: Results of log-linear regressions for “Sorghum or millet” crops

Agricultural yield model	Pearson correlation coefficient (r)	Unstandardized coefficient (yield elasticity) (β)	Standard error of β (σ_β)	95% Confidence interval	
				Lower bound	Upper bound
Ln of “Sorghum or millet” yield ($P_{y\_SORGMIL}$) N=144, mean (Ln($P_{y\_SORGMIL}$)) =5.79, R^2=0.25, p=0.000					
Constant		6.284	0.500	5.294	7.273
Ln of Plot area (LnP_{AREA})	-0,295***	-0.294***	0.091	-0.474	-0.114
Ln of family labour input (LnP_{FLAB})	-0,176**	-0.027	0.045	-0.115	0.062
Ln of mineral nutrient input (LnP_{MINE})	0,010	0.368**	0.157	0.058	0.679
Ln of mineral nutrient input * Ln of family labour input ($LnP_{MINE}LnP_{FLAB}$)	-0,081	-0.044*	0.023	-0.090	0.002
Ln of mineral nutrient input * Ln of family labour input ($LnP_{MINE}LnP_{LABOST}$)	*NA*	*NA*	*NA*	*NA*	*NA*
Ln of pesticides cost (LnP_{CPEST})	-0,047	-0.116*	0.070	-0.255	0.022
Ln of tropical livestock (LnH_{TLUHA})	0,260***	0.141***	0.044	0.054	0.227
Ln of plot Upslope (LnP_{UPS})	-0,110*	-0.137**	0.056	-0.248	-0.025
Wetness index (Ln($P_{UPSLOPE}$/Surface slope))	0,096	0.053**	0.026	0.002	0.105
Ln of plot slope length (LnP_{LS})	-0,074	-0.023	0.087	-0.196	0.150
Ln of plot Distance from homestead (LnPDHOUSE)	0,008	0.053	0.047	-0.039	0.146

Note: The symbols *, **, and *** indicate statistical significance at the confidence level of 90%, 95% and 99%, respectively. NA: Not applicable

3.2.2. Estimated production function of groundnut plots

The regression results of groundnut yield model are shown in Table 4. The model was not found significant (F-statistic $p > 0.01$) in explaining the change in groundnuts yield. Further investigation on the correlation between groundnuts yields and variables of the dataset is needed to improve the fitness of the model to the observed data.

Table 4: Results of log-linear regressions for groundnuts crop

Agricultural yield model	Pearson correlation coefficient (r)	Unstandardized coefficient (yield elasticity) (β)	Standard error of β (σ_β)	95% Confidence interval	
				Lower bound	Upper bound
Ln of groundnuts yield (P_{y_GNUTS}) N=54, mean ($Ln(P_{y\_GNUTS})$) =5.69, R^2=0.23, p=0.143					
Constant		5.477	1.228	3.004	7.950
Ln of Plot area (LnP_{AREA})	-0.410***	-0.534***	0.186	-0.908	-0.160
Ln of family labour input (LnP_{FLAB})	-0.110	-0.050	0.089	-0.229	0.130
Ln of mineral nutrient input (LnP_{MINE})	0.112	0.337	0.274	-0.214	0.888
Ln of mineral nutrient input * Ln of family labour input ($LnP_{MINE}LnP_{FLAB}$)	0.112	NA	NA	NA	NA
Ln of mineral nutrient input * Ln of family labour input ($LnP_{MINE}LnP_{LABOST}$)	0.112	*NA*	*NA*	*NA*	*NA*
Ln of pesticides cost (LnP_{CPEST})	*0.00*	NA	NA	NA	NA
Ln of tropical livestock (LnP_{TLUHA})	-0.051	-0.086	0.129	-0.346	0.174
Ln of plot Upslope (LnP_{UPS})	0.095	-0.015	0.136	-0.289	0.259
Wetness index ($Ln(P_{UPSLOPE}$/Surface slope))	-0.023	0.010	0.066	-0.123	0.144
Ln of plot slope length (LnP_{LS})	0.130	0.195	0.209	-0.225	0.616
Ln of plot Distance from homestead (LnP_{DHOUSE})	-0.170	-0.057	0.105	-0.268	0.154

Note: The symbols *** indicate statistical significance at the confidence level of 90%.
NA: Excluded variables

3.2.3. Estimated production function of rice plots

The Table 5 show estimation results of the rice yield function. The p-value of the F-Statistic indicates that the model is highly significant ($p<0.01$) in explaining the variation of rice yield. The value of R^2 (0.47) means that 47%, close to 50%, of the variation in the observed rice yield is explained by the model. This shows a good fit of the model to the observed data. In effect, according to Studenmund (1997), for a cross-sectional dataset, an R^2 value of 0.50 would be considered as good fit. Le (2005) added that when data is obtained through interviewing plot owners rather than through field measurement (like in the case of this study), there may be considerable errors/distortion associated with either data acquisition that can explained the low value of the R^2.

Table 5: Results of log-linear regressions for rice crop

Agricultural yield model	Pearson correlation coefficient (r)	Unstandardized coefficient (yield elasticity) (β)	Standard error of β (σ_β)	95% Confidence interval	
				Lower bound	Upper bound
Ln of rice yield (P_{y_RICE}) N=58, mean (Ln(P_{y_RICE})) =6.89, R^2=0.47, p=0.001					
Constant		0.332	1.835	-3.362	4.027
Ln of Plot area (LnP_{AREA})	-0.321***	-0.938***	0.313	-1.568	-0.308
Ln of family labour input (LnP_{FLAB})	0.107	0.579***	0.164	0.248	0.910
Ln of mineral nutrient input (LnP_{MINE})	0.151	1.068***	0.284	0.497	1.639
Ln of mineral nutrient input * Ln of family labour input ($LnP_{MINE}LnP_{FLAB}$)	0.044	-0.198***	0.054	-0.306	-0.089
Ln of mineral nutrient input * Ln of family labour input ($LnP_{MINE}LnP_{LABOST}$)	0.040	-0.023	0.016	-0.056	0.010
Ln of pesticides cost (LnP_{CPEST})	0.052	0.141	0.130	-0.121	0.403
Ln of tropical livestock (LnP_{TLUHA})	0.307***	0.414***	0.154	0.104	0.723
Ln of plot Upslope (LnP_{UPS})	0.124	0.042	0.117	-0.195	0.278
Wetness index (Ln($P_{UPSLOPE}$/Surface slope))	0.271**	0.038	0.068	-0.100	0.175
Ln of plot slope length (LnP_{LS})	0.018	0.182	0.205	-0.229	0.594
Ln of plot Distance from homestead (LnP_{DHOUSE})	0.141	0.231	0.222	-0.216	0.678

Note: The symbols **, and *** indicate statistical significance at the confidence level of 95% and 99%, respectively

Like in the case of sorghum, Plot area (P_{AREA}) and Livestock per land unit (P_{TLUHA}) appeared to be main factors affecting rice yield. The Pearson correlation coefficient of P_{AREA} is negative indicating that a bigger rice plot is a factor of low yield. Rice farming in quite labour intensive. A big plot size is likely to be badly managed if not sufficient labour is available. That is why, beyond suitable land availability, rice is often cropped on small plot size to ensure an efficient weed and nutrient management. P_{TLUHA} had a positive effect indicating that a high livestock/land ratio is likely to improve rice yield.

The elasticity (β) of P_{AREA} indicates a dramatic marginal effect (0.938 *100=94%) of rice yield when the plot area increases by 100%. An increase by double of livestock/land ratio causes an increment of rice yield by 41%.

3.2.3. Estimated production function of maize plots

The regression results in Table 6 show that the model is significant (F-statistic $p < 0.01$) in explaining the change in maize yield. The value of R^2 (0.40) indicates that 40% of the variation in the observed maize yield is explained by the model. This shows a good fit of the model to the observed data.

Table 6: Results of log-linear regressions for maize crops

Agricultural yield model	Pearson correlation coefficient (r)	Unstandardized coefficient (yield elasticity) (β)	Standard error of β (σ_β)	95% Confidence interval	
				Lower bound	Upper bound
Ln of Maize yield (P_{y_MAIZE}) N=127, mean ($Ln(P_{y\_MAIZE})$) =6.85, R^2=0.40, p=0.000					
Constant		4.176	0.731	2.728	5.624
Ln of Plot area (LnP_{AREA})	-0.495***	-0.775***	0.106	-0.984	-0.566
Ln of family labour input (LnP_{FLAB})	-0.027	0.167	0.106	-0.042	0.376
Ln of mineral nutrient input (LnP_{MINE})	0.229***	0.301**	0.146	0.012	0.591
Ln of mineral nutrient input * Ln of family labour input ($LnP_{MINE}LnP_{FLAB}$)	0.209***	-0.026	0.031	-0.089	0.036
Ln of mineral nutrient input * Ln of family labour input ($LnP_{MINE}LnP_{LABOST}$)	-0.021	0.003	0.007	-0.011	0.017
Ln of pesticides cost (LnP_{CPEST})	-0.074	-0.022	0.033	-0.088	0.044
Ln of tropical livestock (LnP_{TLUHA})	0.103	0.078	0.055	-0.030	0.186
Ln of plot Upslope (LnP_{UPS})	0.015	0.098	0.062	-0.025	0.222
Wetness index (Ln($P_{UPSLOPE}$/Surface slope))	-0.057	-0.036	0.029	-0.093	0.022
Ln of plot slope length (LnP_{LS})	-0.035	0.039	0.100	-0.160	0.237
Ln of plot Distance from homestead (LnP_{DHOUSE})	0.006	0.035	0.053	-0.070	0.141

Note: The symbols **, and *** indicate statistical significance at the confidence level of 95% and 99%, respectively

The variables plot area (P_{AREA}) and mineral nutrient (P_{MINE}) had a significant effect on yield response. The two variables had different affecting directions. P_{AREA} had a negative effect showing that the larger the maize plot area, the less the farmer is able to draw high maize yield due certainly to management issues. P_{MINE} had a positive effect indicating, as expected, that mineral nutrient use increases maize yield response. The cross effect between mineral fertilizer and family labour input (LnP_{MINE} and LnP_{FLAB}) had a positive effect on maize yield response. This shows that the positive effect of mineral nutrient on maize yield response is affected by labour availability. It may be constrained by limited labour.

The yield elasticities of P_{AREA} and P_{MINE} indicate maize yield response is very sensitive (elastic) to these two variables. In effect, an increment of 100% of maize plot size brings about a reduction of about up to 78% of maize yield (0.775*100 = 778%) all other variables hold constant. At the same time, an increment of mineral nutrient input by 100% occasions the increase of maize yield by 30% (0.301*100 = 30%). The yield elasticity of the cross effect between mineral fertilizer (P_{MINE}) and family labour (P_{FLAB}) was not found significant.

3.2.4. Estimated production function of cotton field

The Table 7 shows estimation results of the cotton yield function. The p-value of the F-Statistic indicates that the model is highly significant ($p<0.01$) in explaining the variation of cotton yield. The value of R^2 (0.37) means that 37%, of the variation in the observed cotton yield is explained by the model. This shows a good fit of the model to the observed data.

The variable plot area (P_{AREA}) negatively affected cotton yield: the Pearson correlation coefficient was negative. This indicates like in the case of food crops that plot size is a factor reducing crop yield response. The size of the plot should be considered as key drivers of yield response in the study zone. On the contrary to plot area, the variables Family labour (P_{FLAB}), Mineral nutrient (P_{MINE}), Cost of pesticides (P_{CPEST}) and Livestock/land ratio (P_{TLUHA}) presented a positive affecting direction on cotton yield response. Higher values of these variables tend to fuel cotton yield response.

The coefficients of significant variables help to appreciate the amplitude of the effect of these variables on cotton yield change (yield elasticities). Though P_{AREA} and P_{TLUHA} had significant correlation with yield response, their yield elasticities were not found significant. The elasticities of the variables Family labour (P_{FLAB}), mineral nutrient (P_{MINE}) were highly significant. An increment of P_{FLAB} by 100% generates a cotton yield increase of 57% (0.573*100 = 57%). This confirms the labour intensive character of cotton crop comparatively to other crops, mainly for pesticides application and fibre harvest. The mineral nutrient had greater marginal effect: indeed, at the actual stage of mineral nutrient use in the study area, an increase of mineral fertilizer by 100% generates an increase of cotton yield by 64% (0.642*100 = 64%).

Table 7: Results of log-linear regressions for cotton crops

Agricultural yield model	Pearson correlation coefficient (r)	Unstandardized coefficient (yield elasticity) (β)	Standard error of β (σ_β)	95% Confidence interval	
				Lower bound	Upper bound
Ln of cotton yield (P_{y_COTTON}) N=77, mean ($Ln(P_{y\_COTTON})$) =6.15, R^2=0.37, p=0.001					
Constant		3.171	0.949	1.275	5.066
Ln of Plot area (LnP_{AREA})	-0.193**	-0.219	0.141	-0.501	0.063
Ln of family labour input (LnP_{FLAB})	0.164*	0.573***	0.151	0.270	0.875
Ln of mineral nutrient input (LnP_{MINE})	0.310***	0.642***	0.154	0.334	0.950
Ln of mineral nutrient input * Ln of family labour input ($LnP_{MINE}LnP_{FLAB}$)	0.167*	-0.128***	0.033	-0.194	-0.061
Ln of mineral nutrient input * Ln of family labour input ($LnP_{MINE}LnP_{LABOST}$)	0.046	-0.004	0.005	-0.014	0.007
Ln of pesticides cost (LnP_{CPEST})	0.267***	0.012	0.025	-0.038	0.063
Ln of tropical livestock (LnP_{TLUHA})	0.259**	0.060	0.096	-0.132	0.253
Ln of plot Upslope (LnP_{UPS})	-0.047	0.076	0.094	-0.112	0.265
Wetness index ($Ln(P_{UPSLOPE}$/Surface slope))	-0.091	-0.039	0.046	-0.130	0.053
Ln of plot slope length (LnP_{LS})	0.048	-0.069	0.147	-0.363	0.225
Ln of plot Distance from homestead (LnP_{DHOUSE})	-0.148*	-0.022	0.077	-0.175	0.131

Note: The symbols *, **, and *** indicate statistical significance at the confidence level of 90%, 95% and 99%, respectively

4. Discussions

4.1. Contextualization of main findings

The present study has identified the main drivers influencing the yield response of the main crops grown in smallholder farms of the village of Pontieba. Out of the management and site condition predictors included in the yield response models, significant predictors related essentially to plot management. These management variables were labor input (P_{FLAB}) and Mineral nutrient input (P_{MINE}). The results are consistent with the findings of Le (2005), Bhujel and Ghimire (2006) who also found that labor and mineral fertilizer are key drivers of crop yield. The negative correlation of plot size and crop yield response indicates the extensive nature of crop production systems in the study zone. The negative correlation of plot size with yield response can additionally due to a bad pest and weed management. This extensive character of the cropping systems in the study area is supported by the magnitude of yield elasticities for mineral nutrient input. In the effect, these elasticities were found to be 0.3 for maize and up to 0.64 for cotton. It means than a 100% increment of mineral nutrient generates up to 30% and 64% yield increment for maize and cotton, respectively. This demonstrates the existence of very low labor and fertilizer use efficiency, i.e. low return to inputs and profitability.

Terrain variable wise, only upslope contributing area was found to be significant for the sole sorghum + millet crop. The non-significance of terrain variables (site specific predictors) for most of the crops can be explained by the nature of the terrain in the area. Indeed the landscape is characterized by relatively low elevation (327m in average) and gentle slope (average slope less than 3 degrees). Also, as shown by Table 2, plots have low slope length (2 m in general). Slope and slope length are erosion correlated variables and they can greatly influence yield response when values are high.

4.2. Added value of the study, implication for policy intervention and farming design

The present study allows apprehending drivers of the yield response of these crop choices. It therefore offers an opportunity for better understanding cropping system in the region and moreover to better guide decision making targeting the improvement of agricultural livelihood in dry lands. It is hard to find studies in the West African region analyzing simultaneously drivers of agricultural yield responses for main crops in smallholder farms. The study can therefore serve as framework for studies in the region and also guide farming design research.

4. Conclusion

Understanding the functioning of farming systems and better sizing the conditions under which the effectiveness of policy interventions can be improved are key to improving food security and agricultural livelihood. Our study by identifying drivers of yield response of main crops in Pontieba, offers the opportunity of holistically sizing smallholder decision making. The study has identified drivers of crop yield responses. It showed that plot area (-), family labor (+) and mineral nutrient (+) are main drivers influencing crop yield response in smallholder farming systems. The study showed that improving crop yield in smallholders farming requires intensifying crop production. It also showed that family labor remains an important factor for crop production. Furthermore, the yield elasticities of mineral nutrient for different crops suggested the existence of important yield gaps. Indeed an increase of mineral nutrient. For reducing this gap there is the need for policy intervention to implement targeted policy improving mineral nutrient use and others sustainable nutrient management practices that help to intensify crop production.

5. The ways forward

This study conducted in the frame of a research aiming at modelling Agricultural Livelihood Systems in the village of Pontieba by adapting the agent-based model LUDAS developed by Le (2005). The study follows a previous study that formulated Agricultural Livelihood System typology in Pontieba. It used the identified typology to model land-use choice making by each Agricultural Livelihood System in Pontieba. The next step of the research will be: performing the agent-based modelling (ABM) of the agricultural livelihood systems in Pontieba by adapting the Land Use DynAmics Simulator (LUDAS) model (Le *et al.*, 2008; Le *et al.*, 2010; Le *et al.*, 2012a; Le *et al.*, 2012b), and/or other integrated systems methods such as material flow analysis (MFA), system dynamics (SD) and participatory Formative Scenarios Analysis (FSA) (Scholz and Tietje, 2002).

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