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Trade-offs between food security and forest exploitation by *mestizo* households in Ucayali, Peruvian Amazon

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Abstract

The Peruvian Amazon is undergoing rapid and uneven economic growth, alongside alarming rates of deforestation, increasing land use change and food security concerns. Although it has been widely acknowledged that food insecurity is intrinsically linked with deforestation, the links have not been thoroughly documented. The aim of this paper is to analyse the trade-offs and synergies between food security and forest exploitation at household level in *mestizo* communities in Ucayali, one of the regions with the highest deforestation rates in the Peruvian Amazon. To this end, 24 farmers were interviewed, surveys were conducted with a sample of 58 households, and an *ad-hoc* simulation modelling tool was developed and applied. Four main types of *mestizo* farming households were identified based on their crop and livestock diversity. For all farm types, the forest mainly represented a set aside area to support a potential increase in agricultural production. However, simulations showed that the different types of households, with different decision rules, lead to different rates of deforestation. The results of this study showed that the most diversified farming households presented the smallest trade-offs between food security and forest conservation, as they are the ones most likely to preserve the forest while ensuring their food security.

Keywords: decision rules, deforestation, agriculture, ad-hoc farm simulation model, Amazonia

1. Introduction

The Amazon hosts the largest area of tropical forest in the world, with very high levels of biodiversity (Foley *et al.*, 2007; Malhi *et al.*, 2008; Lu, 2009). Peru has the largest area of Amazon forest after Brazil (Lu, 2009). The annual estimated extent of deforestation between 2001 and 2014 in Peru was 103,819 ha, mainly concentrated in the departments of Ucayali and Madre de Dios (MINAM, 2015). The Peruvian Amazon is therefore undergoing rapid and uneven economic growth, alongside alarming rates of deforestation and increasing land use change (Galarza and La Serna, 2005; Miranda *et al.*, 2016). Slash-and-burn agriculture, expansion of oil palm plantations and pastures, legal and illegal logging, land clearing and road expansion have been cited as drivers of deforestation in Ucayali in the past 20 years (Alvarez and Naughton-Treves, 2003; Salisbury and Fagan, 2013; Porro *et al.*, 2015), with cocoa expansion recently keeping pace. Gutierrez-Velez and DeFries (2013) argued that 75% of the expansion of high-yield palm oil plantations between 2000 and 2010 occurred in old-growth forests. These forests not only host an immense diversity of flora and fauna of major intrinsic value, but also have a monetary value that could contribute to the local economy. In particular, according to the Peruvian Amazon Research Institute, carbon stocks are a major but unexploited economic asset of the Amazon, estimated at US$ 2.8 billion (IIAP, 2009). Importantly, Ucayali’s forests can provide ecosystem services that are crucial for local food security, as sources of wild fruits, bush meat, medicinal plants and firewood (Murray, 2006.; Porro *et al.*, 2015).

The World Food Summit defined food security as a condition that exists ‘when all people, at all times, have physical and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life’ (FAO, 1996). Food security has four pillars, availability, access, utilisation and stability, which need to be achieved simultaneously. Food availability includes a sufficient supply of food; access includes physical and economic access to food (including entitlements and cash income, respectively); food utilisation involves having the energy and nutrients necessary for a healthy life; and food stability requires that the other three requirements are fulfilled throughout the year and in all years despite economic or political instability (FAO, 2008). Each pillar of food security depends on the provisioning and sustainable use of ecosystem services, which support food production, provide wild foods, deliver resources for income generating activities (to acquire food), and ensure a diversified and nutritional diet in the region (Richardson, 2010; Cruz-Garcia *et al.*, 2016). Consequently, deforestation is a major threat to food security in the Peruvian Amazon, where, between 2010 and 2014, a quarter of children under five suffered from chronic malnutrition (Ministerio de Salud, 2014). It is crucial to achieve food security in a way that is environmentally and socially sustainable (Godfray *et al.*, 2010; Richardson, 2010), particularly in Ucayali, where 56% of the population is vulnerable to food insecurity (MIDIS, 2012).

Interactions between ecosystem services and food security are usually analysed at aggregated levels (Thrupp, 2000), while research on their trade-offs was recently reported to be insufficient (Cruz-Garcia *et al.*, 2016). Understanding trade-offs between food security and forest ecosystem services at household level is particularly urgent in regions where multiple social and environmental drivers are leading to resource depletion. Although deforestation in the Amazon – at a large scale – has largely been driven by companies, larger land owners, the construction of roads, and reinforced by national policies (Dammert, 2014; Fraser, 2014), small-holder *mestizos* (who are settlers from non-Amazonian regions of Peru) have been linked to deforestation as a way to ensure land tenure rights within a political-ecological context where demand of land for commercial agriculture and extractive activities is high (Alvarez and Naughton-Treves, 2003; Porro *et al.*, 2015). For instance, *mestizos* in Ucayali have cleared a great extent of their forest to establish palm oil plantations (Gewin, 2018). However, *mestizo* households still possess some forest patches within their land in which they maintain various useful tree species. Despite the importance of these forest patches to supporting household livelihoods and food security, they often cut down trees for firewood or sell as timber (Cruz-Garcia, 2017). While they recognize the importance of forest ecosystem services for both food security and income generation, to the best of our knowledge, the trade-offs between forest exploitation and food security have not been yet assessed at disaggregated level. This is necessary given that disaggregated analyses at household level can provide critical knowledge on sustainable and locally appropriate management of ecosystem services (Daw *et al.*, 2011; Reyers *et al.*, 2013; Poppy *et al.*, 2014). Such research would not only enable analysis of the sustainability of existing forest exploitation practices but also their effects on food security. It would also deepen our understanding of the factors that influence farmer's management decisions concerning trade-offs at the forest-agriculture interface, i.e. between agricultural expansion and forest conservation.

Whole farm modelling tools make it possible to represent and analyse the trade-offs and synergies concerning household's decisions on farming management practices (Rodriguez *et al.*, 2014), and are useful tools for quantifying the trade-offs between ecosystem services and food security (UNEP, 2011). Some whole-farm modelling tools (Börner *et al.*, 2007; Jourdain *et al.*, 2014) have been used to analyse the effect of different policies on ecosystem services management and food security. These were mainly optimization tools that enabled the definition of the optimal allocation of resources for a set of constraints, maximizing economic or environmental objectives (Börner *et al.*, 2007; Jourdain *et al.*, 2014). However, the assumption underlying these tools is that the decision process used by a farmer under this set of constraints is optimal, a condition that is rarely met in real-life decisions. Consequently, the challenge is to describe forest exploitation – as a management strategy applied by farmers - which may be sub-optimal under imperfect information and resource constraints (Andrieu *et al.*, 2015). Simulation tools can analyse such management strategy without making assumptions about the efficiency (or optimality) of a farmer's decision-making process (Sempore *et al.*, 2015). Compared to optimization, simulation describes the functioning of existing systems and/or analyses their medium- to long-term dynamics under different scenarios. Rule-based simulation models are a specific category of whole-farm simulation models which make it possible to analyse the specific effects of farmers' decision rules on farm performances (Le Gal *et al.*, 2011).

The aim of this paper is to analyse the trade-offs and synergies between the four pillars of food security and forest exploitation at household level among *mestizo* communities in Ucayali, in the deforestation frontier of the Peruvian Amazon. In this study, forest exploitation refers to forest clearing for the extraction of wood, or for the establishment of commercial agriculture. Forest exploitation is one type of management among other forest management practices with varying degrees of impact on forest ecosystem services. The study was framed around the concept of food security instead of other relevant concepts such as food sovereignty (which is intrinsically related to agricultural biodiversity and embedded in the political ecology of the region), in order to align it to the Sustainable Development Goals (SDGs). Certainly, achieving food security (major component of Goal 2) and environmental sustainability (Goal 15) are key components of the SDGs (FAO). This study aims at contributing to the understanding of their interrelations, which could be useful for future interventions and policies focused on achieving the SDGs in the region. In order to shed more light on the trade-offs, a farm level simulation modelling tool was developed and used to (1) analyse the current trade-offs and synergies between food security and exploitation of the forest comparing different types of farming systems; and (2) to explore alternatives for minimizing these trade-offs, and provide policy insights.

2. Methods

2.1 The study area

The Ucayali region is located in the central-eastern part of Peru and is the second largest department in the country, covering an area of 102,400 km^2. In 2012, the total population was 490,000 (Porro *et al.*, 2015), with an estimated 27% increase between 2000 and 2015 (INEI, 2010). About 60% of the population lives in the capital, Pucallpa. Ucayali is the main center of the Peruvian timber industry (Ramos Delgado, 2009). Agriculture contributes to 19% of the regional production (Banco Central de Reserva del Perú, 2012). Crops such as cassava, plantain, papaya and rice account for 78% of the local production, and are grown mainly for household consumption with the surplus for sale. Cash crops, including oil palm (supported by government incentives and formerly by international cooperation), cocoa and coffee (supported by the increasing demand for exports), and camu camu (*Myrciaria dubia*

(Kunth)), are rapidly expanding (Pacheco, 2012; Banco Central de Reserva del Perú, 2012; Bennett *et al.*, 2018). Coca is also produced in an estimated area between 2,000 and 3,000 ha (DEVIDA, 2014). This crop, when grown illegally leads to a significant bias in the analysis of livelihood outcomes as it is an unaccounted, non-transparent and non-quantifiable source of income.

Mestizos account for 80% of the population in Ucayali, and the rest are indigenous communities. *Mestizos* mainly depend on agriculture, livestock, and forestry (Porro *et al.*, 2015). *Mestizo* families have mostly settled near the Federico Basadre highway or along the banks of the Ucayali River and its tributaries. The highway, which connects the city of Pucallpa to Lima (860 Km), was built in 1945 (Pimentel *et al.*, 2004). *Mestizos* make combined use of different environments in the farming-forestry system, including agricultural fields, forests (which are mainly secondary), fallow fields and home gardens (Cruz-Garcia and Vael, 2017). Results of previous studies in the region suggest that deforestation is correlated with wealth: *mestizo* farmers in highly deforested non-remote areas are wealthier than indigenous farmers, and that both remote and non-remote *mestizo* households derive significant income from the sale of timber (Pacheco, 2012; Gutiérrez-Vélez and DeFries, 2013; Porro *et al.*, 2015). In terms of food security, chronic malnutrition in Ucayali is higher than the national average (Guevara Salas, 2009).

Data for the present study were collected in October 2014 (24 individual interviews) and in February and August 2015 (two-round survey of 58 households) in three *mestizo* communities, La Union, Pueblo Libre, and Yerbas Buenas, all located near the Federico Basadre road (Figure 1, Table1). The communities were selected as part of a replication study (Blundo et al., *in preparation*) of a previous study carried out in 2000 and described in Murray (2006). At that time, these communities were part of an international research project in Ucayali on the development of an ecosystem approach to human health assessment, and were selected by local experts as representative of the main livelihood strategies of *mestizo* households in the region.

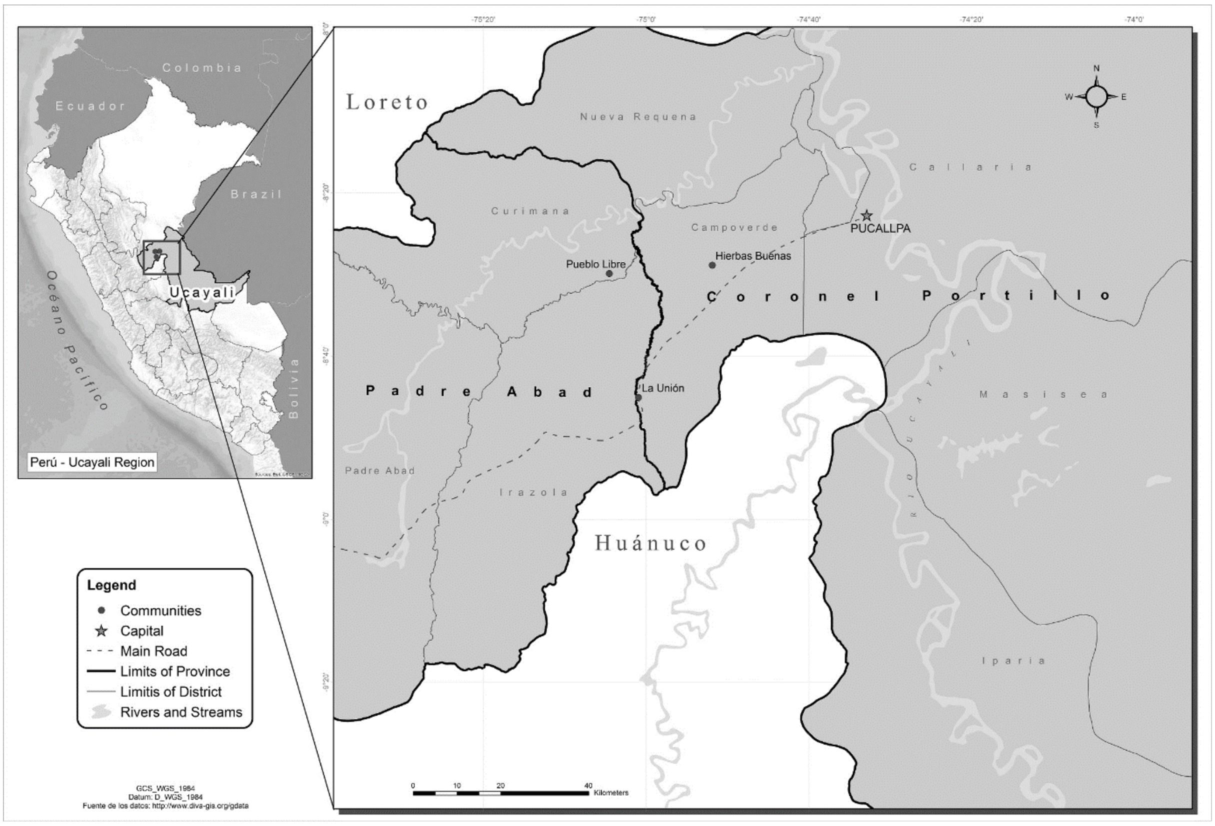


Figure 1: Location of the three *mestizo* communities where the study took place, in Ucayali, Peru

Table 1: Characteristics of the three *mestizo* communities which participated in the study

Community	Number of inhabitants*	Number of families*	Distance to Pucallpa (minutes by road)	% deforestation (2001-2014)**	Forest cover (% area with 60% canopy in 2014)**
Yerbas Buenas	682	84	60	16.8	39.5
Pueblo Libre	354	76	120	36.2	50.2
La Unión	959	145	90	19.6	50.3

* Source*: Dirección Regional de Salud Ucayali, Gobierno Regional de Ucayali (retrieved in July 2017)*

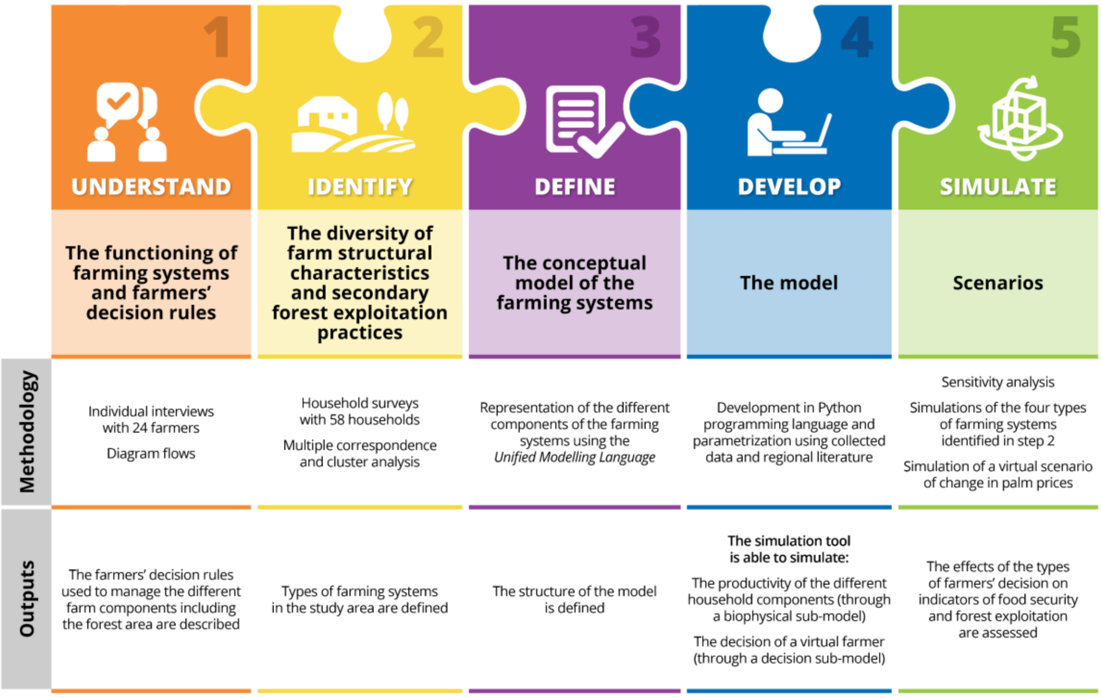
** Estimated by Paula Paz from Terra-i CIAT[1]

2.2. Steps for the development of the simulation modelling tool

The simulation modelling tool was designed to simulate different proxies of the four dimensions of food security: availability, access, utilisation and stability. The tool was developed and applied in five complementary steps (Figure 2):

- Step 1: Individual interviews were conducted with farmers at the study sites to understand the functioning of farming systems and the farmers' main decision rules.

- Step 2: A typology of farming systems in the three communities was built to understand the diversity of farm structural characteristics and secondary forest exploitation practices, based on information collected during the household surveys.
- Step 3: A conceptual model was designed to represent the different farming systems identified in step 2.
- Step 4: The model designed in step 3 was developed and parametrised using collected data in steps 2 and 3, and regional literature
- Step5: The tool developed in step 4 was used to analyse, for the different types of farming systems found in step 2, the current trade-offs between the different dimensions of food security and the exploitation of the forest area.



	1 UNDERSTAND	2 IDENTIFY	3 DEFINE	4 DEVELOP	5 SIMULATE
	The functioning of farming systems and farmers' decision rules	**The diversity of farm structural characteristics and secondary forest exploitation practices**	**The conceptual model of the farming systems**	**The model**	**Scenarios**
Methodology	Individual interviews with 24 farmers Diagram flows	Household surveys with 58 households Multiple correspondence and cluster analysis	Representation of the different components of the farming systems using the *Unified Modelling Language*	Development in Python programming language and parametrization using collected data and regional literature	Sensitivity analysis Simulations of the four types of farming systems identified in step 2 Simulation of a virtual scenario of change in palm prices
Outputs	The farmers' decision rules used to manage the different farm components including the forest area are described	Types of farming systems in the study area are defined	The structure of the model is defined	**The simulation tool is able to simulate:** The productivity of the different household components (through a biophysical sub-model) The decision of a virtual farmer (through a decision sub-model)	The effects of the types of farmers' decision on indicators of food security and forest exploitation are assessed

Figure 2: Overall description of the five steps of the methodology

2.2.1. Step 1: Description of farmers' main decision rules

The individual interviews were based on diagram flows (Diarisso *et al.*, 2015), which are discussion support tools that help define the intensity and determinants of the flows of biomass between cultivated and uncultivated areas, and the rationale for forest clearing. Interviews were conducted with 24 farmers in three meetings, one per community. Farmers were invited to participate in the meetings by local farmer leaders in the three communities, previously instructed to invite 8 to 10 women and men farmers for each meeting. Only individuals for whom farming was the main production activity were invited to participate. Each meeting had 7-8 participants and lasted an average of 2-3 hours. Three researchers conducted the interviews in parallel. During each interview, farmers were asked to individually prepare a diagram describing and mapping the management of different landscape elements and associated flows of biomass among them. To this end, each farmer was asked to start by drawing the location of their house and main geographic reference points. Then, they were asked to draw the different land areas to which they had access and use or maintain (including forests and agricultural fields). Finally, they were asked to draw the flows of biomass among the different components of the map. Each farmer worked on her/his map with a researcher, who provided the necessary support to enable him/her to draw the map, ensured that the map included all relevant details, and enquired about the flows between the different areas: determinants, triggers, intensity, and periodicity, subsequently used to understand the management decision rules concerning the different elements of the landscape. All the participants did this exercise freely, having given their prior informed consent.

2.2.2. Step 2: Typology of farming systems

Data collected in surveys of 58 households conducted in two rounds, one in February (wet season) and one in August (dry season), 2015, were taken from a broader longitudinal study aimed at analysing dietary and land use changes (Blundo Canto *et al.*, in preparation) and used as quantitative data for the modelling tool. The sample was a replication of a study conducted in 2000 and described in Murray (Murray, 2006.), who interviewed all households with children aged 1-10 living in the four *mestizo* and in the four indigenous communities that formed part of her research program. The current study focuses on three of the four *mestizo* communities, only those located along the road, in order to model trade-offs and synergies between food security and forest exploitation of households living in upland ecosystems subject to similar economic and environmental constraints. All the original households were contacted.

Participants gave their prior informed consent and participated freely. The survey was conducted in two rounds and included the following modules: socio-demographic, economic, agricultural production, forest exploitation, food security, and land use change, with a recall period of 6 months. For Step 2 we used responses from the modules on: 1) farm income (how much did they spend on inputs for agricultural production, including livestock, and how much did they gain from selling these products in the past six months); 2) agricultural production (for each area with crops, planted trees, or livestock, which crops, trees or livestock did they produce in the past six months and which was the extension in hectare.); and 3) forest exploitation (for each forest area, within or outside household properties, how many plants and animals did they harvest, gather, collect or hunt and how much wood or timber did they extract in the past six months). A database was built using Stata (StataCorp, 2013) and analysed in Microsoft Excel.

We applied multiple correspondence analysis (MCA) (Greenacre, 1984) and hierarchical clustering (HC) to data collected in the household survey to identify the main types of farming systems based on the structural characteristics of the farm and including exploitation practices related to the secondary forest using ExcelStat. Numerical variables were transformed into categorical variables according to the data distribution (average and quartiles). The explanatory (active) variables were the structural characteristics of the farms (total area, area used to cultivate the main crop, and number of livestock). Dependent variables (area of secondary forest and exploitation) were used as supplementary variables (Table 2). Socio-economic and demographic variables, including household dependency ratio, number of contracted workers, number of family workers, number of income sources in addition to agriculture and livestock farming, were used in the first round of the MCA as supplementary variables but were subsequently deleted since they did not explain the variations found in the first two factors. HC was performed using the outputs of the MCA. The results of the MCA show the main factors contributing to the dispersion of observations. The HC procedure was consequently applied to produce main types of farmers (see section 3.1).

Table 2: Variables used in the MCA

Type of variable	Variable	Modalities
Active variables	Cropping area	0 ha, <10 ha, >10 ha
	Grazing area	Yes, No
	Oil palm crop area	Yes, No
	Cocoa crop area	Yes, No
	Maize crop area	Yes, No
	Lemon crop area	Yes, No
	Orange crop area	Yes, No
	Cassava area	Yes, No
	Plantain area	Yes, No
	Pineapple area	Yes, No
	Livestock	Yes, No
Supplementary variables	Community	La Unión, Pueblo Libre, Yierbas Buenas, Naranjal
	Secondary forest area	0 ha, <0.5 ha, >0.5 ha
	Hunting	Yes, No
	Firewood extraction	Yes, No
	Wood extraction	Yes, No

2.2.3. Step 3: Design of the conceptual model

We used Unified Modelling Language (Magnus and Eriksson, 2000) to represent a virtual farm composed by a forest area, livestock, and the different cropping areas found in different types of farms defined in the previous step (Figure 3). For each of these components some key characteristics and functions were selected in order to be able to calculate proxies for the different dimensions of food security:

- Availability: the proxy for this dimension was biomass production by the different crop and livestock components of the farm (tons of seed/grain/cattle meat or litres of milk) and the forest area owned by the household (only for households that own forest);
- Access: the annual income (US$) of the farm was used as a proxy for economic access to food (Gregory *et al.*, 2005). The physical access to food, which is related to access to land, was not

included since the study only focused on land-owner farmers who are the ones who can make decisions about their land (landless were excluded).

- Utilisation: the proxy for this dimension was energy estimated by the kcal ratio of household production to their needs (%) as proposed by Hammond et al. (2017). Although utilisation also includes nutrient intake, and that it has been recognized that both energy and nutrient intake are the result of good care and feeding practices, food preparation, dietary diversity, intra-household distribution of food, and clean water and sanitation, only the consumption of adequate energy (necessary to meet the physiological needs of family members) was taken into account for this study (FAO *et al*., 2018; FAO, 2006). This was calculated as the ratio of the estimated calorie supply of the different components of the farm (crop, livestock) and the forest area owned by the household, to the overall estimated calorie needs of the household (based on the size of the household and the ages of its members). The ratio is below 100% when the farm and the forest cannot cover the calorie needs of the family, otherwise it is more than 100%. For the calorie supply of crops, we only considered the main staples cultivated in the biggest areas at the study sites: plantain, cassava and maize. We assumed the households first satisfy their caloric needs and then, once these are satisfied, sell the surplus;
- Stability: the coefficient of inter-annual variation in income and the inter-annual variation in production were used as a proxy for stability.

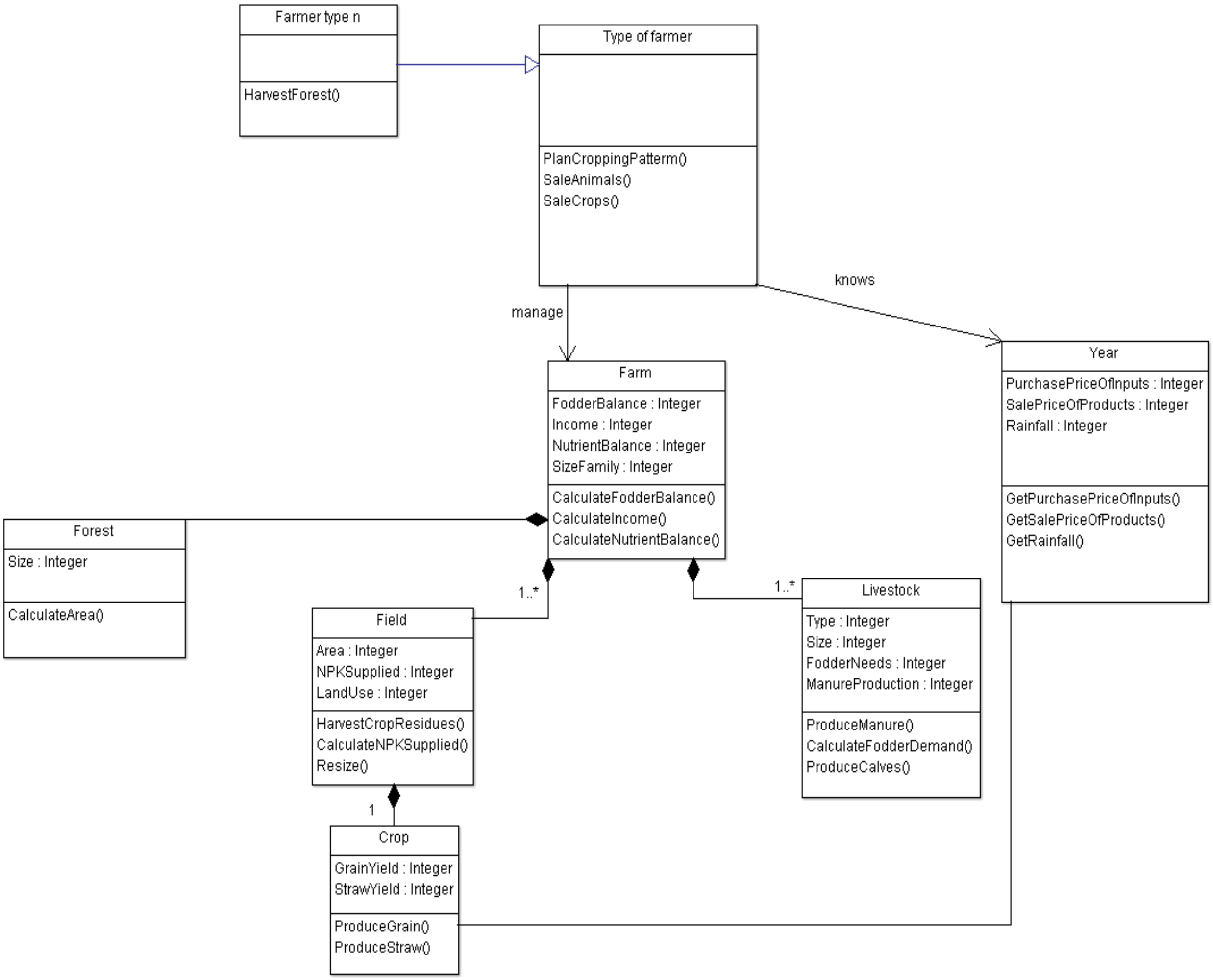


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Figure 3 : Class diagram showing the structure of the model. Each box represents a class or module of the model. The name of the module is indicated in the top section of the box, its main attributes in the middle, and its main functions or calculations in the bottom. These modules are linked between them by relationships indicated by lines. These links can be relationships of composition when the instance of a module is made up of instances of other modules (——◇) or can be relationships of inheritance when a module is derived from another one and consequently has the same attributes and functions but also specific ones (⟶)

2.2.4. Step 4: Development of the modelling tool

We developed an object-oriented modelling tool for more flexibility (thus making it possible to add or delate components without changing the other components of the modelling tool). We used Python a freely distributed interactive, object-oriented programming language (http://www.python/).

2.3. Description of the simulation modelling tool

The aim of the modelling tool is to simulate the trade-offs between the management of the forest areas and the different dimensions of food security. For that, the simulation tool consists of a biophysical sub-model, which simulates the productivity of the different household components and a decision sub-model, which simulates the main decision rules that determine the dynamics of the system.

2.3.1. The biophysical sub-model

The biophysical sub-model focuses on the biophysical components owned by the household, which include the different areas the household uses to ensure their food security, including agricultural fields, grassland and forests (Figure 3). The sub-model is composed of five modules: farm, crop, grass, forest and livestock.

A. Farm module

This module calculates the nutritional household kcal ration (eq.1), the age dynamics of the family, and the annual income of the farm.

$$Cal = -\frac{\left(GY_{Crop} \times S_{Crop} \times NV_{Crop} + ForestP \times NV_{Forest} + AnimalP \times NV_{Milk/Meat}\right)}{\sum_{Age} N\_Family \times NR} \quad \text{(eq. 1)}$$

where Cal is the kcal ration (%), GYcrop is the yield of the staple crop used for self-consumption, SCrop is the area used to cultivate these crops (ha), NV_{Crop} is the average nutritional value of the crop (kgCal.kg^{-1}), ForestP is the food produced by the forest, NVForest is the average nutritional value of forest products (kgCal.kg^{-1}), AnimalP is the production of meat and milk by the cattle owned by the household,

$NV_{Milk/Meat}$ is the nutritional value of the milk or cattle meat(kgCal.kg^{-1}), N_Family is the size of each age class in the family, and NR is the nutritional requirement per person per year (kgCal). For the dynamics of the family, we considered that children and adolescents change age class of every five years (Table 4). The annual income of the farm (GM) is the difference between the income and the cost of cropping and livestock systems, and the sales of wood and timber when forest is cleared.

B. Crop module

Although 7% of farmers grow a large number of crops, we focused on the specific roles of six crops in the farming systems, because they account for about 80% of the production in the average cropping system (Banco Central de Reserva del Perú, 2012). Plantain and cassava are grown for household consumption and for sale; maize is grown for household consumption and sale; oil palm, citrus (lemons and oranges), and cocoa, are cash crops. To estimate grain yields for these crops, we considered the effect of rainfall on yields, as variations in river flows contribute to uncertain productivity and profitability in the region (Labarta *et al.*, 2007), and can have direct effects on food security. To estimate the effect of rainfall on yields, we analysed the Pearson correlation between existing regional (INEI, 2015) annual yields and rainfall (Table 3) between 2002 and 2013. We found a correlation between rainfall and yields of cocoa, oil palm, maize, and lemon. The correlation between rainfall and plantain yields was low, which does not prove no dynamics exist, but rather that, for the data used, other factors such as management or soil characteristics have a greater effect on yields. We consequently used the linear correlation equations (eq. 2, 3, 4, 5) to estimate the effect of rainfall on cocoa, palm, lemon, and maize yields (Y_{crop}, t/ha).

For plantain and cassava, we used a single average value corresponding to the average yield reported by the households surveyed (Table 4).

$$Y_{Maize} = 4 \times 10^{-4} \times Rain + 0.42 \qquad \text{eq.2}$$

where Rain is annual rainfall (mm)

$$Y_{OilPalm} = 0.03 \times Rain - 116 \qquad \text{eq.3}$$

$$Y_{Cocoa} = 1.3 \times 10^{-3} \times Rain - 4.3 \qquad \text{eq.4}$$

$$Y_{Lemon} = 0.012 \times Rain - 4.8 \quad \text{eq.5}$$

Table 3: Correlation between rainfall and crop production for oil palm, cocoa, and maize

Crop	R	p-value
Oil palm	0.55	0.068
Cocoa	0.54	0.063
Maize	0.59	0.058
Lemon	0.51	0.10
Plantain	0.08	0.785
Cassava	0.17	0.603

For oil palm, we considered that production begins in the third year after plantation with an average yield of 400 kg/ha, increasing to 4 t/ha, 8 t/ha, and 11t/ha from the third to the sixth year of the crop, equation 3 was used from the seventh year of simulation (Gobierno Regional de Ucayali, 2012).

C. Grass module

This module simulates the production of grass as animal fodder, based on the work done by Vela Alvarado and Flores Mere (1996):

$$Y_{Grass} = 0.0008 \times Rain + 1.7378 \quad \text{eq.6}$$

D. Livestock module

This module calculates the reproduction of livestock and the fodder balance that drives the dynamics of the system, particularly for type 1 farmers. It is measured as the balance of biomass between the supply of fodder in the different biophysical components and the biomass needs of the type and number of animals.

$$N_{Coh} = N_{Coh} \times (1 - AMR) \quad \text{eq.7}$$

where *NCoh is* the size of each animal cohort, and AMR is the reform mortality rate, according to Bartl *et al.* (2009).

$$N_{Calves} = N_{Cow} \times AC \times (1 - CMR) \text{ eq.8}$$

where *Ncalves is* the number of calves, AC is the annual calving rate, and CMR is the calf mortality rate according to Bartl *et al.* (2009).

$$FodB = \sum_{Crop} \left(Stock_{Crop} \right) + Y_{Grass} \times S_{Grass} - \sum_{Coh} DR_{Coh} \times 365 \text{ eq.9}$$

where FodB is the fodder balance, StockCrop is the fodder stocks made up of maize stalks (kg) calculated in the Crop module, YGrass is the yield of the grazing area (kg/ha), SGrass is the surface area of grazing land (ha), DR is the fodder requirement of each cohort (kg/day).

This module also calculates milk (P_{Milk}) and meat (P_{Meat}) production.

$$P_{Milk} = N_{Cow} \times Y_{Milk} \times D \quad \text{eq.10}$$

where Y_{Milk} is the milk production per animal according to Sheen and Riesco (2002), D is the duration of lactation according to Bartl *et al.* (2009).

$$P_{Meat} = N_{Cow} \times RR \times Y_{Meat} \text{ eq.11}$$

where RR is the replacement rate of cows according to Bartl *et al.* (2009), Y_{Meat} is the yield of edible meat per cattle according to OEEE-MINAG (Oficina de Estudios Económicos y Estadísticos Ministerio de Agricultura, 2011).

E. Forest module

At our study sites, the forest is used for hunting, to collect leaves and firewood for own consumption or sale. Although it has been reported that *mestizo* farmers from Ucayali also gather wild fruits from the forest (Cruz-Garcia and Vael, 2017), the amount of gathering events reported in the household surveys was low. The mapping exercise during the individual interviews indicated that forest is usually considered by farmers as a reserve of land that enables them to increase grazing and cropped areas when needed, and a reserve of wood to sell when required. In the forest module, a cleared hectare of forest is consequently associated with the average value of marketable wood (Sears *et al.*, 2014).

Type 3 farmers with highest diversity, practice hunting (Table 5). To provide a proxy for this activity we chose "carachupa" (or nine-banded armadillo, *Dasypus novemcinctus*), which was the most frequently hunted animal in the forest according to the household survey. We found that they extract one “carachupa” each five hectares: this value was multiplied by its calorie content (Table 4).

Table 4: Main parameters of the modelling tool

Modules	Name of the variable		Value	Reference
Farm	Average daily calorie needs per age class	Children 1-5 years old (kcal day^{-1})	1,160	(FAO/WHO/UNU, 2001)
		Children 5-10 years old (kcal day^{-1})	1,694	
		Adolescent 10-18 years old (kcal day^{-1})	2,531	
		Reform of 18 to >60 years old (kcal day^{-1})	2,525	
	Annual cost of palm (US$ ha^{-1})		166 to 2,087[1]	(Gobierno Regional de Ucayali, 2012)
	Annual cost of maize (US$ ha^{-1})		594	(Agraria, 2012)
	Annual cost of cocoa (US$ ha^{-1})		617 to 1,133[2]	(Agraria, 2013)
	Annual cost of Limon (US$ ha^{-1})		900	(INEI, 2015)
	Sale price of oil palm seed (US$ ton^{-1})		185	(Gobierno Regional de Ucayali, 2012)
	Sale price of maize (US$ ton^{-1})		259	(Agraria, 2012)
	Sale price of cocoa (US$ ton^{-1})		1700	(INEI, 2015)
	Sale price of Limon		88	(INEI, 2015)
Livestock	Fodder needs per TLU[3] (kg day^{-1})		6.25	(Boudet, 1975)
	Milk production per animal (kg day^{-1})		4.3	(Sheen and Riesco, 2002)
	Yield of edible meat per cattle (%)		51	(Oficina de Estudios Económicos y Estadísticos Ministerio de Agricultura, 2011)
	Local reproduction parameters for livestock	Annual calving (%)	65.3	(Bartl *et al.*, 2009)
		Calf mortality (%)	12.3	
		Reform mortality (%)	2.93	
		Replacement rate (%)	17.6	
		Duration of lactation (days)	255	
	Nutritional value of milk (kcal L^{-1})		495	(Murray, 2006.)
	Nutritional value of cattle meat (kcal kg^{-1})		305	
Crop	Nutritional value of maize (kcal kg^{-1})		361	(Murray, 2006.)
	Nutritional value of plantain (kcal kg^{-1})		122	
	Nutritional value of cassava (kcal kg^{-1})		121	
	Average yield of plantain (kg ha^{-1})		12,400	(INEI, 2015)
	Average yield of cassava (kg ha^{-1})		13,900	(INEI, 2015)
Forest	Nutritional value of one "carachupa" (kcal)		172	(Murray, 2006.)
	Marketable wood (US$ ha^{-1})		450	(Sears *et al.*, 2014)

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[1] The costs for oil palm vary according to the year of the crop, the first year includes the cost of stablishing the crop, and subsequent years include maintenance costs.

[2] The costs for cocoa vary according to the year of the crop, the first year includes the cost of stablishing the crop, and subsequent years include maintenance costs

[3] Tropical Livestock Unit, animal of 250 kg of live weight

2.3.2. The decision sub-model

The decision sub-model simulates a virtual farmer and monitors the clearing of the forest according to the state of the biophysical sub-model. The management decisions made by the virtual farmer have an impact on the food security dimensions simulated by the biophysical sub-model through feedback loops. A series of simplified decision rules (in the form of "*If* conditions *then* action" rules) was developed for each type of farming system based on the individual interviews (see section 3.1).

2.4. Scenarios

To understand the functioning of the modelling tool, a sensitivity analysis was conducted on input data and parameters with the highest uncertainty (parameters estimated from the literature). In both cases, we assessed how variations of -10 or + 10% affected the simulation results compared to the default value. The sensitivity analysis was conducted of changes in parameters (sale price of oil palm seed, maize, and plantain, yield of oil palm, maize, plantain, cocoa and citrus, annual calving, calf mortality, reform, and replacement rates) and input data (number of cows, area of maize, oil palm, plantain, grassland) for each type of farmer. This analysis enabled us to understand which parameter and input data have the most effect on the income of each type of farmer. Changes of +10% and -10% were applied to the default values defined in Tables 4 and 6. Sixty-eight simulations were run.

The dynamics of the different types of farmers were compared for 10 simulated years in order to analyse the current trade-offs between the different dimensions of food security and the exploitation of their forest area. The simulations used rainfall data from the Aguaytia station (latitude: -9.02, longitude: -75.30, altitude: 270 m) from January 2003 to December 2014. For these simulations, we built virtual farms considering the structural characteristics of the different types of farms, but assuming that they all started with the same total area, forest reserve area, and family composition. Expansion of cash crops at the study sites is largely supported by favorable public policies and incentives, especially for oil palm (Banco Central de Reserva del Perú, 2012). Therefore, we modeled a decrease in oil palm prices for farmers cultivating oil palm, in order to simulate the effects of macroeconomic changes that could affect the sale prices, such as a decrease in public incentives or a drop in international prices. The sale price of palm oil in the region has been increasing since 2000, but with variations that can lead to an inter-annual variation and a 50% decrease in the average price (Figure S1), so simulating such an event is indispensable. To better understand the sustainability-related issue facing these farmers, we simulated the effect of a 50% decrease in the sale price of palm oil.

3. Results

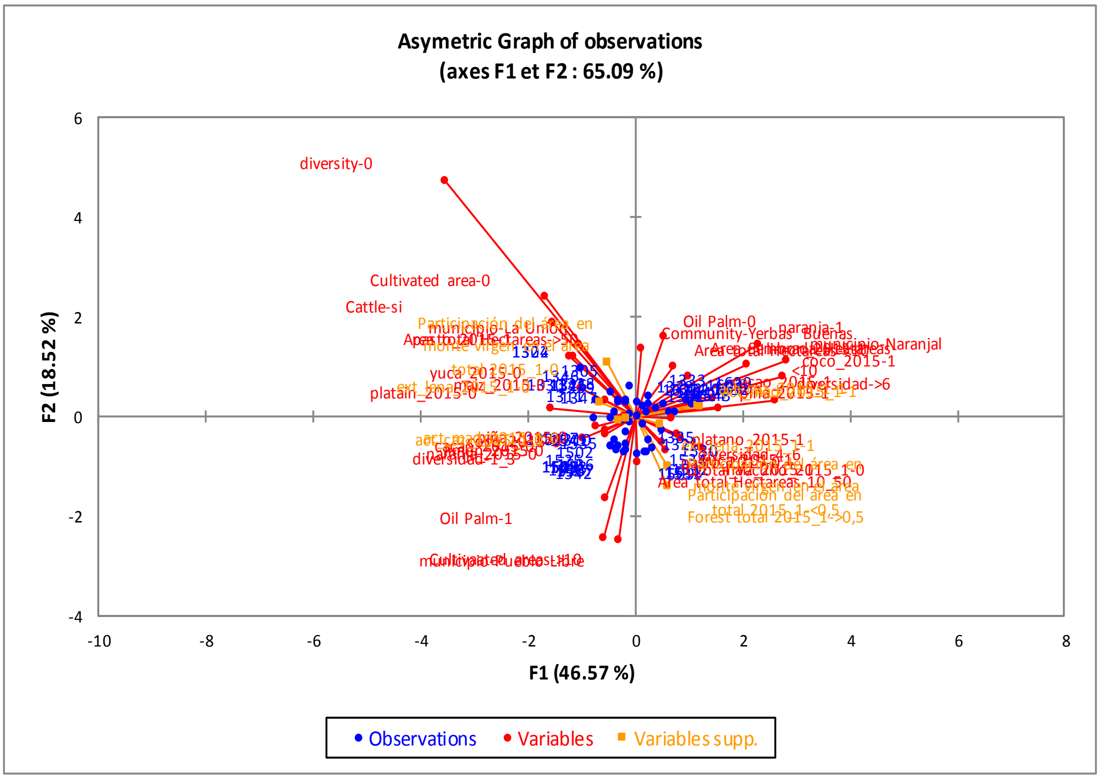
3.1. Types of farming systems and their virtual decision rules for forest clearing

The first step of the study allowed to understand the rationale for forest clearing. Indeed, four of the seven interviewed livestock breeders in this first step did not own any forest. They cleared the forest for pasture as the herd increased, leading to an increase in demand for fodder. Oil palm (one of seven farmers) and - more recently - cocoa (five of the seven) have been introduced by these farmers as an alternative to livestock production because of the reduced productivity of grazing areas. Farmers producing oil palm (12) declared having started its cultivation in the 2000s as a result of government subsidies and other incentives to cultivate alternative crops to coca. In these farms, the residual forest area may still be relatively high (> to 50% of the total area of the farm for five of the twelve farmers) but is mainly considered (nine of the 12 farmers) as a land reserve where the forest could be cut to increase the area for oil palm or other cash crops. Three of the 24 farmers mentioned that the clearing of residual forest areas was linked to domestic shocks (illness, increasing educational expenses, and so on, which encourage the farmers to clear forest for alternative uses).

The second step of the study permitted to identify four types of farmers. Indeed, the results of the MCA showed that the first two factors combined explained 67% of the dispersion of observations (Figure 4). The first factor dissociates farms with livestock and grazing areas (to the left) from farms with no livestock. The latter presents high crop diversity (all crops except oil palm), and more intense use of the forest, as they extract leaves and firewood from secondary forests. The second factor mainly dissociates farmers with large cropping areas, secondary forest, who cultivate oil palm (to the bottom) from farmers with small cropping areas who do not cultivate oil palm (at the top). The HC procedure produced four main types of farmers which we named according to their main characteristics:

- Type 1: “livestock farmers”,
- Type 2: “moderately-diversified crop farmers”
- Type 3: “highly-diversified crop farmers”
- Type 4: “oil palm farmers”

The main characteristics of each type of farmer are summarized in table 5. These characteristics correspond to the prototypal farmer in each class, and other farmers in the same class may differ.



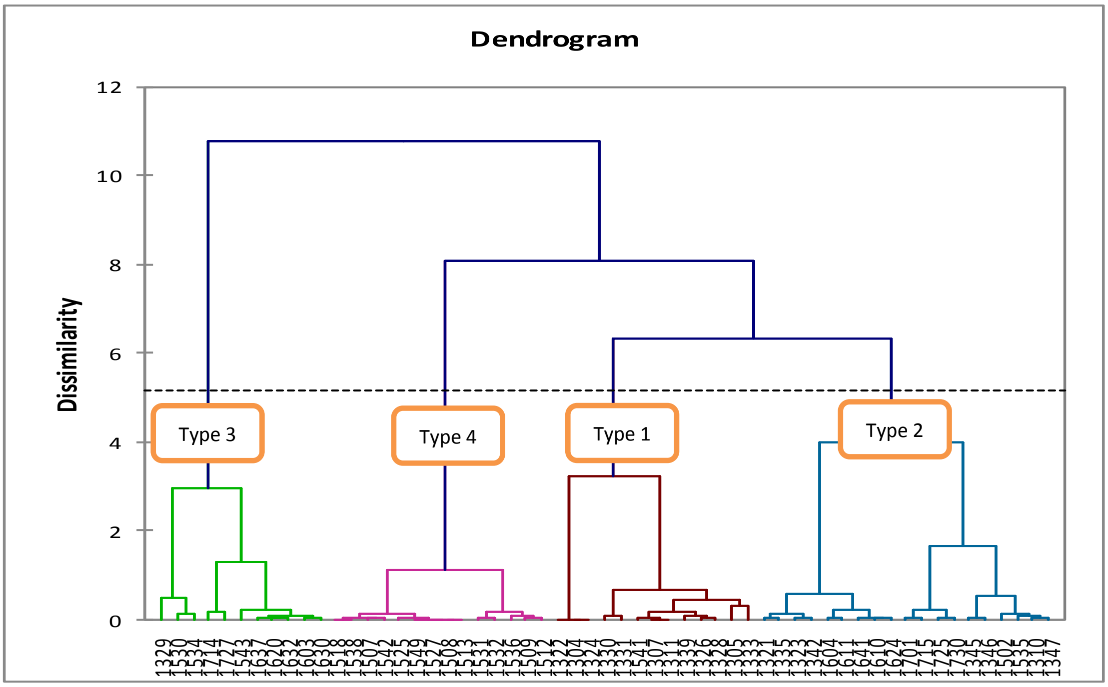


Figure 4: Types obtained based on the multiple correspondence analysis and hierarchical clustering

Table 5: Average characteristics of the types of farming systems

	Type 1 (n=13)	Type 2 (n=19)	Type 3 (n=11)	Type 4 (n=14)
Total cultivated area (ha)	0	<10	<10	>10
Oil palm	no	no	no	yes
Plantain	no	yes	yes	Yes
Cassava	no	yes	yes	yes
Cocoa	no	yes	yes	no
Maize	no	no	yes	no
Citrus	no	no	yes	no
Pineapple	no	no	no	yes
Grazing areas	yes	no	no	no
Livestock	yes	no	no	no
Forest area	no	yes	yes	yes
Firewood extraction	no	no	yes	no
Hunting	no	no	yes	no
Wood extraction	no	yes	no	no

[1] Citrus include lemon and orange

According to the first two steps of the study, virtual rules for forest clearing were defined for each type of farmers:

- Type 1: if the fodder balance is negative in two subsequent years then an area of x will be cleared and grass planted

- Type 2: if the income is negative in two sub-sequent years then an area of x will be cleared and cocoa will be introduced

- Type 3: same decision rule as type 2, the difference between the two types being more crops are cultivated

- Type 4: if the income is more than US$ 1,300 (which corresponds to the average oil palm utility according to Gobierno Regional de Ucayali (2012)), then an area of x will be cleared and oil palm will be introduced

The specific size of the cleared patch can be adjusted to take into account the structural differences between types of farmers. The structural characteristics of the farm are used as inputs for the modelling tool.

Table 6: Original characteristics or inputs of the simulated farms per household type, before simulation.

		Type 1	Type 2	Type 3	Type 4
Crops	Original maize area (ha)	0	5	3	0.5
	Original oil palm area (ha)	0	0	0	5
	Original cocoa area (ha)	0	0	1.5	0
	Original plantain area (ha)	0	1	1	0.5
	Original citrus area (ha)	0	0	0.5	0
Forest	Original forest area (ha)	25	25	25	25
Grazing area	Original grassland area (ha)	7	0	0	0
Animals	Original number of TLU	5	0	0	0
Original composition of the family	Children	2	2	2	2
	Adults	2	2	2	2

3.2. Sensitivity of the simulation results to changes in parameter and input data values

The sensitivity analysis showed that for type 1 farmers, results were more sensitive to changes in the initial size of the herd than changes in the values of the animal reproduction parameters, rainfall or grassland area (Figure 5). For this type of farmer, increases in the replacement rate and mortality rates lead to a decrease in income. Provided that all the farmer's forest area has not yet been cleared, each decrease in the production of the grassland area per animal unit is offset by a decrease in the forest area and consequently a change in this input data had no impact on income.

For type 2 farmers, income is highly sensitive to changes in the area under plantain and maize. Decreases in plantain and maize areas increase the farmer's income because of the decision rule that introduces cocoa production after two consecutive years with a negative income. The introduction of cocoa increases the average income.

For type 3 farmers, income is mainly affected by changes in price, yield, and area under cocoa and citrus. The surplus from maize and plantain is low, consequently changes in areas, price, and yield of these crops do not affect income.

For type 4 farmers, an increase in the sale price, yield, and area under oil palm has a positive effect on income. As mentioned above, changes in yields, areas or in the price of maize and plantain do not significantly affect income.

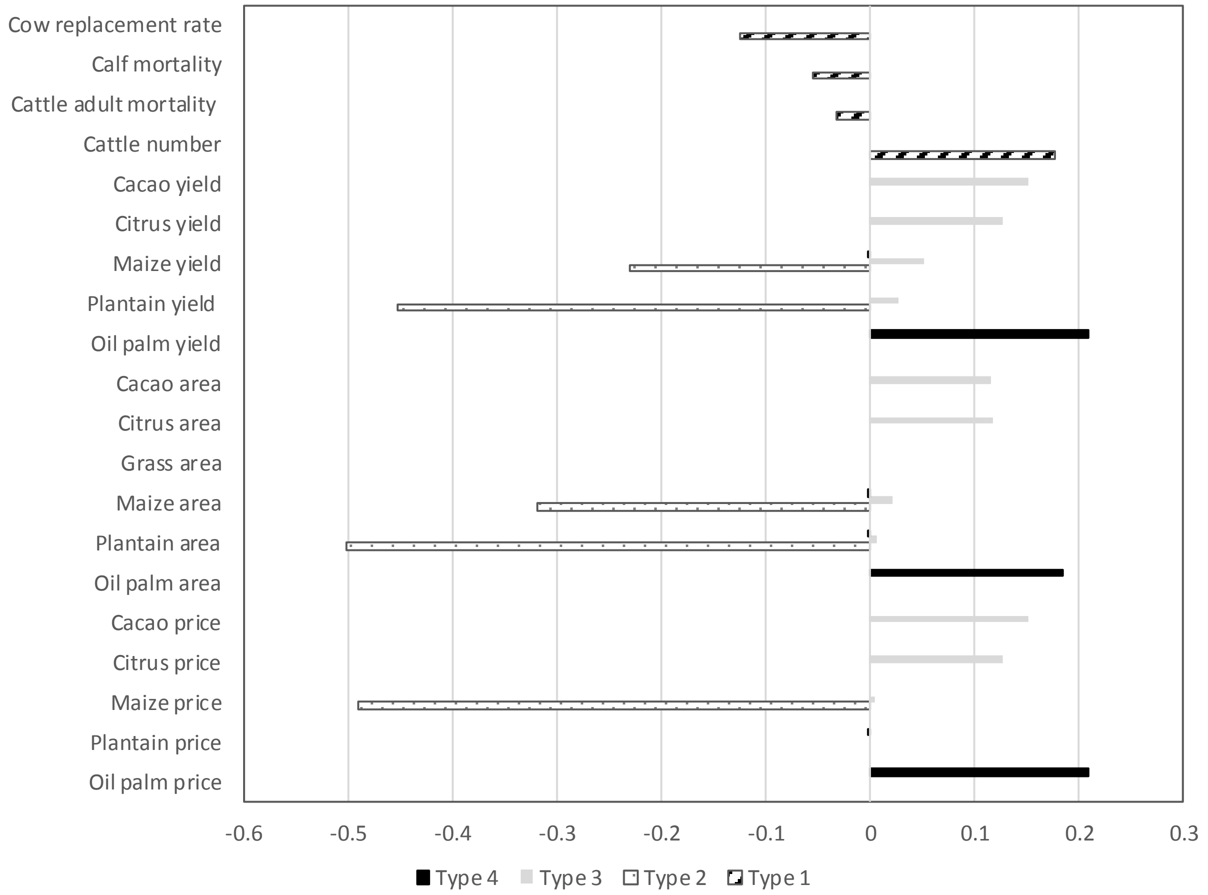


Figure 5: Relative effect on income between +10-10 scenarios for the different input and parameters and per type of farmers

3.3. Performances of the four main types of farmer

The simulations showed that each farming system leads to specific performances at a 10-year horizon depending on the dimensions of food security, on specific trade-offs within these dimensions and between the food security dimensions and forest exploitation (Table 7, figure 6). None of the simulated farms had a positive impact on all the criteria considered. Type 1 shows the highest stability linked to the lowest coefficient of variation of income and a relatively low coefficient of variation of productivity. The low coefficient of variation in income is related to regular sales of animals. Despite being stable, this income (economic access) is one of the lowest due to increased purchases of fodder over the years (because of the growth of the herd linked to a positive natality rate). Type 2 achieves full satisfaction of the utilisation dimension, but the lowest stability, leading to a high coefficient of variation in income. This system mainly produces staple crops and income depends on the surpluses that are sold. Type 3 also satisfies the utilisation dimension, does not lead to deforestation, and has one of the highest stability rates and income. Type 4 has the best economic performance enabled by the cultivation of oil palm but does not satisfy the utilisation dimension (only 26% of the caloric needs fulfilled), and its stability is one of the lowest because this type of farm is completely dependent on sales of palm oil. In addition, 20% of the forest is cleared at the end of the 10 simulated years.

Table 7: Characteristics of the simulated farms at the end of the simulation, indicating the effect of the type of farming system on food security and deforestation for each household type (the original characteristics before the simulation are listed in Table 6)

		Type 1	Type 2	Type 3	Type 4	Type 4 decrease in the sale price of palm oil
Access	*Average annual income of the 10 simulated years (US$)*	**808**	**1684**	**3245**	**7008**	**2,962**
Availability	**Average biomass production (t)**	**3.8**	**11.1**	**7.8**	**1.1**	**1.1**
Average utilisation	**Average ratio between production and household needs (%)**	**48**	**100**	**96**	**26**	**26**
Stability	**Coefficient of variation of income**	**0.19**	**1.3**	**0.39**	**1.2**	**1.4**
	Coefficient of variation of productivity	**0.21**	**0.23**	**0.18**	**0.31**	**0.31**
Deforestation rate at the end of the simulation (%)		**72**	**6**	**0**	**20**	**0**

*** The original deforestation rate was the same for all four types of farm**

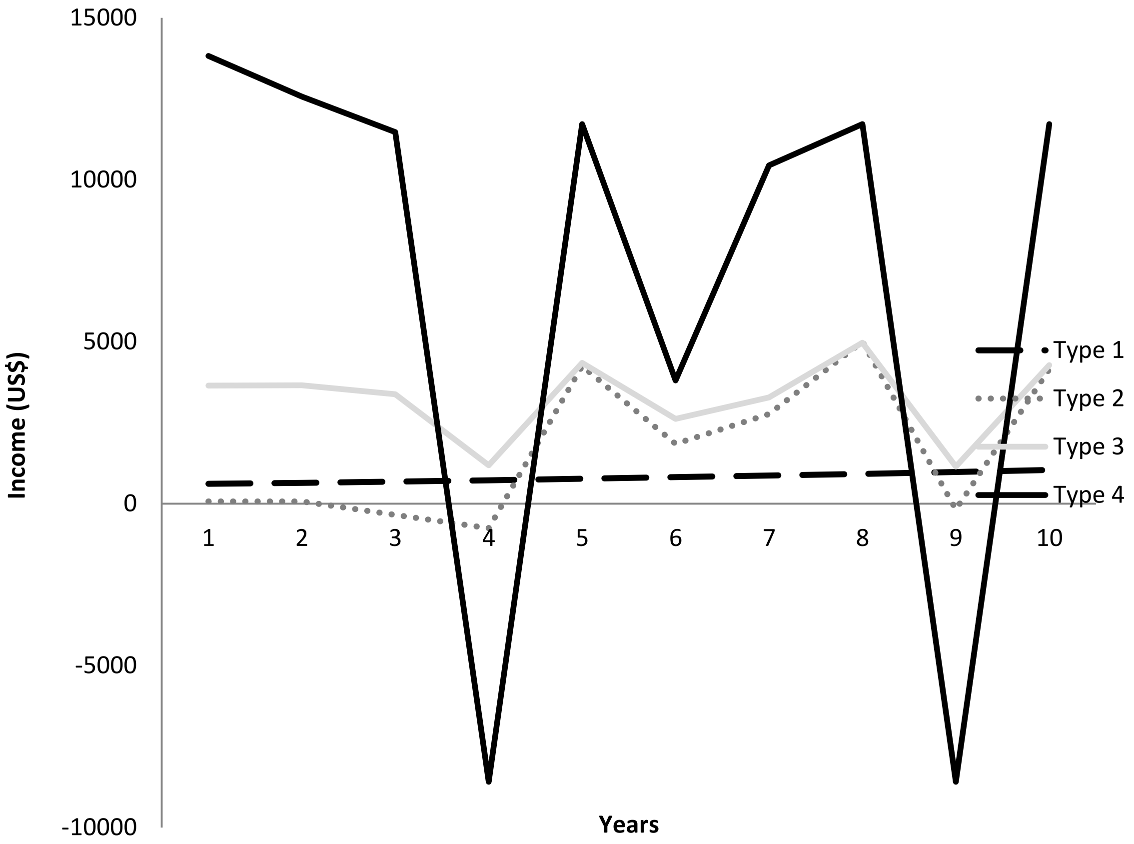


Figure 6: Simulated variation of income for the four types of households Effect of a decrease in oil palm prices on income

3.4. Decrease in sale price of oil palm seed

This scenario led to a decrease in the annual income and an increase in the coefficient of variation of income linked to high economic losses during years with low rainfall (Table 7, Figure 7). Consequently, the threshold of 1,300 US$ which triggers deforestation (section 3.1) was not reached and no forest was cleared.

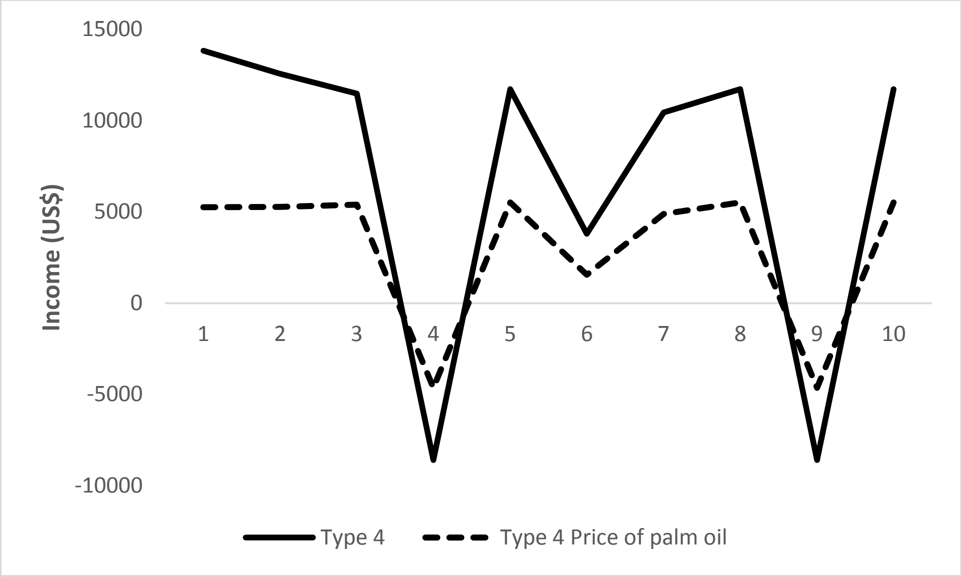


Figure 7: Simulated variation of income for the type 4 after a decrease in the sale price of palm oil

4. Discussion

4.1. Trade-offs between food security and forest exploitation

The simulations presented in this paper made it possible to quantify the trade-offs between food security and forest exploitation in *mestizo* communities, and showed that the different decision rules identified by the farmers can lead to rapid deforestation. Indeed, our simulations showed that the management practices of cattle breeders, oil palm farmers, and moderately diversified farmers led to deforestation over the 10-year simulation period. Consequently, for these types of farmers, the forest was gradually undergoing deforestation. Residual forest area at the end of the simulation period amounted to only 28% of the original forest area for livestock farmers, 80% for oil palm farmers, and 94% for moderately diversified farmer types.

Conversely, the strategy and decision rules of very diversified farmers did not lead to forest clearing over the simulated 10-year simulation period. Such results highlight the contrasting dynamics in *mestizo* communities that lead to specific forest exploitation patterns (Porro *et al.*, 2015) and the importance of carrying out disaggregated analyses with different farmer types, even within relatively small spatial areas.

Specific trade-offs were found among the dimensions of food security, and between these dimensions and forest exploitation for the different types of farmers identified. Our simulations showed that there is no ideal type achieving best performances in all food security dimensions and with respect to deforestation simultaneously. Nonetheless, crop diversification appears to be the strategy that best supports all four dimensions of food security, especially utilisation and stability, allowing income stability (but not necessarily income increases) with low rates of deforestation. These results are in agreement with those of multiple studies highlighting the importance of agricultural biodiversity to achieve food security, and sustainable food and farming systems (Thrupp, 2000; Frison *et al.*, 2011; Bioversity, 2016; Jones, 2017; Zimmerer and de Haan, 2017). These findings also emphasize the need to incorporate strategies based on agricultural biodiversity as part of initiatives and interventions that aim at achieving the SDGs 2 and 15 in the Amazon.

The less diversified strategies of the other types of farmers produced high values in one dimension of food security, such as income (related to food access), but generated substantial trade-offs in the other dimensions. For moderately diversified farming systems, that are subsistence-oriented, there are trade-offs between availability and utilisation on the one hand, and access and stability on the other. For oil palm farmers, there are trade-offs between economic access on the one hand, and availability, utilisation, stability, and forest clearing on the other. For livestock farming systems, there are trade-offs between stability on the one hand, and access, availability, utilisation, and forest clearing on the other. The livestock farming system faces the highest constraints since the constant increase in the number of livestock requires expanding the grassland areas. Such expansion is mainly based on the availability of forest areas, which are becoming increasingly scarce. A similar conclusion applies to oil palm farmers where the dynamics of the system is largely based on the availability (and decrease) of forest areas.

Additionally, we simulated changes in the sale price of palm oil, a cash crop that has undergone major expansion in recent years in the region. Such price changes can be the result of changes in subsidies, public incentives or market shocks, and decreasing trends for oil palm prices have been reported in recent years. Our simulations showed that such price changes have strong adverse effects on the income stability of oil palm growers, especially when associated with unfavourable rainfall patterns, but stimulate reduced deforestation rates in the medium term.

Although it has been reported that *mestizo* families in the study sites know a variety of species of wild fruits from secondary forests, agricultural fields and home gardens (Cruz-Garcia and Vael, 2017), we found that gathering of forest fruits was minimal. This could be related to the reduced availability of forest and the increased orientation of the production towards monocropping and markets. In addition, some farmers make use of destructive harvesting practices – i.e. cutting down trees to collect fruits – even for tree species they perceive to be decreasing in abundance (Cruz-Garcia, 2017). In this context, it is necessary to promote sustainable management practices that ensure the conservation of forest species that can play a major role on food and nutrition security, and raise awareness about their potential contribution to nutrition.

Deforestation in Ucayali is driven not only by small and medium producers but also by large enterprises, logging and mining activities (Fort and Borasino, 2016). However, focusing on the effect of individual decision rules of small-scale farmers with respect to forest clearing can provide guidance for policy makers who aim to prioritize specific farming systems. If food security and income stability with low deforestation rates are a priority, systems based on the diversification of agricultural production and the conservation of forest appear to be appropriate. On the other hand, if the objective is to increase income and the promotion of oil palm farming systems is selected for that, policy makers should be aware that this would involve a higher risk of income instability linked to low agricultural diversification, and high price volatility associated with high deforestation rates.

4.2. Strengths and limitations of the study and recommendations for future research

We built an ad-hoc modelling tool (Affholder *et al.*, 2012) that allowed us to both synthetize our knowledge on the functioning of farming systems in the deforestation frontier (steps 1, 2 and 3) and to analyse the interaction between forest exploitation and food security at household level (steps 4 and 5).

The tool built did not aim to represent the whole complexity of existing farming systems but rather to zoom into this complexity, by focusing on the consequences of farmer's management decisions (these decisions were identified based on the interviews and surveys conducted with different types of farmers). Consequently, the simulation outputs were not expected to provide an exhaustive representation of reality, but to support the comparison of different types of farming systems in relation to forest exploitation and food security. A major benefit of using a simulation tool is that it allows the exploration of the multiple effects of a particular change in the environment or in the productivity of farming systems (i.e. the sensitivity analysis and scenarios explored related to the reduction of oil palm prices). The role of simulation tools for synthetizing existing knowledge and exploring new conditions has been highlighted by several studies (van Ittersum and Donatelli, 2003; Affholder et al., 2012).

Agent based models have been developed to analyse socio-environmental systems (Iwamura *et al.*, 2016) and are particularly relevant to evaluate interactions between agents and their collective management of resources. In our case study, which was conducted with *mestizo* communities in Ucayali, the forest is considered by farmers as a private resource, often cleared to ensure land tenure rights or to obtain an additional income, rather than as a collective resource. The modelling tool we built was based on context specific data, but the method we used for its development was cost-efficient: the data corresponding to the variables used for the bio-physical sub-model was collected in standard farmer surveys or derived from the literature. The decision-making rules describing farmers' behaviour have been collected using focus groups, interviews, and surveys.

Different socio-demographic variables, such as off-farm employment or the size of the family could produce variations within each 'type' of farmer. However, they did not explain variability within the data when the typology for this particular study was built and consequently were not included in the modelling tool. . Factors such as disease or the death of a family member, or children continuing their studies after school, are economic shocks at household level that might influence farmers' decision-making, thus could be incentives to cut down trees to obtain extra income. We discussed these factors in the step 1 of the study but did not include them in the modelling tool.

The object oriented structure makes it simple to introduce more complexity in the modelling tool (Andrieu *et al.*, 2015) even if this is not always desirable since it is generally associated with more assumptions and increased errors (Passioura, 1996).

There are some aspects that could be incorporated to the simulation tool in future studies. For instance, seasonal stability in addition to inter-annual stability. Likewise, future studies could also explore the consequences of forest exploitation on nutrition, which is certainly relevant in the context of micro-nutrient deficiencies and the increasing need of diverse diets. In addition, home gardens – which play an essential role in the food security of rural households (Galluzzi *et al.*, 2010) – were not analysed separately but were included in the analysis as a component of the farm. Future modelling could distinguish the contributions of home gardens and cultivated fields as complementary environments for achieving food security. Finally, the present study paves the road for future simulations on the trade-offs between food security and forest exploitation in other scenarios, for instance, under increased incentives to improve the quality of pastures or the genetic quality of livestock, or under new incentives such as payment for forest conservation and reforestation.

5. Conclusion

We developed a methodology based on five complementary steps to facilitate the analysis of the trade-offs and synergies between food security and forest exploitation at household level among *mestizo* communities in Ucayali. First, we identified decision making rules with farmers; second, we conducted farm household surveys; third, we built a typology of their main characteristics; fourth, we developed an ad-hoc modelling tool that makes it possible to analyse current trade-offs and synergies between the four pillars of food security and forest exploitation for the different types of farming households, and five we applied the tool to compare the different types of farming systems found in the study sites. Four main types of farming households were identified based on their crop and livestock diversity: livestock farmers, moderately-diversified crop farmers, diversified crop farmers, and oil palm farmers. For all four types, the forest mainly represented a set aside area to support potential growth of agricultural production. However, over a ten-year simulation period, farm diversification appears to be the strategy that best supports forest conservation and all four dimensions of food security, particularly utilisation and stability.

This study makes an innovative methodological contribution to the existing literature, by showing the importance of agricultural biodiversity to achieve food security through the combination of participatory methods, structured surveys, multivariate analysis, and simulation tools. This tool allows to quantify the role of farming practices on food security and forest exploitation, which provides important insights for policy makers. Further research could focus on improving the modelling tool used in this study taking into account additional variables (e.g. to have a more detailed assessment of the different dimensions of food security), and to simulate other scenarios, such as conservation incentives or agricultural subsidies.

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Notes

[1] The area considered for the analysis of forest cover and deforestation rate was based on a 5-km diameter surrounding the community given that: (a) maps with the formal community boundaries did not exist for the study communities, (b) local peoples not only use their own forest but also forest

belonging to their neighbours and neighbouring communities. The 5-km diameter was selected to capture the presence of nearby forest, either private or protected which might be used by these communities. The forest cover was estimated using the percentage of area with 60% or more canopy for each community. Given that the most recent information concerning areas with 60% or more canopy dated from the year 2000, this information was estimated for 2014 using data on the percentage of deforestation for the 2001 – 2014 period (Global Forest Watch 2016). Global Forest Watch uses Landsat satellite images with a 30 m resolution. Sixty percent canopy was chosen rather than 30% canopy (which is too low to capture actual forest cover) following the recommendations of Hansen et al. (Hansen *et al.*, 2000). In addition, the area under oil palm plantations (obtained from images of Google Earth from 2010 to 2013) was deduced for the Peruvian communities, where palm oil is increasingly popular, in order to have better quality data. Although the data was corrected for oil palm plantations, the forest cover might also include some extensions with fruit trees or timber plantations, and primary forest is not differentiated from secondary forest.

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Supplementary material

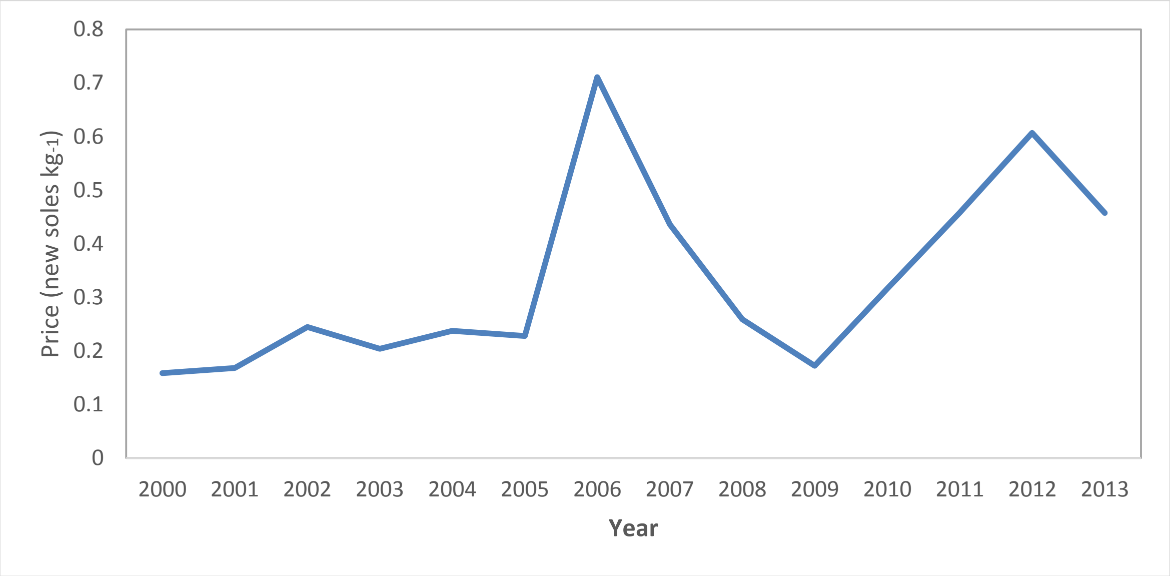

Figure S 1 : Change in oil palm price between 2000 and 2013