UNIVERSIDAD POLITÉCNICA DE MADRID

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA AGRONÓMICA,
ALIMENTARIA Y DE BIOSISTEMAS

MODELS FOR SUSTAINABLE MANAGEMENT OF AGROECOLOGICAL SYSTEMS IN CENTRAL AMERICA IN A CHANGING CLIMATE ERA

TESIS DOCTORAL

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INGENIERO AGRÓNOMO
MASTER EN AGROINGENIERÍA

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Carlos Gregorio Hernández Díaz-Ambrona
TITULAR UNIVERSIDAD

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UNIVERSIDAD POLITÉCNICA DE MADRID

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MODELOS DE GESTIÓN SOSTENIBLE DE LOS SISTEMAS AGROECOLÓGICOS EN CENTROAMÉRICA EN UNA ERA DE CLIMA CAMBIANTE

Resumen

Los sistemas agrícolas minifundistas tienen un papel importante en la producción mundial de alimento (proporcionando en torno al 70% del alimento global, e involucrando sobre 500 millones de familias). Los pequeños agricultores de las zonas montañosas del corredor seco Mesoamericano son fundamentales para poder mejorar los sistemas agrícolas. La clave está en que los pequeños agricultores de subsistencia son a la vez productores y consumidores, con una producción de alimento insuficiente debido a las condiciones climáticas y medioambientales extremas o a ingresos escasos como para suplementar su producción con productos del mercado. La modelización ofrece una manera de ensayar y mejorar nuestro conocimiento sobre los complejos sistemas agrícolas. Para abordar los problemas de los pequeños agricultores, en primer lugar desarrollamos, describimos y evaluamos un modelo biofísico y socioeconómico de los sistemas agrícolas minifundistas basado en el cultivo intercalado de maíz y frijol en las zonas montañosas de Centro América.

Una vez el modelo para la seguridad alimentaria sostenible y la reducción de la pobreza en *Smallholder Agricultural Systems in Highland Areas of Central America (SASHACA)* hubo sido desarrollado y evaluado, se aplicó en Guatemala para evaluar el impacto de las dotaciones de los pequeños agricultores en su bienestar. Finalmente, el modelo SASHACA se utilizó en Guatemala y Nicaragua para establecer una definición de agricultura familiar adaptada al contexto regional y centrada en pequeños agricultores de subsistencia o semi-subsistencia.

El modelo SASHACA integra conocimiento científico y practico del manejo de cultivos, mano de obra, contenido de agua en el suelo, nitrógeno, consumo de alimento y componentes económicos del sistema. La evaluación del modelo se realizó por medio de un amplio conjunto de ensayos para la valoración de modelos dinámicos y mediante la comparación estadística de datos simulados frente a observados en las encuestas. El modelo simula de manera realista las variables de salida y muestra una representación conductual lógica. La máxima incertidumbre relativa de las variables de salida varía de un 30% a un 53% para los análisis univariables y multivariables (MVSS) respectivamente. El modelo se presenta como adecuado para la simulación de una amplia gama de sistemas agrícolas minifundistas en las áreas montañosas de América Central, y potencialmente en otras localizaciones.

Para la primera aplicación en Guatemala, nuestro esfuerzo se centró en aumentar el conocimiento y comprensión sobre las oportunidades y desafíos a los que se enfrentan los pequeños agricultores, y los inextricables vínculos entre humanos y sus ambientes biofísicos, sociales y económicos. Examinamos los efectos del cambio de dotaciones de los pequeños agricultores en la trayectoria a largo plazo de los factores asociados con la pobreza y la seguridad alimentaria. Se realizaron simulaciones univariables y MVSS para evaluar la variabilidad en las dotaciones de los pequeños agricultores. Los resultados respaldan la hipótesis de la existencia de umbrales en la disponibilidad de tierras, fuerza de trabajo familiar, disponibilidad de empleo en otras explotaciones, y la adquisición de insumos, los cuales determinan la trayectoria de bienestar de los pequeños agricultores. Los hogares en la región confían parcialmente en los ingresos obtenidos del empleo en otras explotaciones como parte de su estrategia de subsistencia. Los descubrimientos de este estudio confirman que los hogares necesitan una superficie de 0.6 ha de cultivo asociado de maíz y frijol complementado con ingresos del trabajo en otras explotaciones (2.2 meses al año) para conseguir los requerimientos de alimento anuales. Por otro lado, existe también una fuerte interacción entre un manejo agrícola eficiente y la capacidad de trabajo, la cual a su vez depende de la tecnología implementada. Por encima de 0.75 ha de cultivo de maíz y frijol asociados, la escasez en disponibilidad de fuerza de trabajo conlleva caídas de rendimiento de 13% en maíz y 21% en frijol.

Además, el modelo SASHACA se usó para evaluar cómo factores tales como el tamaño familiar y su composición, la productividad, la capacidad de trabajo, o la superficie y la distribución de los cultivos afectan los resultados de bienestar a largo plazo en las zonas montañosas de Guatemala y Nicaragua. Los niveles de seguridad alimentaria de los hogares empeoran a medida que el tamaño familiar crece. Sin embargo, la evolución de los ratios de dependencia a lo largo del tiempo puede modificar la situación de bienestar familiar. La disponibilidad de trabajo y terreno interactúa afectando al bienestar del hogar. El tamaño deseable de la finca para un pequeño agricultor de subsistencia en las zonas montañosas de Guatemala se establece en el rango de 1.25-3.05 ha y entre 2.05-3.25 ha para el contexto Nicaragüense, dependiendo de la fuerza de trabajo disponible.

Abstract

Smallholder agricultural systems have an important role in world food production (providing about the 70% of food globally, and involving over 500 million families). Agricultural smallholders in highland areas of the Mesoamerican dry-corridor are central to improve farming systems. The key issue is that the subsistence smallholders are joint producer-consumers, with insufficient food production due to extreme environmental and weather conditions or scarce incomes to supplement their own production from market sources. Modelling offers an approach for testing and improving knowledge about complex agricultural systems. To tackle smallholder famers problems we firstly developed, described and assessed a biophysical and socio-economic model of the smallholder agricultural systems based on maize-bean intercropping in highland areas of Central America. Once the model was developed and evaluated, the sustainable food security and poverty alleviation in Smallholder Agricultural Systems in Highland Areas of Central America (SASHACA) model was used in Guatemala to assess the impact of smallholder endowments on their welfare. Eventually, SASHACA model was used in Guatemala and Nicaragua to establish a family farming definition adapted to regional context with a focus on subsistence or near-subsistence smallholders.

The SASHACA model integrates scientific and practical knowledge of crop management, labour, soil water content, soil nitrogen, food consumption and economic components of the system. Model evaluation was conducted through a wide set of tests for assessment of dynamic models and statistical comparison of simulated versus observed data derived from surveys. The model simulates realistic outputs and presents logical behavioural representation. The maximum relative uncertainty of output variables ranged from 30% to 53% for univariate and multivariate sensitivity analyses (MVSS) respectively. The model proved to be adequate for assessing food security under scenarios in low data availability areas. The SASHACA model proves to be adapted to simulate a wide range of smallholder agricultural systems in highland areas of Central America, and potentially in other locations.

For the first model application in Guatemala, our effort aimed to increase awareness and understanding about the opportunities and challenges faced by smallholder farmers, and the inextricable links between humans and their biophysical, social, and economic environments. We examined the effects of changing smallholder endowments on the long-term trajectory of factors associated with poverty and food security. Univariate and MVSS were carried out to evaluate the variability in smallholder endowments. The results support the hypothesis of thresholds in land

availability, family labour force, off-farm labour availability, and purchased inputs determining the welfare trajectory of the smallholders. Households in the region rely partly on off-farm labour as a subsistence strategy. The findings of the study confirm that households need an area of 0.6 ha of maize and bean intercrop complemented with income from off-farm labour (2.2 months a year) to provide annual food requirements. There is also a strong interaction between land management efficiency and labour capacity which depends in turns on the technology implemented. Above 0.75 ha of maize and bean intercrop, a shortage in labour availability causes yield reductions of 13% in maize and 21% in bean.

Additionally, SASHACA model was used to assess how factors such as family size and composition, field productivity, labour capacity, or area and crop allocation affect household long term welfare results in highland areas of Guatemala and Nicaragua. The food security levels of the household worsen as the household size grows. However, evolution of dependency ratios over time might modify the welfare situation of the family. Labour and land availability interact affecting household welfare. The resulting desirable farm size for subsistence smallholder farms in the highlands of Guatemala is established in the range of 1.25-3.05 ha and 2.05-3.25 ha for the Nicaraguan context depending on the household workforce.

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1 INTRODUCTION

1.1 Research context

This research was completed as part of the *Comunidades Rurales del Milenio* (CRdM) program. The Universidad Politécnica de Madrid (UPM) team participating in this international cooperation program was coordinated by Dr. Carlos Gregorio Hernandez Díaz-Ambrona based at the UPM's AgSystems research group. The research was undertaken from 2012 to 2022 at the Department of Agricultural Production, School of Agricultural Engineering (UPM). During this period, I spent nine months, in a pre-doctoral temporary transfer, as a visiting scholar at the School of Land and Food at the University of Tasmania (UTAS) in Australia, hosted by Dr. David Parsons, who co-supervised this thesis. As part of my field work, I spent three-months in Guatemala, Honduras and Nicaragua. I also spent three months in Brazil as a visiting-scholar at the Centro Xingó de Convivência com o Semiárido and at the Escola Superior de Agricultura Luiz de Queiroz (ESALQ). Furthermore, I participated in the IX Edición of the business start-up contest Actua-UPM, receiving the Accésit Award to the business project AgerDroid to develop agricultural mobile applications for helping smallholder farmers in developing countries. I also received the scholarship Redemprendia "Nuevos emprendedores: Aprendiendo a emprender" to further develop this enterprise named AgerDroid. The whole research was developed as part of the international PhD in Agro-environmental Technology for Sustainable Agriculture (TAPAS) program.

Sustainability and food security are still the two most important challenges in the Post-2015 UN Development Agenda Both are included in the 17 Sustainable Development Goals (SDG) ratified at the United Nations Sustainable Development Summit held in New York in September 2015.

Comunidades Rurales del Milenio, which is a UPM international cooperation initiative, has two main objectives: (1) establishing a successful methodology, sourced from local demands, to support the Sustainable Development Goals (SDGs), especially the three first SDGs, no poverty, zero hunger and good health and well-being; (2) triggering a sustainable, participatory and replicable process in which different stakeholders effectively and efficiently coordinate their actions. The project aims to offer an alternative development model based on local capacity building integrated with national development policies. The initiative was designed to enact a participatory monitoring and evaluation process to facilitate social learning, strengthen the project and gain knowledge for future development projects.

1.2 Statement of the problem

Food and Agriculture Organization of the United Nations (FAO) estimates the number of undernourished people on 720-811 million people (FAO et al., 2021) around 75% of whom are concentrated in rural areas (FAO, IFAD & WFP, 2012). While the global prevalence of moderate or severe food insecurity has been slowly on the rise since 2014, the estimated increase in 2020 was equal to that of the previous five years combined (FAO et al., 2021). Paradoxically, smallholder farmers living in low income countries with agriculture and food production as the core business (Dioula et al., 2013) are specially affected by chronic food insecurity and undernourishment (FAO, IFAD, & WFP, 2015). People living in mountainous areas (12% of the global population) are among the poorest and most disadvantaged people in the world (FAO, 2011). In Central America 60% of land used for agriculture and livestock is located in hillside areas (IICA IFPRI and CIMMYT, 1997). Smallholder farmers have to face multitude of challenges, namely production constraints derived from fragile soils often more suitable for perennial forestry than for agriculture, unhelpful land policy, lack of investment, and social and environmental constraints (Dioula et al., 2013; Jansen et al., 2006). All these, make mountainous agricultural systems more vulnerable to food and nutritional security.

Agriculture has a key role in the 2030 Sustainable Development Goals Agenda (da Silva, 2015; Ki-moon, 2014), being the common thread which holds the 17 SDGs together. The Sustainable Development Goal to "End hunger, achieve food security and improved nutrition and promote sustainable agriculture" (SDG2) recognizes the inter linkages among supporting sustainable agriculture, empowering small farmers, promoting gender equality, ending rural poverty, ensuring healthy lifestyles, tackling climate change, and other issues addressed within the set of 17 Sustainable Development Goals in the Post-2015 Development Agenda (Ducker, 2022). Moreover, smallholder farmers are crucial to achieve sustainable food and nutrition security, and poverty reduction (IAASTD, 2009; FAO, 2012). FAO's SOFA report (FAO, 2014) estimated that there are about 570 million farms worldwide. Nearly 90% (FAO, 2014) of which are considered smallholder farms, contributing to about 70-80% of the world's food production (Bacon et al., 2014;

Sumpsi, 2011). Thus, increasing knowledge on smallholder agricultural systems and the key factors affecting their welfare is needed to cope with the above problems in these areas and to achieve more sustainable agricultural systems.

1.3 Objectives of the study

The main objective of this thesis is to identify and estimate the impact of key factors affecting smallholder farming households welfare in highland agricultural systems, and evaluate their actual and optimal situation purposing a desirable farm land size range in terms of labour capacity.

Specific objectives:

1. Development, evaluation, calibration, and application of a dynamic simulation model to improve knowledge and assess dynamics of the Coupled Human and Natural System (CHANS) under study – Smallholder agricultural systems in hillside areas.

2. Assessment of the effect of changes in individual or combined variables on overall smallholder farms welfare trajectory in agricultural systems in hillside areas. Outline thresholds of endowments determining and identifying bottlenecks and turning points on smallholder farms welfare evolution.

3. Examination of the actual welfare situation of smallholder farms in mountainous areas and refinement of the smallholder farm definition integrating the key sustainability indicators identified. Establishing a desirable farm land size of subsistence and near subsistence smallholders in terms of household labour capacity. This could be useful to policy makers by enabling them to better target their policies toward the most needed households.

1.4 Hypothesis

To delineate the objectives pointed above we stated from four main hypothesis arising from previous research and observation in the region.

1. Hillside areas share similarities in agro-ecological, political, socio-economic and cultural, as well as human aspirations, and thus are affected likewise from development initiatives and policies. Thus, livelihood strategies of smallholders in hillside areas of Central America are comparable.

2. Smallholder farm welfare trajectory can be adequately explained by its endowments of natural (soil quality, topography, and land), human (size, composition, education, labour availability) financial (credit, savings, transfers), social capital or assets, and geographic determinants (access to markets and public services, population density, and time to the main road; Jansen et al. (2006)). Changes or threshold on these factors may affect smallholder farms welfare trajectory.

3. Most of smallholder farms in hillside areas are not able to earn their lives relying just on their farm production. They generally need an extra source of income for their livelihood often coming from off-farm labour.

4. The farm size threshold frequently used to define smallholder farming can be contextualized depending on local agro-ecological and socio-economic conditions. Therefore, it would allow the definition of a clear cut-off point to define smallholder farming adapted to each context.

1.5 Modelling in low data context

In low data contexts such as hillside areas in Central America, lack of information representing model parameters, constrains the performance of detailed and highly complex models, and often forces final model users to ´guess´ parameters (or use default values) that are often not available in developing areas (Tittonell et al., 2010). As stated by O'Neill and Rust (1979) there must be a compromise between the loss of accuracy introduced by simplifying models and loss in accuracy through the accumulation of errors due to the estimation of a large number of parameters in complex models. Simpler models may have less explanatory power, however they often perform better and more robust than detailed and complex models when studying farm scale systems in low data environment (Tittonell et al., 2010). Simpler models manage better the uncertainty caused by both lack of data and imperfect knowledge of some processes (Brooks et al., 2001). Thus, to overcome data availability problems encountered when calibrating and applying models in low data contexts we followed a minimum data approach (e.g. Antle et al., 2010; Antle and Valdivia, 2006; Pfister et al., 2005; Stoorvogel et al., 2004).

1.5.1 Simulation model

The Oxford Reference dictionary (2022) defines the term model as *"a simplified description, especially a mathematical one, of a system or process, to assist calculations and predictions"*. According to the Spanish Royal Academy of Language (RAE, 2022), a model is a *"theoretical framework, especially a mathematical one, of a system or complex reality (i.e., the economic evolution of a country), that is developed to ease its comprehension and the study of its behaviour"*. In this thesis, simulation should be understood as the process of developing a model of a real system and conducting experiments with it to understand the behaviour of the system, Shannon (1975).

All models are simplified representations of the reality in accordance with the purpose on the study (Vayssières et al., 2009; Jones et al., 2017). Any model should be developed to solve a specific problem (Garedew et al., 2012). To assess functioning and sustainability of livelihood strategies in smallholder subsistence agricultural systems one should focus on the critical issues related with smallholder agriculture: productivity of individual farmers, access to financial and physical resources (e.g. land, water, seeds, fertilizers, pesticides, labour), weather variability (e.g. storms, floods or droughts), ability to grow crops, pest and disease incidence, crop yields, presence and support of organizations, and food prices (Rodríguez et al., 2008; VanLoon et al., 2005).

1.5.2 Use of simulation models

Simulation modelling is a flexible tool that do not require the many simplifying assumptions needed by most analytical techniques (Jones et al., 2017). Data needed for simulation models are usually less costly than data collected using a real system (Centeno, 1996). Moreover, the relevant time steps in the evolution of some systems may be counted in decades. Another approach would be to compare variables from past and present states of the rural community system. However it would be a simple comparison of two static states of the system, while sustainability is, by definition, dynamic (Barreteau et al., 2004). Thus, models allow assessment of future situations, and can save money and time (Lee et al., 2008; Matthews & Stephens, 2002). According to Verburg et al. (2004) and Teeuwen et al. (2022), simulation models contribute clarifying human-environment interactions (knowledge integration), helping in decision making (hypothesis contrast, estimation of the consequences due to a change in the system), and dissemination of knowledge (technology transfer, teaching applications). Thornton and Herrero (2001) said "*Modelling realistically offers the only way of identifying and quantifying the subtle but highly significant interactions that occur between the* *various components of smallholders systems*". Simulation allows testing hypotheses under different scenarios, without the need to physically repeat experiments (Lee et al., 2008; Matthews & Stephens, 2002). However, models are planning and assessment tools not forecasting instruments. They help to generate questions rather than giving accurate answers (Garedew et al., 2012). The use of different scenarios in models, allows testing the impact of alternative external actions (real-world what-ifs), such as agricultural practices, technology diffusion, policy changes, or climate variability (Voinov and Bousquet, 2010). Conventional empirical (econometrics or statistical) or mathematical programming methods do not capture all dynamics, interactions, and feedback effects composing smallholder agricultural systems (Stephens et al., 2012).

The real impact on the socio-economic and environmental aspects of the smallholder agricultural systems is not clear - there are many drivers such as demographic trends, rural policies, climate change, agricultural land availability, financial and physical resources availability (e.g. water, seeds, fertilizers, pesticides, labour), public demand, food prices, and trade policies that cause smallholder agricultural systems to evolve constantly (Verburg et al., 2004; Teeuwen et al., 2022). Thus, further development of smallholder agricultural systems models will help to improve knowledge on these still uncertain aspects. Also, many existing models are set up for developed regions. They usually require a large amount of data inputs generally not available in developing countries and may not be adequate to simulate low input systems of developing countries where farmers seek to avert risk and where food security is defined by seasonal oscillations (Pfister et al., 2005).

However despite its advantages, modelling is not a panacea. According to the aim of the model and the type of problem to be faced there is a need to define the level of abstraction against the critical components of the system to include in it (explanatory vs. descriptive approach) (Parker et al., 2003). An experimental frame must be defined to guide data collection, modelling, validation and verification. Spatial and temporal scale consideration is important when dealing with complex systems in order to couple sub-models across disciplines. Also, spatial heterogeneity at a fine spatial scale may not show up as an aggregate, so there is a loss of information of scale-dependent phenomena existing in the system of interest. Therefore, it is important to rigorously define the appropriate spatial and temporal scale for decision making according to the final purpose of the model (Parker et al., 2003).

Despite these disadvantages, simulation remains a valuable technique to address a variety of problems, at the design, planning, and operation levels, and can be used to provide information for decision making, or provide a solution (Pritsker, 1992).

1.5.3 Types of simulation models

There is no clearly superior approach for simulating, models are developed to solve specific problems and different problems require different models (Lee et al., 2008; Sanchez, 2020). Simulation models can be classified as continuous (variables can change continuously) or discrete (variables change in discrete times and by discrete steps), according to the type of system under study (Centeno, 1996). Based on their change over time, models can be dynamics (change over time) or static (do not change over time). Our interest is in discrete dynamic simulation modelling of CHANS.

There are many categorizations of CHANS (Agarwal et al., 2000; Letcher et al., 2006; Veldkamp and Lambin 2001; Verburg et al., 2004; Voinov and Bousquet, 2010). Ones may focus on the subject matter of the models, others on modelling techniques or methods used (from simple regression to advanced dynamic programming), or on the final use of the models. For instance, Agarwal et al. (2000) agree on the existence of four main factors in models of complex dynamic systems: time, space, biophysical and human. Lambin et al. (2000) categorize models aiming to address the questions why?, where?, and when?, which in fact is a different way of calling the four factors identified by Agarwal et al. (2000) biophysical and human (why?), space (where?), and time (when?). Parker et al. (2003), An (2012), and (Wijk et al., 2012) simply present some models according to the techniques implemented. A review of models may focus on techniques in conjunction with assessments of model performance for particular criteria, such as time scale or spatial resolution (Agarwal et al., 2000; Jones et al., 2017).

Usually authors are consistent in the main types of models in CHANS; however some terms may vary within literature or new types of model may emerge (Table 1). We do not intent to do an exhaustive review of models, only highlight the main modelling possibilities to couple human and natural systems – CHANS.

Table 1. Classification of models types along different authors.

Reference	Dynamic systems	Econometric	Statistical	Stochastic	ABM	Spatial dynamic	Knowledge based	Hybrid	Others
(Agarwal et al., 2000)	X	X	X	X		X	X		X
(Lambin et al., 2000)	X	X	X					X	
(Parker et al., 2003)	X	X	X		X	X	X	X	X
(Voinov and Bousquet, 2010)	X				X				X
(An, 2012)		X			X	X	X		
(Letcher, 2012)	X				X		X	X	X
(Wijk et al., 2012)	X				X				X

ABM: Agent based modelling. Others includes: Psychosocial and cognitive models; Neural networks and evolutionary programming; Bayesian Networks (Probabilistic); Participatory based models; Fuzzy cognitive mapping, Mathematical programming.

1.5.4 Model selection

As stated above there is no clearly superior approach for modelling. However, there are modelling techniques more adequate for an specific modelling task than others. Among the techniques to simulate CHANS dynamics we deepened in the ones judged more adequate to assess smallholder subsistence agricultural systems.

Econometric models are often criticized by their assumptions of rationality, profit maximization, equilibrium seeking, linearity and homogeneity, but they are grounded in economic theory (Wijk et al., 2012). In contrast, smallholder agricultural systems and mainly in developing countries may be highly influenced by cultural values and try to avert risk in the first place (Lee et al., 1995; Pfister et al., 2005). Statistical models only provide insight into empirical relationships over the past history of a system. They can be used for short-range projections in time (5-10 years), but are less useful to analyse path development or emerging situations under alternative future situations (Agarwal et al., 2000; Stéphenne and Lambin, 2001). System dynamic (SD) modelling and Multi-Agent Systems (MAS) modelling are able to overcome most of these weaknesses by incorporating social scientist involvement, emergence, participatory processes and bottom up modelling (Teeuwen et al., 2022). Both can capture high degree of dynamic complexity without loss of relevance. Nevertheless, the validation MAS approach is yet to be tested (Ekasingh and Letcher, 2008). Involvement of smallholders in model development is as important as the model results themselves (Matthews, 2007;

Voinov and Bousquet, 2010; van den Belt 2004). Inclusion of stakeholder declarations in modelling leads to more suitable decisions and reduce conflict helping to reach a common viewpoint among several agents (Etienne et al. 2003). Thus, participatory modelling appears as an important technique to involve local stakeholders, address their real problems and requirements, and thus to improve model performance (Voinov and Bousquet, 2010). The integration of modelling frameworks to combine the strengths of different modelling techniques seems a promising approach (Wijk et al., 2012). According to Ekasingh and Letcher (2008) integrated modelling obtains better results when there is a balance between "hard" and "soft" systems approach. Hard models are too mathematical and complex but can be improved by soft models. Scale problems may appear when integrating biophysical (large scale) and social (small scale, problems dealing with aggregation) sciences.

After these considerations we further reviewed Participatory modelling, SD, and MAS approaches for being considered the most adequate for assessing smallholder subsistence agricultural systems (Voinov and Bousquet, 2010; Wijk et al., 2012).

1.5.4.1 Participatory modeling

Is the generic term for models involving stakeholders in its development, there are many clones of stakeholder involvement with very subtle differences among them as group modeling building, mediated modeling, companion modeling, participatory simulation, shared vision planning or collaborative learning (Voinov and Bousquet, 2010). Participatory modeling is a bottom-up approach enabling to involve local stakeholders and to address their real problems and requirements (Knapp et al., 2011). The type of interaction with stakeholders may vary from simply extraction of information, to co-learning (the synthesis of information is developed jointly with stakeholders), or co-management (development of synthesis and decision-making) (Voinov and Bousquet, 2010).

Local stakeholders who live and work in the region contribute increasing knowledge and understanding of the system (i.e. identifying components, data gaps, dynamics and processes; Mendoza and Martins, 2006), relating the model with the real local needs, helping in data collection and integration, scenario development, interpretation of results, and development of alternatives (Voinov and Bousquet 2010) (Table 2). Inclusion of local smallholders also enhances acceptance of policies or institutional decisions at the same time that increase transparency of the decision-making process (Mendoza and Martins, 2006). Stakeholder contributions combined with technical knowledge from researchers or facilitators, improve model results and adaptation to the context. According to Etienne (2011) the three key choices for a successful participatory model are: rigorous definition of the territory boundary and problem to be addressed, involvement of facilitator/s, and careful selection of working group members since the representativeness and richness of the model depends on the group composition. This selection should be made following an iterative process, since selected smallholders reveal others previously unknown (Mendoza and Martins, 2006).

However, participatory modeling has its drawbacks (Table 2). Participants involvement is a time-consuming technique, and the group selection may influence the representation of the real world system. Also, there is a lack of scientific confidence on resulting models as a consequence of their difficult validation and verification. However, frequently participant involvement is more important than numerical accuracy (van den Belt, 2004).

Table 2. Main advantages and disadvantages of participatory models.

Advantages	Disadvantages
Collective learning and planning	Time consuming
Exchange of perceptions	Ad-hoc solution
Adaptation to the context	Challenge in communication
Local knowledge	Bias by smallholder selection
Increase acceptance	Difficult validation and verification
	Lack of transition probabilities and time frames

Source: Prepared by the author on the basis of An, 2012; Garedew et al., 2012; Knapp et al., 2011; Martin et al., 2012; Voinov and Bousquet, 2010.

1.5.4.2 System dynamic models

In SD, components are represented by stocks (state variables) and flows (rate of change) as set of differential equations depending on functions and data structures (Costanza and Ruth, 1998). System dynamic modelling allows describing non-linearity and interactions to represent the evolution and dynamic behaviour existing in smallholder agricultural systems. Also, cause-effect relationships, feedback loops, delays and socio-ecological interactions can be represented. SD approach is flexible and intuitive due to its graphical interface. However, SD grows quickly in size and complexity, which difficult data availability (Letcher, 2012). They do not include treatment of spatially explicit information (except Simile). Moreover, they operate at an aggregate level which difficult model parameterization. Some observations (e.g. decision making) cannot be straightforward up-scaled. Thus, errors may arise when using average values to simulate non-linear dynamics. Besides, uncertainty and postulated model design may lead to behaviours that do not match real world (Table 3).

Table 3. Main advantages and disadvantages of system dynamic models.

Advantages	Disadvantages
Include feedbacks and delays	Quickly growth in complexity
Dynamic processes	Lack of balance between data availability and accuracy
Flexible	Difficult treatment of space
Socio-ecological interactions	Coarse temporal and spatial resolution
Non-linear cause-effect relationships	Difficult to up-scale observations
Software easy to use	Uncertainty and feedback loops may create unreal behaviour

Source: Prepared by the author on the basis of Agarwal et al., 2000; Garedew et al., 2012; Lambin et al., 2000; Letcher, 2012; Parker et al., 2003; Voinov and Bousquet, 2010; Wijk et al., 2012.

1.5.4.3 Multicriteria decision analysis

To model complex phenomena involving human or institutional behaviour its helpful to represent them as MAS (Multi-Agent system) and use an ABM (Agent based modelling) approach. ABM is a way to explore dynamic behaviours of a complex system, before implementation of expensive management plans (Etienne et al. 2003; Botti and Julian, 2019). ABM describes the system of interest in terms of individuals and their multiple non-linear interactions such as feedback, learning and adaptation. Interactions between agents and agents-environment are implemented by means of rules and algorithms and routines are provided to organize societies of agents. MAS allows links to other software as GIS, databases or biophysical models (Voinov and Bousquet 2010) coupling decision models with spatially-explicit information including heterogeneity (Schreinemachers and Berger 2011). MAS models (Voinov and Bousquet 2010), have been recognized to be well suited to express the co-evolutions of the human and landscape systems in response to policy interventions (Le et al. 2010; Bitterman and Bennett, 2016). Policy interventions or institutions constrain the actions of agents and so influence the collective outcome (Voinov and Bousquet 2010). Participation of stakeholders and final users improve the model (Matthews 2007). Relations villagers-environment are defined by rules extracted from interviews (Saqalli et al. 2010).

ABM provides a framework for analyzing hypotheses and understanding interactions between biophysical and socio-economic subsystems (e.g., subsistence farmers) and how it affects subsistence farmers livelihoods and poverty (Matthews 2006). ABM seeks a dynamic structure where the rules evolve as the agents interact, perceive and learn about the system and remember the rules which suits them better. Thus, rules guiding the system along desirable trajectories are rewarded while the rest are excluded from decision making mechanism (Matthews 2006). For example, according to Matthews (2006) technology diffusion method, smallholders are able to adopt new strategies from the neighbour generating higher return among the ones immediately around. These rules selected to be included in the decision making procedure will guide agents actions which may have an effect on the environment, and as a consequence will modify future perceptions, decisions and actions (Matthews 2007). Hence, emergent behaviour may arise as a consequence of individual aggregation. It should be warned that in some cases misleading results may be attained (An, 2012). It is also possible to develop an ABM model that reproduces a statistically correct meta-phenomenon with a model structure representing incorrect or unreal processes (Parker et al., 2003).

MAS models cannot predict the exact behaviour of smallholder subsistence farmers or communities, however model structure and assumptions are more important than predictions (Matthews 2007). In ABM each simulation might produce different outcomes due to inclusion of uncertainty and path dependence in the models. They are not as powerful as mathematical proofs but robust results can be attained by replicating findings with the repetition of multiple independent simulations, using several modelling approaches, or improving already empirically parameterized and tested models. The last, would be favoured by providing model source code and stimulating the use of common language among models (Parker et al., 2003). Other limitations of ABM approach are its difficult validation and verification (which can be tackled by historic simulation and experts), the scarcity of effective constructions to represent agents interactions and adaptive decisions (An, 2012), the determination of the level of uncertainty, the comparison among models (An, 2012), the context dependence of the model (environment, shortage of information, multiple goals, trust, loyalty, emotions), and the challenges in coupling ABM with biophysical models due to different assumptions (scale, modelling structure, modelling language) and understanding of the system among interdisciplinary research teams, sub-models overlap or use of different data sources for different sub-models (Kline et al., 2017).

Table 4. Main advantages and disadvantages of Agent Based Modelling (ABM).

Advantages	Disadvantages
Human-environment systems	Require detailed information
Agents make inductive, discrete and evolving choices	Uncertainty and path dependence change outputs in each simulation
Emergent behaviour	Difficult validation and verification
Time and scale well handle	Low acceptance of model predictions
Cognition (rule based approach)	Inherently local
Integration (Participation and disciplines)	Less known processes may limit accuracy
When basic unit is individual	Difficult comparison and coupling with other models
Interactions, feedbacks and heterogeneity	

Source: Prepared by the author on the basis of An, 2012; Letcher, 2012; Parker et al., 2003; Verburg et al., 2004; Voinov and Bousquet, 2010; Wijk et al., 2012.

1.5.4.4 Agent Based against System Dynamic Modelling

The best two methods to capture the dynamic nature of sustainability, seem to be ABM and SD models. Thus we present a deeper insight into the advantages and disadvantages of these two methods (Table 5).

MAS represent the simplest set of rules that reproduce a pattern observed in the real world. Alternatively, SD base predictions in what we know about human behaviour and the surrounding environment in a particular context (Vanclay, 2003). SD endeavours to represent reasons for people behaviour, rather than a simple set of rules reproducing an observed pattern (Vanclay, 2003; Verburg et al., 2004)

In terms of modelling technique MAS and SD follow similar approaches, but whereas ABM represent several individual households, together with their interactions, SD models generally focus on one household or an average representation of a population of households (Wijk, 2012). For example, in a model of Wolf-Sheep Predation with ABM, the modeller provides the rules for how wolves, sheep and grass interact with each other. Then, the emergent aggregate-level behaviour can be observed (e.g. how wolves and sheep populations change over time). With SD the modeller programs how populations of agents behave as a whole. For the same Wolf-Sheep Predation example, the modeller would specify how the total number of sheep would change according to the number of wolves, and the output of the simulation would show how both populations change over time (NetLogo, 2016).

The challenge in ABM is to obtain sufficient data at the individual level to develop a well-parameterised and validated model of decision-making, because observed outcomes are not enough for validation (Verburg et al., 2004). These models rely on dominant narratives of the functioning and direction of change of the system, which may not suffice to capture other features of complex dynamics and which in some cases leads to unrealistic results (An, 2012; Batterbury and Warren, 2001; Nielsen and Reenberg, 2010; Rasmussen et al., 2012).

Table 5. Comparison between Agent Based Modelling (ABM) and System Dynamics (SD) approaches.

System Dynamics	Agent Based Modelling
Set of equations (flows and levels)	Set of agents (behaviours)
Relationships: Equations produce evolution for the observables over time. Relationships have no explicit representation.	Relationships: guided by behaviours through which individual interacts
Level of focus: System level observables (variables)	Level of focus: Behaviours through observables at individual level
Observables affected by multiple individuals (modularization crosses boundaries among individuals)	Modularization follows boundaries among individuals
Well suited for physical processes but difficult to include spatial explicit information	Where unit of decomposition is individual and physical distribution is desirable (proximity interactions)
Intuitive (drag-and-drop tools)	Processes dominated by discrete Decision Making
Uses averages of variables over time and space	Validation at individual and system levels
Assumes homogeneity among individuals	Able to construct some structures impossible in SD
When dynamics are non-linear, local variations from averages can lead to deviations in overall system behaviour	Model familiar processes rather than translate them into equations related to observables
Quickly growth in complexity	Difficult to validate the model
Difficult to up-scale observations	Challenge to obtain sufficient data at individual level
	Uncertainty and path dependence change outputs in each simulation
	Less known processes may limit accuracy

Source: Prepared by the author on the basis of Agarwal et al., 2000; An, 2012; Garedew et al., 2012; Lambin et al., 2000; Letcher, 2012; Parker et al., 2003; Parunak et al., 1998; Verburg et al., 2004; Voinov and Bousquet, 2010; Wijk et al., 2012**.**

1.6 Smallholder farms welfare in hillside areas

1.6.1 Sustainability

The word "sustainable" has become very popular mainly due to the width and ambiguity of this term which can be used under very different ways depending on the context, perspectives and goals (VanLoon et al., 2005). There are more than 300 definitions of “sustainable development” and “sustainability” (Johnston et al., 2007).

According to British Oxford Dictionary the definition of sustainable is something *"Capable of being sustained or continued over the long term, without adverse effects"* (ORD, 2022). The definition of sustainable development is *conserving an ecological balance by avoiding depletion of natural resources*. For us it seems a good enough definition for sustainable development the one presented in the *Our Common Future* report produced by the World Commission on the Environment and Development (WCED, 1987) *"…development which meets the needs of the present without compromising the ability of future generations to meet their own needs"*. This definition includes the consideration of a long term perspective in sustainability and tries to reconcile the apparent contradictions between *developing* and *being sustainable* (VanLoon et al., 2005).

Sustainability should be considered in a global context across different disciplines. These considerations should include three factors: Environmental, economic and social. It is useless to solve technical problems without at the same time addressing socio-economic aspects (Berkes et al. 2003; Matthews and Stephens 2002, Matthews 2007). After the Rio+20 Summit, an institutional component was added to the three generally accepted fundamental dimensions (i.e., environmental, economic and social), and sustainable development started to be understood as a process of adaptation to changing circumstances over time. This institutional component also enhances the integration between the local and global scales and among the other three dimensions to provide a comprehensive outlook. The 17 Sustainable Development Goals (SDGs) proposed by the United Nations Post-2015 Development Agenda adopted this holistic view. The SDGs were grouped into six essential elements: people and dignity (social dimension); prosperity (economic dimension); planet (environmental dimension), and justice and partnership (institutional dimension; UN, 2014).

1.6.2 Food and nutritional security, and poverty

The concept of food security has evolved over the last decades being gradually enlarged. Initially it focused mainly on availability of food and on food production (UN, 1975); then the accessibility to food (physical, economic and sociocultural) was explicitly included, its utilization (FAO, 1996) and lastly the stability of access were also encompassed (FAO, 2009). According to the Food and Agriculture Organization (FAO), *"Food and nutritional security exists when all people at all times have physical, social and economic access to food, which is safe and consumed in sufficient quantity and quality to meet their dietary needs and food preferences, and is supported by an environment of adequate sanitation, health services and care, allowing for a healthy and active life"* (FAO, 2012). This definition implicitly assembles the concepts of sustainability and food security (Burlingame and Dernini, 2010; Ericksen, 2008; Pinstrup-Andersen and Herforth, 2010; Richardson, 2010). Also, Hunger Zero is the objective 2 in the 17 Sustainable Development Goals (SDGs) from the United Nations to transform our world. It argues that if done correctly, agriculture can generate enough food and incomes to support sustainable rural development.

One in nine people in the world today, between 700-828 million, (FAO et al., 2022) are undernourished. These estimates imply that, since 2015, the progress made during the previous decade in terms of undernourishment has been eroded, bringing the world back to hunger levels that prevailed in 2005 (FAO et al., 2022). Most of those hungry people live in developing countries. Agriculture provides livelihoods for 40 % of global population which makes it the largest employer in the world. It is the largest source of income and jobs for poor rural households. In Central America the prevalence of undernourishment reached 8.9 % in 2018-2019 (FAO et al., 2021). There exist big disparities between these countries, with Guatemala and Nicaragua as the two countries presenting the biggest undernourishment rates (16.8 and 19.3 % respectively). In Central America, prevalence of moderate or severe food insecurity in the total population reached an average rate of 31 % in 2018-2020 period, with Guatemala presenting the highest rates 49.7 % in the same period (FAO et al., 2021) and Nicaragua presenting 23 % (FAO, 2013). These undernourishment numbers are not surprising in a region with such high levels of poverty. End of poverty is the first of the 17 SDGs . More than 656 million people live in extreme poverty and are struggling to fulfil the most basic needs (World Bank, 2022) with an estimation of an additional 75 million to 95 million people living in extreme poverty in 2022, compared to pre-pandemic projections. Central America presents a 47 % of poverty rate with Guatemala 52.4 %, Honduras, and Nicaragua 24.9 % among the five poorest countries in the continent (World Bank, 2022). Similarly, the percentage of extreme poverty reaches 20 % in Central America. Rural areas present larger rates of poverty, exceeding 60 % in Nicaragua or 70 % in Guatemala and Honduras (FAO, 2013). Maize provides 61 % of dietary calories in the Central American diet and beans from 10 % to 16 % of protein intake. In rural areas, these figures rise to values of 78 % and 22 %, respectively (Alarcón and Adrino, 1991; Salcedo and Guzmán, 2014).

1.6.3 Smallholder farming households in Central America

As pointed above the SDGs clearly recognize the centrality of food security, nutrition and sustainable agriculture development. Agriculture is an important employer and driver of economic growth in developing countries (FAO, 2012)(FAO, 2018). Smallholder farmers have a major role on sustainable food, nutrition security and poverty reduction (IAASTD, 2009; FAO, 2012). Globally more than 80% of smallholders operate in local and domestic food markets (FAO, 2018).

Rural areas hold half of the world's population and 40% of global population derive their livelihoods directly from smallholder agricultural production systems (FAO 2008; (Saqalli et al., 2010). Smallholders often live in remote and environmentally fragile locations and are frequently part of marginalized populations (IFAD and UNEP, 2013). Smallholder farmers provide over 80% of the food consumed in a large part of the developing world. Paradoxically, most of the chronically food insecure and undernourished populations (FAO, IFAD, & WFP, 2015) are smallholder farmers living in developing countries with agriculture and food production as the core business (Dioula et al., 2013). This paradox is explained by the number of challenges faced by the smallholder farmers, namely production constraints, high vulnerability to risks and shocks, land policy, lack of investment, and social and environmental constraints (Jansen et al., 2006; Dioula et al., 2013; FAO, 2018). Thus, measuring food security and rural communities sustainability using family farms as the basic unit seems adequate (IAASTD, 2009; Saqalli et al., 2010). As stated in the definition of food security a family must be food secure "at all times". Temporary food insecurity may be overcome when weather, wages or employment opportunities are favourable, when the household receive remittances, or when harvest comes. When food insecurity is more severe, trying to achieve temporary food security, households may draw on informal social networks, seek food aid, ration food, eat less preferred food, search for food or begging, or borrow money which can contribute to debt accumulation and asset lost, decapitalization (Bacon et al., 2014; IAASTD, 2009; Maxwell et al., 1999). This is reflected in household livelihood strategies. About 89% of the 1.350.000 family farms in Central America are found in Guatemala, Nicaragua, El Salvador and Honduras, being more than half of them in Guatemala (55%; PRESANCAII and FAO, 2011).

1.7 Subsistence smallholder farming

Due to our focus on developing countries, we use the terms family farming and smallholder farms interchangeably (Garner and de la O Campos, 2014; Schneider, 2016). FAO (2014) differentiates three broad categories of family farm according to their capacity for commercial production and innovation: large family farms, small or medium-sized family farms and subsistence or near-subsistence family farms.

1.7.1 Subsistence and near-subsistence smallholder farms

Fan et al. (2013) classified smallholder farms into three similar broad categories: commercial smallholder farms, subsistence farmers with profit potential, and subsistence farms without profit potential. Other authors also established similar classifications (Berdegué and Fuentealba, 2011; Chappell et al., 2013; Fradejas and Gauster, 2006; Soto Baquero et al., 2007; Vorley, et al., 2012). Different strategies and policies are needed for each different class of farm (FAO, 2014a; Fan et al., 2013, HLPE, 2013). Thus, the importance of clearly defining and identifying all of them.

There is a large body of smallholder and subsistence farming in the dry land tropics (Morton, 2007). According to Berdegué and Fuentealba (2011), from the 15 million of family farms in LAC (400 million ha) almost 10 million (controlling 100 million ha) are within the subsistence farms category. Mountain agricultural systems, heavily reliant on rain-fed production and subsistence farming, do not always secure enough food to fulfil annual family needs. In addition, constrains of mountain zones (i.e. small farms, physical inaccessibility, low inputs and yields, economic marginality) restrict food access, even if this food would be sold or purchased (Arnés et al., 2015).

Barnett et al. (1997) defined subsistence agriculture as *‘’farming and associated activities which together form a livelihood strategy where the main output is consumed directly, where there are few if any purchased inputs and where only a minor proportion of output is marketed’’*. FAO (2014) also defined subsistence or near-subsistence smallholders as those *"who produce essentially for their own consumption and have little or no potential to generate a surplus for the market"*. They also added that subsistence farmers have to buy food and obtain most cash from off-farm work. Subsistence and near subsistence farms depend to a large extent on other external sources of income (mainly off-farm or non-farm work) to supplement farm production. However, these alternative forms of provisioning can complement subsistence agriculture rather than substitute it.

For various cultural, political, and economic reasons, subsistence farmers prefer self-sufficient agriculture practice (Isakson, 2009; FAO, 2018). Some authors (Quijano, 2001; Brass, 2003) argument that subsistence oriented agriculture is an act of desperation by poor with no other alternatives. However, many other scholars argue that is a manifestation of food sovereignty and cultural identity (Barkin, 2002, 2006; Gibson-Graham, 2006; De Frece and Poole, 2008). For most of these subsistence farms, emergence from poverty requires rural development policies and effective social protection and specific strategies directed to subsistence family farms (FAO, 2014; FAO, 2018).

1.7.2 Carrying capacity

Carrying capacity relates to sufficiency of agriculture; by definition carrying capacity is the number of people (or animals) that can be sustained by primary production from a given area. Carrying capacities depend on performance of producers and thus is related to the environment and intensity of cultivation. One important relation often overlooked in discussions of carrying capacity and input-output relationship is the link between yield and area. The area needed to attain a certain production is inversely related to the yields obtained in that given area. That is, with low yields the area required to meet a given production is larger than with higher yields. The two main reasons why yields may be small are: climate and actual yields of the area under cultivation below attainable yields. Thus, increasing yields and/or the area under cultivation appear as the two options for rising food supply, leading to intensification or the advance of the agricultural frontier (Connor et al., 2011; Connor, 2021).

In some regions of Central America, the combination of yields and area under cultivation often lead to primary productions below the subsistence needs of the household. Thus, subsistence smallholder farmers have to cope with seasonal food shortages by borrowing money and food, seeking off-farm labour, changing diet, and/or selling livestock.

1.7.3 Redefinition of smallholder farming

During the International Year of the Family Farm (FF) in 2014, family farming was defined by as an activity predominantly reliant on family labour and linking family and farm co-evolving and combining economic, environmental, social and cultural functions (HLPE, 2013). The small size and the family-operated nature of smallholder farms are broadly agreed. However there is less agreement in other terms that should also be included in the definition of family farm such as management, source of livelihood, residence, generational or family linkages, community and social networks, and efficiency and capacity to operate the farm. Despite its inaccuracy, land size is the most widespread criterion. It is accepted to consider smallholder agriculture as “farms of 2 hectares or less” (Hazell et al., 2010; IFAD and UNEP, 2013; Nagayets, 2005; Nagayets, 2005; Wiggins et al., 2010).

There is a need to develop a definition of smallholder farming based on a broader set of terms gathering the specificities of each region (*socio-economic and environmental aspects*). This new definition would bring more light to the establishment and differentiation of categories of smallholder farms. The identification of such categories of smallholder farms and the establishment of their actual and potential situation are essential for the design and implementation of development strategies, policies and programs.

2 MATERIALS AND METHODS

2.1 Study area and Data collection

The study was located in the Dry Corridor or Central America. The rural mountainous communities of Camotán (14°49’13” N and 89°22’24” W, Chiquimula, Guatemala) and San José de Cusmapa (13°16’-13°18’ N and 86°39’-86°42’W, Madriz, Nicaragua) were selected because of their integration into the Rural Communities of Millenium development program. Primary production data for smallholder agriculture is scarce (Arnés et al., 2015). Most of the secondary data available are national or regional. Thus, in order to better define and characterize smallholder agricultural systems we used mixed methods (observation, participatory rural appraisals, semi-structured household surveys (Arnés et al., 2015). Participatory rural appraisals were performed in each community to get an overview of their functioning. At that point, a total of 131 surveys were carried out in Camotán (Guatemala) and San José de Cusmapa (Nicaragua), where development projects have been established since 2006 (Rural Communities of Millenium). The semi-structured household surveys were performed from October to December 2013, corresponding with the harvest of maize and second bean cycle. Surveys were calculated according to Morales Vallejo (2012) for a confidence level of 95 % and a sample error of 8 %.

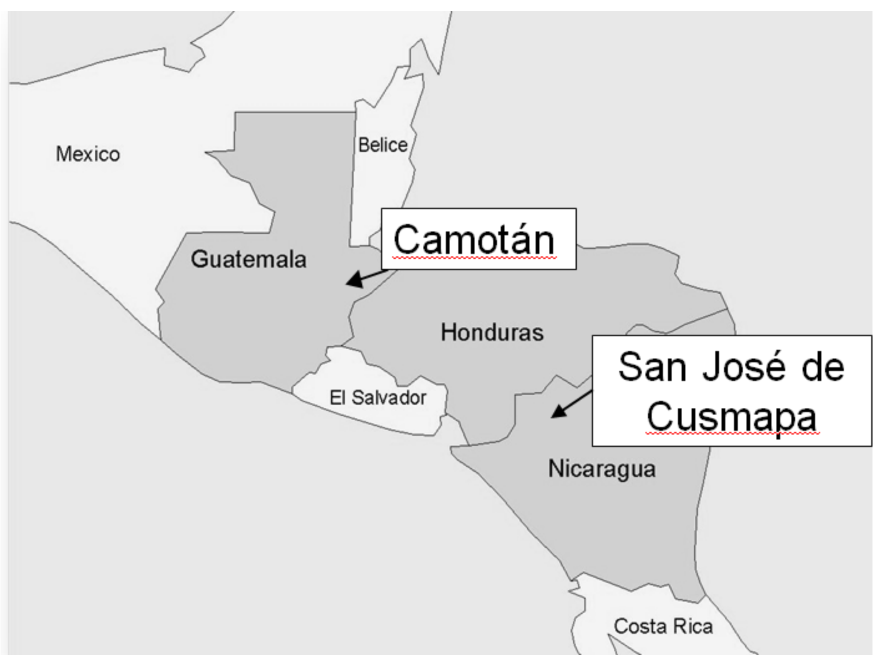


Figure 1. Location map of the two study areas. Camotán in Guatemala and S.J. Cusmapa in Nicaragua.

According to that, 64 semi-structured household surveys were performed across two communities in the Camotan municipality of Guatemala (Arnés et al., 2015; Marín-gonzález et al., 2018). Thus, 30 households were surveyed, out of a total of 161 households in El Tular (El Tular Centro and San Lorenzo hamlets), and 34 households, out of the 357 households present in El Limón (Limón Timoté, Peña Blanca, Changüis and Limoncito hamlets) represented in Figure 2. In both communities, all participants in development projects (18 households; Tarancon and Trueba, 2010) were surveyed as well as some non-participants (46 households). In S.J. de Cusmapa, municipality of Nicaragua, 67 surveys were performed in three communities. All communities had participated in farmer field schools development projects. The date of inclusion in those development projects varies for each community (Figure 3): El Terrero (2006), Los llanitos (2009) and El Angel2 (2010).

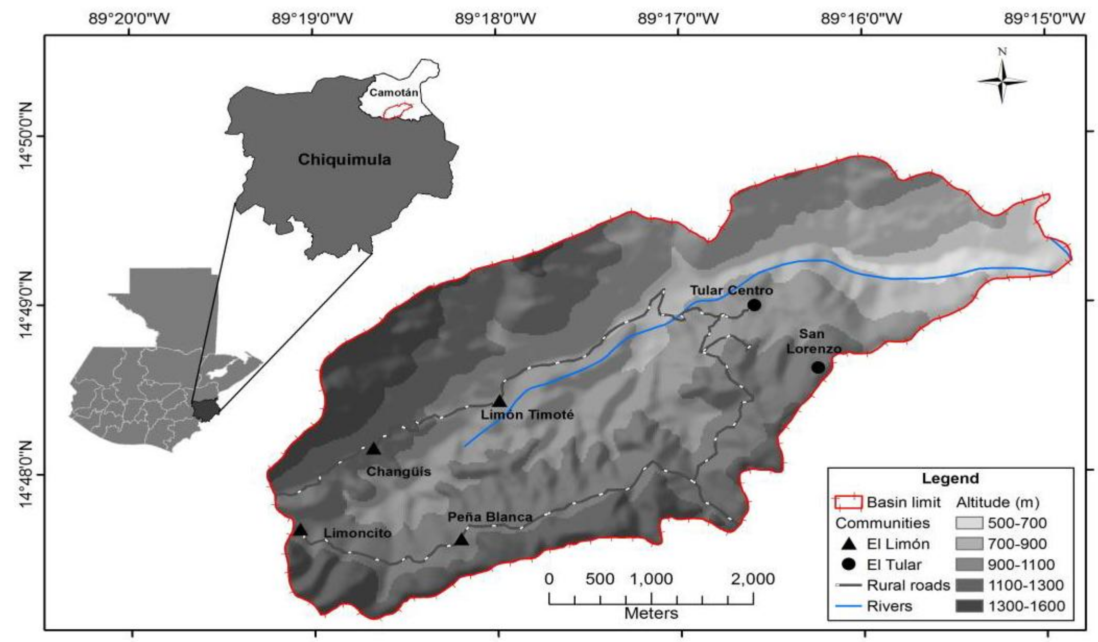


Figure 2. Location map of the communities investigated in Camotán (Guatemala)

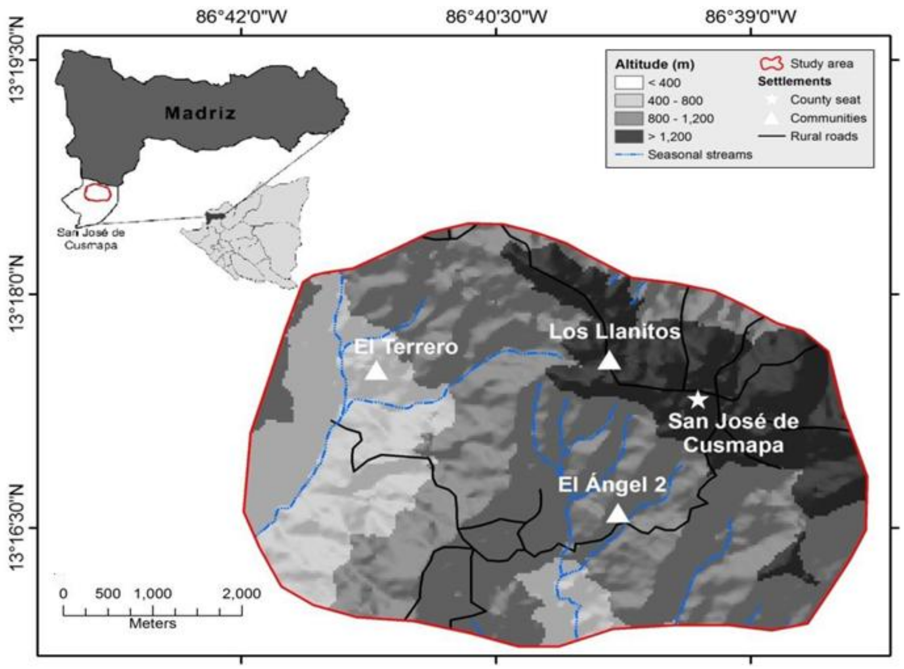


Figure 3. Location map of the communities investigated in San José de Cusmapa (Nicaragua)

All communities in both study areas show differences in environmental aspects (altitude, soils, vegetation, water availability and weather, Table 6). Furthermore, the three communities studied in Nicaragua show also differences in elapsed time from their inclusion in technical training projects.

Table 6. Family and housing distribution, number of surveys accomplished and number of participants in development projects surveyed, altitude of the sectors in the communities of El Tular and El Limón (Camotán, Chiquimula, Guatemala) and at El Terrero, Los Llanitos and El angel2 (S.J.Cusmapa, Nicaragua). Range of precipitation and temperature in Camotán and S.J. Cusmapa.

	CAMOTÁN, GUATEMALA		**S.J. CUSMAPA, NICARAGUA**		
Parameter	El TULAR	EL LIMÓN	El TERRERO	LOS LLANITOS	El ANGEL2
Families	211	416	46	78	72
Housing	161	357	42	64	60
Inhabitants	1327	1406	252	317	333
Surveys	30	34	20	24	23
Beneficiaries in develop. projects	13	5	9	15	11
Altitude (masl)	960	1250	700	1280	1000
Precipitation (mm)	1200-1700		1200-1400		
Temperature (°C)	16-34		18-32		

*Surveys in Tular were performed in Tular Centro and San Lorenzo villages. Surveys in El Limón were performed in Limón Timoté, Peña Blanca, Changüis and Limoncito villages.
Fte: Participatory rural appraisal (PRA) 2011 and (INSIVUMEH, 2013) and (INETER, 2013) for precipitation and temperature data.

The survey was divided into two parts (Appendix 1 in Supplementary material). The first part included information on socio-demographic characteristics of the household, household properties, agricultural assets, participation in community organizations, food intake, purchases and expenses, and household incomes. The second part included farmer decision-making processes in agricultural practices. First, semi-structured interview proof questions were tested with four technicians (following Wood and Ford, 1993). Thereafter, a simplified semi-structured interview was conducted with six local farmers in order to validate the survey (Dury et al., 2013). These surveys focused on the decision-making processes involved in the management of staple crops (maize and beans) namely, seed bed preparation, sowing, weeding, fertilization, management of pest and diseases, maize bending, harvest and post-harvest. Questions aimed to reveal the main factors affecting management decisions, e.g. deadlines for starting or finishing an activity, amount of inputs used, number of people undertaking each activity (from household or hired labour) and time required to accomplish an activity (Figure 4).

Figure 4. Picture interviewing one of the smallhoder farmers at El Limón, in Camotán, Guatemala.

Weather data consisted of long-term daily records from Camotán weather station (Guatemala, N 14^o 49' 14'', W 89^o 22' 22'', 450 m.a.s.l., INSIVUMEH, 2013) and from Cusmapa (Nicaragua, INETER, 2013, solar radiation was generated from monthly data, Annexe) which are the closest physically to the rural communities investigated. We used daily precipitation, temperature, and solar radiation data from 1992 to 2012 to assess long-term agricultural system dynamics. Other parameters used in this study were collected from literature, fieldwork observations, or established as a panel consensus with technicians and researchers of the region.

Daily weather variables are a key input to analyse risk related to climate variability (Wijk et al., 2012). Weather variability due to irregular rains and extension of heat-wave periods, is assessed along with the rest of variables since it directly affects crops development and yields. Rainfall varies, both in annual average amount and in seasonal distribution. This is important because in Guatemala and Nicaragua there are two sowing seasons: *primera* (may-august) and *postrera* season (September-December). For example in Guatemala, this implies that years with an annual rainfall close to the expected average rainfall (over a 21-year period) can experience drought episodes if this rainfall distribution is very uneven (Table 7). As in 2001 and 2009 when about 50 % of the annual precipitation felt during the first two months of *primera* season and more than 70 % during the first four months. The years with lowest rainfall were 1994, 1998, 2002, and 2003 receiving from 834 to 1060 mm (Table 6). Other years (1992, 1993, 1996, 1997, 2001, 2004, 2009 and 2012) received a smaller amount of rainfall than the average of the 21-year period (1223 mm).

Table 7. Yearly average maize and bean yields in Guatemala, average rainfall in Camotán weather station.

Calendar Year	Average maize yields (kg ha^{-1})	Average bean yields (kg ha^{-1})	Average rainfall (mm)	Percentage rainfall *"Primera"* (%)	Percentage rainfall *"Postrera"* (%)
1992	1883	818	1125	76	22
1993	1851	825	1090	72	25
1994	1957	679	907	57	41
1995	1944	744	1580	63	26
1996	1820	656	1069	54	35
1997	1494	592	1196	59	36
1998	1699	628	1060	57	40
1999	1738	697	1349	59	39
2000	1781	714	1238	70	28
2001	1841	735	1154	73	25
2002	1745	723	834	49	51
2003	1646	723	1040	55	41
2004	1577	719	1131	47	44
2005	1352	623	1233	71	24
2006	1495	573	1239	64	32
2007	2529	698	1401	60	38
2008	2276	474	1759	62	34
2009	1972	837	1126	83	17
2010	1989	835	1620	75	20
2011	1988	840	1367	57	37
2012	2000	907	1157	62	34
ANNUAL	1837	716	1223	63	33

Maize and bean yields (FAOSTAT, 2015). Average rainfall (National Institute of Seismology, Vulcanology, Meteorology and Hydrology abbreviated INSIVUMEH in Spanish). Primera (May-August), Postrera (September-December).

Guatemala and Nicaragua represent an important part of smallholders agriculture, 55 % of maize is produced in farms smaller than 3.45 ha in Guatemala (Fuentes Lopez et al., 2005) and 47 % of farmers produce in farms smaller than 3.49 ha in Nicaragua (INIDE, 2012). They also present a large percentage of hillside area with subsistence farming and agricultural daily labour as main livelihoods, low Human Development Index, and high taxes of poverty and undernutrition (Table 8). Both nations are among the ten most vulnerable to climate change, and natural disasters in the region which difficult poverty and food insecurity alleviation (Bruni and Santucci, 2016; Kreft et al., 2015; WFP, 2015a).

Table 8. Development indicators of Guatemala and Nicaragua.

Parameter	Unit	GUATEMALA		NICARAGUA	
		Value	Reference	Value	Reference
Population below international poverty line	%	49	(Align, 2021a)	13	(Align, 2021b)
Agriculture minimum wage	€/month	287	(Align, 2021a)	103	(Align, 2021b)
Rural living wage	€/month	339	(Align, 2021a)	232	(Align, 2021b)
Agricultural workforce	%	31	(Align, 2021a)	31	(Align, 2021b)
Agriculture share of GDP	%	9		15	
United Nations Human Development Index 2020[a]	n.u.	127/189	(UNDP, 2020)	128/189	(UNDP, 2020)
Contribution of agriculture to the domestic economy	%	12	World Bank, 2015	25	World Bank, 2015
Percentage of hillside area	%	80	Fuentes Lopez et al., 2005	35	SIAGUA, 2015
Chronic undernutrition rate for children < 5 [b]	%	46.5	WFP-SESAN, 2020	17	WFP, 2015
Population in poverty [c]	%	52.4	World Bank, 2022	24.9	World Bank, 2022

[a] UNHDI is calculated over a total of 189 countries. [b] Guatemala has the 5th highest rate in the world and in the region of Madriz (Nicaragua), this rate reaches 30%. [c] In Nicaraguan rural areas poverty reaches 50% and extreme poverty, 16% of the population.

The main productive activities in the Dry Corridor or Central America are rain-fed staples for self-consumption: maize and beans. Coffee (*Coffea Arabica* L.) is cultivated as a cash crop. In some cases, they grow sorghum (*Sorghum bicolor* L.) and raise livestock, predominantly poultry. A few farmers also grow vegetables such as tomatoes (*Lycopersicum esculentum* Mill.) or squash (*Cucurbita moschata* L.). Seasonal rainfall patterns define a rainy season (from May to October) and a dry season (from November to April) (INSIVUMEH, 2013). The growing season of rain-fed staple crops follow these seasonal patterns, distinguishing two seasons: "*primera*" (May to August) and "*postrera*" (September to December).

The use of chemical versus manual weeding depends on the staple crop, its developmental stage and on the current resources of the household. Overall, manual weeding is widespread for both bean and maize in the study areas. However in the management of bean crop, its use is generalized (88 % of farmers in Guatemala and 77 % in Nicaragua), whereas for maize, the application of manual weeding (59 % in Guatemala and 62 % in Nicaragua) is reduced in comparison with chemical techniques. Paraquat and Glyphosate are the most commonly used active ingredients in the region. Nitrogen is usually the most limiting nutrient in both regions. In the case of maize there are two nitrogen applications; basal application of triple 15 (NPK 15-15-15; Nitrogen, P_20, and K_2O, respectively), and a top dressing of urea. In the case of bean, farmers apply at least one dose of fertilizer with triple 15 (NPK 15-15-15). A second application for beans is uncommon (Bacon et al., 2014). In Guatemala, most farmers (89 %) undertake the two nitrogen applications for maize, whereas in Nicaragua just a minority of farmers (23 %) do both applications. Once the maize is ripe, most farmers bend it to avoid damage to the grain caused by late rains. In Guatemala, most farmers (67 %) undertake one dose of fertilizer with triple 15 (NPK 15-15-15) for bean crop, whereas in Nicaragua 38 % assume this application.

Small-scale farmers in Latin America have long supplemented their agricultural production with income from wage labour and the production and marketing of non-agricultural commodities (Bernstein, 2009; Deere, 1990; Kay, 2001). Numerous studies document the equal dependency of households upon subsistence-oriented agriculture and wage labour as sources of income (Align, 2021a, Bryceson et al., 2000; Deere, 1990; Isakson, 2009; Shelley, 2003). In the study regions the two main sources of off-farm labour are coffee plantations and other farms in the rural community. Labour within the community may be remunerated or returned as "*mano vuelta*". Which means that a farmer receives help from others in return for helping them in their field activities, in lieu of payment.

2.2 Smallholder endowments on food security in Agricultural Systems in Highland Areas of Central America (SASHACA) model development, calibration and validation

We purposed a dynamic model, Smallholder endowments on food security in Agricultural Systems in Highland Areas of Central America (SASHACA), of various subsystems (weather, soil, crops, family members and food consumption, labour, and household cash flow). SASHACA captures the essential processes, interactions and feedbacks determining short and long term farming system dynamics in highland of Central America. The model was developed in order to be relatively undemanding in terms of inputs due to its final application to data-scarce environments. The variables used as inputs are relatively easy to obtain either in primary or secondary sources of information or, failing that, from interviews with farmers (Knook and Turner, 2020).

The scale for decision making in our model is established at the smallholder farm level and we used a daily temporal scale. A major drawback with crop models, which are an important part of the whole model used in this thesis, is the large gap in knowledge and the lack of models for biotic components such as pests (including weeds) but also for beneficial organisms such as earthworms (Bergez et al., 2010).

2.2.1 Overview of the model SASHACA

The model was built in Vensim® DSS for Windows, Version 5.8d (Ventana, 2009). The model structure represents a smallholder agricultural system in hillside areas (Figure 5). SASHACA includes representation of discrete events and farmer decision making during the crop cycle. Maize and bean (*Phaseolus vulgaris* L.) as companion crops are simulated simultaneously. A daily time unit is used to capture crop response to environmental conditions and competition for resources, which enables more realistic simulation of yields. Interrelations and feedbacks allow description of outcomes and critical points of the system, taking into account different management decisions, which is consistent with the intended application of this model. The model is launched from a Microsoft® Excel 2007 interface via a custom-built application using Visual Basic.

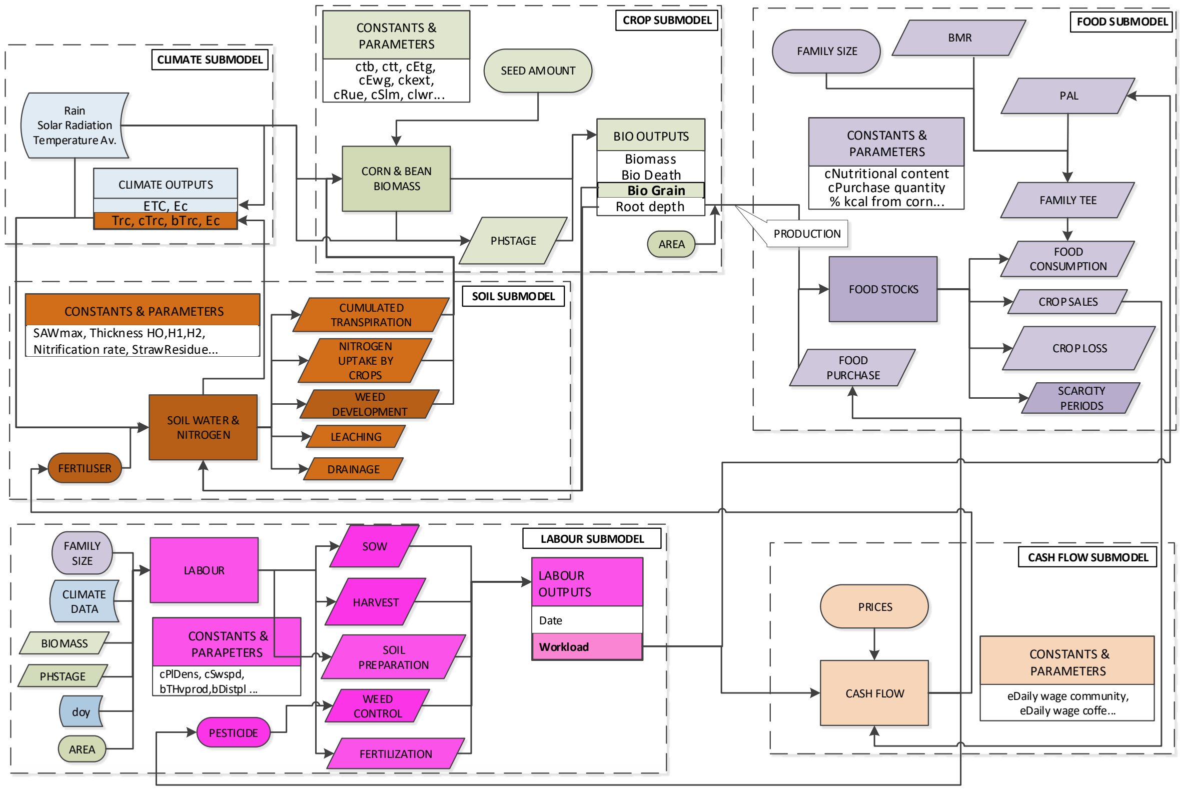


Figure 5. Schematic representation of SASHACA model general structure, main sub-models, inputs, constants, parameters and variables, and main interrelations. Each sub-model is enclosed in a dashed line rectangle with its name in the top right corner. Rectangles represent the main state variables, Parallelograms represent the other important variables, Rounded rectangles show the most important parameters of each sub-model. Stacked rectangles indicate other constants and parameters. Arrows represent interactions between constants, parameters, and variables.

Where *ctb: Base temperature for development; ctt: thermal time for development; cEtg: Optimum temperature for development of maize; cEwg: Effect of water on growth; ckext: Canopy extinction coefficient of maize; cRue: Radiation use efficiency of maize; cSlm: Ratio leaf mass to leaf area; clwr: Ratio leaf mass to absolute crop mass; ETC: Potential evaporation; Ec: Maximum evaporation under standard conditions; Trc: Maximum transpiration under standard conditions; cTrc: Maximum maize transpiration under standard conditions; bTrc: Maximum bean transpiration under standard conditions; SAW max: Maximum soil available water; Thickness H0, H1, H2: Thicknesses of horizon 1, 2, and 3 respectively; cPlDens: Plant density in maize; cSwspd: Speed of maize sowing; bTHvprod: Speed of maize harvest; bDistpl: Distance between furrows in bean.*

2.2.2 General model assumptions

The smallholder has an initial set of endowments (land, soil, food stocks, and household cash) and a time allocation distribution varying according to the livelihood strategy. This means that different starting conditions may be used to explore critical endowments and issues for each livelihood strategy. The farm area is assumed to be constant during simulations. The two crops modelled compete for resources because they are grown as an intercrop. Weeds affect crop growth and yields - when weeding is not done, crop growth rate is reduced by a coefficient ranging from 10 % to 45 % depending on the timing and length of weed competition (Oerke, 2006). Pests and diseases are only included in the model as food losses during storage (Pfister et al., 2005). The family is composed of combinations of seven types of individuals with different energy requirements. Farmers sell crops over a certain stock threshold when their food requirements are fulfilled. Food and input prices vary with the time of year. The model assumes that the minimum work efficiency never drops below the efficiency level reached at basal metabolic rate, even when staple stocks are depleted. In such a case, the model supposes that the lack of energy is supplied by other food sources (NGOs providing food assistance to improve the food security situation of the most vulnerable households, other family support, school support, or other food items not accounted in the model). The starting dates for different agricultural labour activities are triggered by the phenological stage, calendar dates, events or accumulation of events (e.g. storms, rainy days, dry days, time, or other activities), or any other farmer decision making rule; however the farmer can delay these activities by up to two weeks if available labour is scarce. The availability of off-farm work remains constant during the simulation. Specific assumptions and descriptions for each sub-model are detailed in each section.

Values for inputs and constants, ranges for parameters, and model equations are contained in the Supplementary material Tables 1-4. Constants are fixed numerical values that do not vary under specified conditions (seed weight, radiation use efficiency, Kc, etc.) Parameters are fixed numerical characteristics of a population (Garnett, 1997) that must be calibrated to the context and can be modified to analyse different scenarios (sowing density, labour speed, nitrogen dose, etc.)

2.2.3 Submodels

2.2.3.1 Weather sub-model

The weather input data consists of long-term daily records of precipitation, temperature, and solar radiation data, and is used to calculate potential evapotranspiration, and crop potential transpiration (Allen et al., 2006). Maize has priority in soil water use because it is sown first and consequently is deeper rooted, more fully exploring the soil profile. Maize is also taller, thus reducing air movement above beans (Allen et al., 2006). Maximum soil evaporation under field conditions is calculated according to the number of days since the last rain event and is used to estimate real evapotranspiration (Connor et al., 2008). Days of the year are used to trigger farmer decisions of sowing and harvesting.

2.2.3.2 Crop dynamics sub-model

Crop models based on Connor et al. (2008) are used for daily maize and bean simulation. They have a common structure and are similar to other biological growth models (Díaz-Ambrona et al., 2013; van Ittersum et al., 2003). Crop dynamics are described for a generic crop; however, parameters are specific for maize or bean (Supplementary material Table 3). Crop models capture the effect of radiation, temperature, and rainfall on crop growth and development. Furthermore, crops are modelled as companion crops competing for water and nutrients. Crop growth (Charles-Edwards et al., 1986; Donatelli, 1995; Penning de Vries et al., 1989) is calculated daily as a function of intercepted solar radiation and radiation use efficiency for actual soil-water and temperature conditions (crop growth model parameters and outputs in Supplementary material Table 3 and Table 5 respectively). The crop models account for soil-water and temperature (Connor et al., 2008), weeds and nitrogen effects on growth (Hernández Díaz-Ambrona et al., 2011). Intercepted radiation is a function of leaf area index which is calculated from accumulated biomass according to the actual phenological stage of each crop (Boons-Prins *et al.*, 1993; Chen *et al.*, 1994). Phenological stages are calculated through thermal time from sowing to flowering and from flowering to maturity. Grain yield is calculated from daily crop growth during the grain-filling period. Root growth is also included in the crop dynamics sub-model (Connor et al. 2008). Root depth depends on root penetration rate until the maximum available root depth is reached (Supplementary material Table 3). The portion of crop residue remaining at harvest (Supplementary material Table 3) together with the biomass that decomposed during the crop cycle becomes part of the surface organic matter which releases nitrogen for use by the subsequent crops. Bean nitrogen fixation (Johnson et al. 2008, Liu et al., 2011) is included in the bean dynamics sub-model and affects bean growth through nitrogen availability.

2.2.3.3 Soil water and nitrogen sub-model

The soil water sub-model is based on Connor and Fereres (1999). Soil water is simulated in three horizons (Campbell, 1991). Consequently, as roots grow, root depth increases and the water content of each soil layer is gradually used for plant transpiration. Rainfall and irrigation add water to the first soil layer and plant transpiration and evaporation draw water. Water uptake may occur at different layers simultaneously, according to root growth. The level of transpiration depends on potential transpiration of the corn-bean intercropping system and on water availability in the soil. Actual evaporation is a function of potential evapotranspiration, actual crop transpiration and soil available water. Evaporation events only occur in the wetted part of the first soil layer and are affected by the time since last rain or irrigation. Water infiltrates to the next layer once maximum available water-holding capacity is exceeded. Excess water from the lower horizon drains into the subsoil. Along with water stress, nitrogen is one of the major limitations to plant growth (Parsons et al., 2011a) but also requires careful management to avoid water contamination. Nitrogen is usually the most limiting nutrient in mountainous areas of Central America and is the main form of nutrient supplementation by farmers (Carrazón, 2008; Pfister et al., 2005). The soil nitrogen sub-model is based on O'Leary and Connor (1996). The soil nitrogen sub-model involves crops, soil water, and labour sub-models.

2.2.3.4 Labour sub-model

Analysis of labour is a focus of this paper, since peaks in workload often become a bottleneck for the performance of smallholder agricultural systems (Norton et al., 2006). Off-farm labour either within the community or outside (e.g. on coffee farms) is critical in these smallholder agricultural systems (Isakson, 2009). Daily labour allocations for the main cropping activities and off-farm labours include: soil preparation, sowing, weed control, fertilizing, maize bending, harvest, labour in coffee plantations, and labour in other fields within the community. Labour length (Eq. 32) is the total amount of hours needed to complete an activity, considering the technology in use (Supplementary material Tables 2-3). For most activities the time required depends on the plot size, plot design and labour speed, which in turn depends on work efficiency (Eq. 141; Food sub-model section) and the number of people working on the farm. The model includes hired workforce through "*mano vuelta*", meaning that a farmer receives help from others in return for helping them in their field activities, in lieu of payment. The level of fulfilment of family food requirements and the technology factor define the efficiency of work, which also affects duration of the task. Each activity can be delayed by a week, but if further delayed may not be initiated (Tittonell et al., 2007; Wijk et al., 2009; Zingore et al., 2006). Sowing can be delayed by up to two weeks; however farmers may miss the opportunity to sow due to a lack of labour availability. Harvesting is conducted when the crop is mature.

Seed bed preparation for maize is a function of plot size, plot design and labour speed. The beginning of this activity depends on labour availability and farm size. Farmers start soil preparation at the end of the dry season. First sowing of beans does not need any further seed bed preparation since it is sowed as a companion crop of maize. Seed bed preparation for the second sowing of beans (*"postrera"*) can be done either manually or with herbicides, which reduces time required for soil preparation (Supplementary material Table 2, Table 3).

Sowing labour is done by placing three or four seeds in individual holes by means of a spike (Eq. 20, Crop dynamics sub-model section) and depends on workload availability (Eq. 44, 46). First sowing of maize and beans may start from April to the beginning of June, depending on the beginning of the rainy season and labour availability. Farmers usually sow maize after three storm events within early April and mid-May. If the rainy season occurs later, the model assumes that they will sow maize after the first significant rainfall event, when daily precipitation is greater than 7 mm (Allen et al., 2006).

Both chemical and manual weeding are simulated. When herbicides are used the time required for weeding is reduced by approximately half (Supplementary material Tables 2 and 3). Weed incidence (Eq. 59-62) is considered during two periods: (i) from the first weeding labour to the second weeding labour; and (ii) from the second weeding labour to maize bending. Weed incidence is related to weather conditions and former weed control activities. Weeding dates change according to the weather. The model includes two fertilizer applications for maize and one for beans, according with the farmer practice. The timing of fertilizer application in the model depends on the crop phenology.

After maturing, maize is defoliated and bent. Harvest activities also include removing grain from cobs, and transport to the household where the product is stored. Harvest date may vary depending on the weather, yields and family food security level. There is also a daily consumption of maize from maturity (*"milpa camagua"*) until the main harvest takes place. Farmers typically consume part of the production before it dries completely. This activity is not very time consuming and is not included in the overall account of harvest labour.

Off-farm labour is modelled as a yearly labour per household occurring during a specific period of the year when the activity must be performed. From December to February during coffee harvest, many farmers go out of the community to labour on larger farms (Bacon et al., 2014). During the rest of the year, if they have the opportunity, they may delay their own farm activities to work on other farms within the community. The income from off-farm activities depends on the number of household members working off-farm, the wage they receive per hour worked, and the amount of hours worked per year.

2.2.3.5 Food sub-model

Maize and beans are the main products in the farmers' diets and account for the majority of their labour time. The average total energy expenditure (TEE, Eq. 132; Supplementary material Table 2) of a family is calculated by multiplying the basal metabolic rate (BMR) by physical activity level (PAL) of each family member (PNUD, 2011). BMR is calculated for a specific body weight and age for each family member (Schofield, 1985). PAL is calculated according to main daily activities, time allocation and energy cost of each activity (FAO/WHO/UNU, 2001; UNU 1989; Table 9). A more detailed description is in Supplementary material Table 1).

Table 9. Average Physical Activity Level (PAL), Basal Metabolic Rate (BMR), and Total Energy Expenditure (TEE) for each of the members and the average of a typical family in mountainous areas of Central America.

Sex, age and weight	**Lifestyle**	**PAL**[a]	**BMR** (kcal day^{-1}person^{-1})	**TEE** (kcal day^{-1} person^{-1})
Any sex, under 3 years and 5 kg	Sedentary or light	1.7	435	735
Female, 3-10 years and 20 kg	Moderately active	1.9	892	1654
Male, 3-10 years and 20 kg	Moderately active	1.9	958	1777
Any sex, of 10-18 years and 50kg	Vigorously active	2.4	1543	3747
Woman, of 18-30 years and 50kg	Vigorously active	2.2	1228	2731
Man, of 18-30 years and 60kg	Vigorously active	2.4	1596	3876
Any sex, 30-60 years and 50kg	Moderately active	1.9	1447	2749
Average person[b]	Vigorously active	2.1	1157	2467

[a]*PAL = Physical Activity Level or energy requirement expressed as a multiple of 24-hour BMR*
Source: FAO, 2008*; FAO/WHO/UNU, 2001; UNU 1989.*
[b]*The average person in a household composed of seven members*

Actual daily consumption of staples is calculated according to their nutritional value (FAO INFOODS, 2010, Supplementary material Table 3) in order to provide a certain percentage of TEE. The family tries to meet its daily potential food needs (Eq.137-138). Under a certain level of staple stock, the family reduces its consumption, adapting to the size of food stocks (following consumption pattern "c" in Pfister et al., 2005). The limit for this reduction is the basal metabolic rate of the family (Table 9). When consumption is reduced, global work efficiency (Eq. 141) decreases.

Staple stocks depend on crop production, crop sales, staples purchases, actual consumption, and losses during storage. Crop production in terms of dry matter is calculated from yearly yields and cultivated area. The household sells part of their production if it is above a certain amount, even when it does not cover their annual food needs. The household buys staples when their stocks decrease under a certain amount, provided they have enough money to buy them. Purchase priority is given to maize, since it is the most important product in their diet. When consumption needs are bigger than stocks and the household is not able to buy food, the family incurs a food shortfall. The model assumes that the family obtains enough food to cover at least basic metabolic needs of the household. Food rationing, dietary change (i.e. eating less-preferred foods), or the ''busqueda'' which represents a desperate search or begging, are common coping mechanisms of the households during the lean months (Bacon et al., 2014).

2.2.3.6 Cash flow sub-model

The cash flow sub-model describes how smallholder cash surpluses devoted to agricultural inputs and food purchase change according to several livelihood activities, including labour allocation, purchase or sale of staples, or agricultural inputs application. Cash flow outcomes influence management decisions through interrelations and feedbacks to other sub-models such as food, labour, or soil water and nitrogen sub-models. Although the cash flow sub-model is simple, the algorithms defining decisions to invest surplus cash are important in defining overall household behaviour. The annual family cash surplus balance is calculated from expenditures and incomes to maintain household food supply. The cash flow is the difference between incomes from agricultural and off-farm labour, and expenditures from fertilizers, herbicides, and food purchase over time. Cash flow is allowed to become negative, representing the level of indebtedness attainted by some farmers to obtain agricultural inputs.

Agricultural labour income is the sum of sales income from maize and beans, off-farm labour and other sources of income. The income from maize and bean, depends on the rate of staple sales and the sale price. Off-farm labour income depends on the type of off-farm labour, the wages, and the number of family members working off-farm. Other sources of income (i.e. cash crop sales, poultry sales, and other off-farm activities) are included as exogenous variables which are constant throughout the simulation.

Agricultural input and food expenditures are calculated on the current price of the commodities (Eq. 161-162). Agricultural inputs (fertilizers and herbicides) and food purchase are the main expenditures considered in the model. Transport expenditure in food purchase is included in food price. Hired labour, is not accounted for monetarily, but implicitly in the time span of agricultural activities through "*mano vuelta*". Other smallholder expenditures such as services, clothing and footwear, health, or education are included as external variables.

2.2.4 Model performance and evaluation tests

The model was tested to assess the structure, interrelations, equations, and parameters (Sterman (2000); Krause et al., (2005); Pfister et al., (2005); Robinson, (1997); Rötter et al., (2012), Parsons et al. (2011b)). According to Sterman (2000) we performed “tests for assessment of dynamic models” which include assessment of integration error, dimensional consistency, boundary adequacy, extreme conditions, behaviour representation, and sensitivity analysis. Data from the surveys are farmers’ perceptions and represent a snapshot of the system at a certain moment.

Nonetheless, we also judged appropriate the comparison of simulated data derived from a calibration and an independent evaluation set with the actual data derived from surveys. This procedure provides an additional way of assessing model performance.

Behaviour representation was tested throughout the model development process and compared with observed (MAGA, 2011; Bacon et al., 2014). This analysis was done comparing the actual timing for the main household activities (values from the surveys) and food scarcity periods (MAGA, 2011) to the simulated outputs of a year with heavy early rains and a year with scarce late rains. The comparison was made for a virtual household represented by the average of all surveyed smallholders. The virtual household depends on a mixed beans/maize crop, purchasing and selling staples, purchasing fertilizer, with off farm and non-farm incomes, remittances, coffee sales, and other minor sources of income and expenditure.

The ranges and probability distributions selected for the sensitivity analysis were drawn from the literature (Supplementary material, Table 3) giving emphasis to regional and local literature, especially for variables with a high error margin (e.g. due to highly variable smallholder conditions). The probability distribution for all parameters was Random Uniform, except for journal hours which follows a vector distribution going from six to ten hours by intervals of one unit. The same virtual average smallholder used for the behaviour representation test was used for the sensitivity analysis. First, univariate sensitivity analysis was implemented to assess the direct effect of parameters or constants on output variables. Sensitivity was calculated as the percentage of change in an output variable as the consequence of a 1% change in a constant or parameter. Second, a Monte Carlo simulation (a type of multivariate sensitivity simulation, MVSS) was done to assess the effect of simultaneous change of several constants or parameters on the main outputs. For MVSS, only constants or parameters that were identified in the univariate sensitivity analysis as having a larger effect were retained. Relative uncertainty is the coefficient of variation of the output variable, and is calculated by dividing the simulated standard deviation (SD) by the simulated mean (Pfister et al., 2005; Wolf et al., 1996). Sensitivity represents the change of an output variable in consequence of a unitary variation of a parameter, whereas uncertainty reflects the change of an output variable due to the range selected for the sensitivity analysis of each parameter.

2.2.5 Calibration and independent evaluation

Before assessing model performance through statistical comparison of simulated outputs with actual data, the 64 surveys of Camotán (Guatemala) were divided into calibration (80% of surveys) and independent evaluation (20% of surveys) sets (AASHTO, 2010) as shown in Table 10. The distribution and size of the calibration data covered the range of the system (Supplementary material, Table 3) as suggested in the literature (Marín-González et al., 2013; Sterman, 2000).

Table 10. Statistics of calibration data set and evaluation data set for the main variables used for evaluation.

Variable	Unit	Calibration set					Independent evaluation set				
		Obs.	Min	Max	Mean	SD	Obs.	Min	Max	Mean	SD
Maize area	ha	51	0.0	1.6	0.6	0.3	13	0.2	0.9	0.5	0.2
Average bean area	ha	51	0.0	1.6	0.3	0.3	13	0.0	0.5	0.2	0.2
Household size	person	51	1	13	7	3	13	3	12	6	3
Household labour	person	50	1	4	2	1	13	1	3	2	1
Household TEE	kcal	51	872	5322	2433	1059	13	1204	3643	2128	775
Bean consumption	kg household^{-1} year^{-1}	51	47	745	232	138	13	83	331	201	90
Maize consumption	kg household^{-1} year^{-1}	51	439	2912	1304	660	13	445	1989	1082	496
Bean Yield	kg ha^{-1}	44	193	2132	650	349	11	386	1287	758	280
Maize Yield	kg ha^{-1}	49	515	4289	1401	753	13	515	3431	1889	810
Bean Purchase	kg year^{-1}	51	0	363	39	74	13	0	297	66	101
Bean sale	€ year^{-1}	51	0	598	42	116	13	0	359	39	99
Maize purchase	kg year^{-1}	51	0	2041	259	396	13	0	1270	288	419
Maize sale	€ year^{-1}	51	0	268	9	40	13	0	120	9	33
Coffee labour off-farm	day year^{-1} person^{-1}	51	0	150	45	34	13	0	112	51	44
Community labour off-farm	day year^{-1} person^{-1}	51	0	208	62	53	12	0	160	45	46
Expenditure on nitrogen	€ year^{-1}	49	2	490	152	108	13	36	222	101	56
Annual household Cash flow	€ year^{-1}	51	-2494	3720	215	935	13	-695	707	122	424

Household TEE: Average total energy expenditure of the household; SD: Standard deviation. Obs.: Number of observations.

Households were allocated to calibration and evaluation sets, ensuring that each set covered a similar range for productive endowments (labour and land), family characteristics (size and composition, number of farmers, energy and food requirements), external inputs (fertilizers, seeds), smallholder cash flow (crops sales, off-farm labour, food purchase, other incomes and expenditures), and food stocks (crops yields, staples consumption).

2.2.5.1 Model Calibration

Once structure was evaluated and all previous model testing completed, constants and parameters were re-examined. Calibration was done individually for each sub-model, ensuring that any constant and parameter had a clear real-life meaning. Constants were specified based on information from the literature or by measurement of actual farmer conditions. As the model includes social and human dynamics it requires a broader pool than just numerical data, including written and mental mapping data, known as "soft variables" (Sterman, 2000). Thus, parameters were estimated based on a dataset selected from semi-structured surveys with household heads, but also from observations, expert knowledge, and interviews with key people (technicians, NGO staff or researchers). The model was calibrated for a virtual smallholder, representing the average values of the calibration set.

2.2.5.2 Model Evaluation

Model outputs for the variables of greatest interest for our model purpose were compared with real data from surveys as an evaluation of the calibration process. The variables assessed were total energy expenditure of the household, annual maize and bean consumption rate, maize and bean yields, annual expenditure in fertilizer, annual bean and maize purchase, annual bean and maize sale, and annual cash flow of the household. We compared the average value of a 21-year simulation for the virtual smallholder corresponding to the average values of the smallholders composing the calibration dataset, with the average value of observed calibration data set from the surveys (Figure 7 and Figure 8). The independent evaluation dataset was used for a detailed assessment of model output representation of real behaviour following the same procedure as for model calibration. Averages of a 21-year simulation were compared with actual data from surveys from the independent evaluation data set (Figure 7 and Figure 8). This comparison was made for the simulation outputs of a virtual smallholder, corresponding to the average values of the smallholders composing the independent evaluation dataset. Confidence intervals were calculated to describe how reliable the simulated results are, and so to allow comparison with our model simulations.

2.3 SASHACA model application in Guatemala: Impact of smallholder endowments on their welfare in highland areas of Central America

SASHACA was used to analyse consequences of individual changes or combinations of them over a 21-year period (from 1992 to 2012). Therefore, Univariate and Multivariate Sensitivity Simulations (MVSS) are run for land availability (maize and bean area), off-farm labour opportunities and the use of agrochemicals (fertilizers and herbicides). Changes in these endowments, were used to analyse the effects on maize and bean yields, household net cash income, smallholder workload, and food security levels and so establish smallholder welfare level. Also, we delineate thresholds in endowments leading to sustainability of the agricultural system.

Land availability is a function of productivity and efficiency of the agricultural system but at the same time affects smallholder net cash income. Off-farm labour opportunities are an important source of incomes determining household cash flow. The use of agrochemicals (fertilizers and herbicides) has an associated cost. However, they also have an effect on yields, and in the case of herbicides, a considerable reduction on workload. Average speed of manual weeding in maize is 32 m^2 h^{-1} $person^{-1}$ whereas when using herbicides it increases up to 120 m^2 h^{-1} $person^{-1}$.

Following Louhichi and Gomez y Paloma (2014) we used a typical household, representative of the smallholder farms in the region. This household is an *observed virtual household* representing the average of the variety present in the survey for each variable and parameter in the model (Table 6). However, some of the variables and parameters are altered in order to assess variation according to each analysis (area, use of fertilizers and herbicides, yields, family size, off-farm labour availability), defining a *simulated typical household*.

To more fully represent the variability of the region, the analyses cover the whole range of values for each of the main variables and parameters defining households in Guatemala (Table 11). This approach allows a more general interpretation and better understanding of the effect and importance of each endowment, rather than being applicable only to very similar smallholder farms.

Table 11.Descriptive statistics of the model simulation variables and parameters (SASHACA) for a typical household representative of farmers in Guatemala.

Model simulation parameters	Units	Min	Max	Mean	SD
Maize area	ha	0.09	1.59	0.57	0.31
Bean area	ha	0.04	1.62	0.25	0.30
Maize yield	kg ha^{-1}	515	4289	1503	785
Bean yield	kg ha^{-1}	193	2132	671	337
Household size	people	1	13	6.5	3
Household labour force equivalent	people	1	4	2	0.8
Household dependents [a]	people	0	11	5	2.4
Nitrogen use	kg N ha^{-1}	0	384	121	78
Maximum off-farm labour (coffee farms)	day $year^{-1}$ $household^{-1}$	0	300	79	73
Maximum off-farm labour (community farms)	day $year^{-1}$ $household^{-1}$	0	416	87	98
Off-farm wage (coffee farms)	€ day^{-1} $person^{-1}$	0	--	4.9	2.1
Off-farm wage (community farms)	€ day^{-1} $person^{-1}$	0	--	2.5	0.6
Average energy consumption	kcal $person^{-1}$	872	5322	2371	1010
Average maize consumption [b]	kg day^{-1} $household^{-1}$	1.20	7.98	3.45	1.73
Average bean consumption [b]	kg day^{-1} $household^{-1}$	2.04	0.13	0.62	0.35

[a] Household dependent members do not contribute to farm labour, but do consume household food resources. All values are calculated from surveys. [b] Rural consumption of maize and bean is up to 2.8 and 6.6 times greater than the national average (86 and 8 kg $person^{-1}$ $year^{-1}$), respectively (Arnés Prieto, 2015).

A household is considered to experience food shortfall whenever availability of any of the staple crops is less than the actual needs. Food secure days are the total number of days in a year where there is no shortfall. Cash flow is simulated as the difference of incomes from staples, off-farm labours, cash crops, and incomes from other activities, and the expenditures from fertilizers, herbicides, food purchase and other expenditures over the years. Net cash income is the difference of incomes and expenditures for each year. The workload is simulated per person and includes on-farm and off-farm agricultural activities during the year. The yields are simulated for both staple crops and depend on weather, soil fertility and management.

2.3.1 Simulating land availability and crop area allocation

As pointed in the previous section we explore welfare behaviour (through the variables yields and food security, workload, and cash flow) of a typical household for different maize and bean area allocations based on farmers ability to trade food products. They sell staples above a certain production threshold at a price varying according to the product and the period of the year. In this study case, this production threshold was set on 900 kg of maize, which corresponds to about seven and a half months of consumption, and 110 kg of bean, which corresponds to about five months of household consumption. Also, they can purchase maize and beans according to their food requirements and cash availability (supplementary material in Marín-González et al., 2018).

To study the effects of land availability on smallholder welfare different crop areas were allocated to the simulated typical household. This study was divided in two parts: Inter-annual variability in household food security levels, and average long term variability in smallholder welfare levels. Firstly, we examined changes independently for each staple crop area allocation (Inter-annual variability in food security levels), through a univariate sensitivity simulation keeping all other parameters constant (Table 17). We assessed changes in the area grown of each crop (0.05-1.60 ha for maize and 0.01-1.62 ha for bean using an interval of 0.1 ha). Thus, we analysed how the extent of maize and bean areas affect long-run (21-year) smallholder farmer food security levels and observed the inter-annual variability. For the study of changes in maize area allocation, we fixed the bean area to the average value of the surveyed population (0.25 ha). Then, for the study of changes in bean area allocation we fixed the maize area to the average value of the surveyed population (0.57 ha).

Secondly, we simultaneously assessed variability in both crop areas using a MVSS. We used the outputs of the MVSS, with an interval of 0.2 ha. Topographic graphs were used to plot the effect of crop areas on the average cash flow, workload and food security levels for the average value of a 21-year simulation (average long term variability). We analysed combinations of maize and bean area allocations ranging from the minimum area to 2.5 ha, provided that the sum of maize and bean in the region, is equal or smaller than 2.3 ha. This gives a general overview of all possible situations. However the analysis was focused in situations more commonly found in the region. That is, maize and beans combinations where maize area allocation is equal or greater than bean area allocation (which is the case for the 94% of households). This corresponds to the area underneath the bisector line in the topographic graphs.

2.3.2 Simulating off-farm labour dependency

We used MVSS to analyse long-term household dependency on off-farm employment and its impact in household welfare, measured by cash flow, staples yields, and food security levels. Off-farm opportunities are divided in two types according to their occurrence within the year and the wages received (Table 12). These are: work on coffee farms and work on other people's farms within the community. In the case of employment on coffee farms, the range of off-farm work availability investigated ranges from no work availability to the entire period of the coffee harvest. The coffee harvest begins in December and extends until February and was a reported activity for more than 80% of the households interviewed. During the rest of the year, farmers work on other people's farms within the community. About 75% of households interviewed engaged in this type of off-farm work at least once a week during the resting nine months of the year when coffee harvest is not happening. The range considered here spans from no work opportunities to 4.6 months, which corresponds to about four days a week during the nine months.

Three scenarios emerging from combinations of work on coffee farms and work on farms at the community are simulated: 'Pure on-farm labour', on-farm labour with 'Average off-farm labour' availability, and on-farm labour with 'Plentiful off-farm labour' availability. The scenario ´Pure on-farm labour´, assumes a typical household working exclusively on their own farms either because they are pure basic grains farmers or because there is not enough off-farm opportunities. The scenario 'Average off-farm labour' represents a typical household working off-farm the average number of days in the survey. Thus, it assumes a maximum labour opportunity of 1.1 months a year on both off-farm sources of employment. The scenario 'Plentiful off-farm labour' characterizes a typical household working the upper limit of days explored in the MVSS for both forms of off-farm employment. Thus, it assumes a maximum labour opportunity of three months a year of off-farm work on coffee farms and 4.6 months a year on farms at the community (Table 12).

Table 12. Long term off-farm opportunity scenarios simulated for a typical household in the region.

Off-farm opportunities scenarios	**Maximum labour opportunities at coffee farms** (month year^{-1})	**Maximum labour opportunities at community farms** (month year^{-1})
Pure on-farm labour	0.0	0.0
Average off-farm labour	1.1	1.1
Plentiful off-farm labour	3.0	4.6

This last scenario would represent a situation in which there are plentiful off-farm employment opportunities and therefore most households would be able to benefit from it. The three scenarios consider an off-farm labour force equivalent to two men[1] for either type of off-farm employment.

2.3.3 Simulating agricultural inputs use

We analyse the effect of two different weeding technologies (manual and chemical) and four nitrogen application levels on household welfare. The nitrogen levels included: no nitrogen application (0N), nitrogen applications equal to the first quintile (70 kgN ha^{-1} ; 70-N), the average nitrogen application in the region (121 kgN ha^{-1}; 121N), and nitrogen applications equal to the third quintile (155 kgN ha^{-1}; 155N) of the sample interviewed. Nitrogen is applied in early stages of development in both crops (maize and bean), in some cases there is also a second fertilization of maize before bloom. The analysis is for farms of two sizes: the average land area of the region (0.57 ha; A), and for a typical household with double the land area of the region (1.14 ha; DA). The annual household net cash income, food security levels and yields of maize are calculated during a 21-year simulation for the eight combinations resulting from the nitrogen applications and household land size (Table 13). We just analyse the effect of Nitrogen application on maize yields because the average nitrogen amount used in bean fertilization is four times smaller than the amount used on maize and not all farmers do it (less than 50%).

[1] men, in this document stands for any adult person with capacity to work

Table 13. Nitrogen application and household land size combinations simulated to explore long term agricultural inputs use of the typical household in the region.

Code	Nitrogen application and household land size combinations investigated	Nitrogen application[1] (kgN ha^{-1})	Maize area (ha)	Bean area (ha)
0N-A	No nitrogen application, average area	0	0.57	0.25
0N-DA	No nitrogen application, double area	0	1.14	0.65
70N-A	Low nitrogen application, average area	70	0.57	0.25
70N-DA	Low nitrogen application, double area	70	1.14	0.65
121N-A	Average nitrogen application, average area	121	0.57	0.25
121N-DA	Average nitrogen application, double area	121	1.14	0.65
155N-A	High nitrogen application, average area	155	0.57	0.25
155N-DA	High nitrogen application, double area	155	1.14	0.65

[1] *Nitrogen application includes two fertilizations in maize and the average nitrogen amount used in bean fertilization*

To analyse variability we conducted a resampling test, consisting on swapping the order of the yearly weather data for the 21-year period and repeating the same process four more times. For each variable investigated (household net cash income, food security levels and yields) we carried out a two way analysis of variance (ANOVA), to determine the significance of the two factors affecting the results: weather variability (21 years) and nitrogen dose (0, 70, 121 and 155 kg N ha^{-1}) and its interaction. For the variables where nitrogen application shows a significant effect in the results, we used TukeyHSD (Honest Significant Difference) test to study the differences between each pair of N application rates. The residuals versus fitted values and the normal probability plots were performed to assure the applicability of the ANOVA and TukeyHSD test. The whole process was done for the average land area (A) and for an area double the size of the region (DA). The distribution of the output variables was represented in boxplots with different letters indicating significant differences among Nitrogen applications.

A similar analysis was performed to examine the interaction between weeding technology (manual or chemical) and farm area (Table 14). The impact of the treatments was assessed on workload, household net cash income, food security levels and yields of maize during a 21-year simulation.

Table 14. Weeding technology and household land size combinations simulated to explore long term agricultural inputs use of the typical household in the region.

Code	Weeding technology & household land size combinations	Weeding technology	Nitrogen application[1] (kgN ha^{-1})	Maize area (ha)	Bean area (ha)
M-A	Manual weeding, average area	Manual	121	0.57	0.25
Ch-A	Chemical weeding, average area	Chemical	121	0.57	0.25
M-A	Manual weeding, double area	Manual	121	1.14	0.65
Ch-A	Chemical weeding, double area	Chemical	121	1.14	0.65

[1] *Nitrogen application includes two fertilizations in maize and the average nitrogen amount used in bean fertilization*

The results of the long run simulation are presented in box-plots for each combination of nitrogen application, weeding technology implemented and land size scenarios.

2.4 SASHACA model application in Guatemala and Nicaragua: Family farming definition adapted to regional context with a focus on subsistence or near-subsistence smallholders

We used the SASHACA over a 21-year period to refine the family farm definition focusing on subsistence and near-subsistence smallholders. SASHACA model was used to integrate regional factors in the family farm definition. SASHACA requires specification of daily weather data, soil characteristics, crop allocations, plot design, fertilization rates, staples percentage on diet, family size and composition, off-farm labours, and other incomes and expenditures. Throughout this case study we use SASHACA to investigate the effect of changes in family size and composition, which are directly linked to family labour force, and the effect of changes in soil productivities on the typical household welfare parameters. Here, household welfare is investigated through the outputs: yields, food shortfall, workload, net cash income, and cash flow. Our analysis emphasizes food access and availability. Yields are simulated for both staple crops and depend on weather, soil fertility, and management. Workload, net cash income, cash flow, and household food shortfall are calculated in the same way explained in point 2.3 (SASHACA model application in Guatemala: Impact of smallholder endowments on their welfare in highland areas of Central America). Here, we firstly explored how different factors absent in the size-definition of family farm affect smallholders welfare. Secondly, we determined a desirable farm size for smallholder farms according to those factors in the study areas and following Scoville (1947) definition of family farm.

To explore how different factors absent in the size-definition of family farm affect smallholders welfare, we kept using a typical household representative of the smallholder farms in the region. The typical household represents the average values of the variety present in each region for each main variable and parameter in the model (Table 15).

Table 15. Descriptive statistics of the model parameters (SASHACA) for a typical household representative of farmers in Guatemala and Nicaragua obtained from surveys.

Model simulation parameters	Units	Guatemala		Nicaragua	
		Mean	SD	Mean	SD
Maize area	ha	0.57	0.31	0.93	0.54
Bean area	ha	0.25	0.30	0.36	0.27
Maize yield	kg ha^{-1}	1503	785	820	429
Bean yield	kg ha^{-1}	671	337	716	387
Household size	people	6.5	3	6.5	2
Household labour force equivalent	people	2	0.8	2	1
Household dependents[1]	people	5	2.4	5	2
Nitrogen use	kgN ha^{-1}	121	78	26	26
Maximum off farm labour (coffee farms)	day $year^{-1}$ $household^{-1}$	79	73	39	40
Maximum off farm labour (community farms)	day $year^{-1}$ $household^{-1}$	87	98	26	69
Off farm wage (coffee farms)	€ day^{-1} $person^{-1}$	4.9	2.1	3.3	2.7
Off farm wage (community farms)	€ day^{-1} $person^{-1}$	2.5	0.6	0.6	0.9
Average energy consumption	kcal $person^{-1}$	2371	1010	1790	598
Average maize consumption	kg day^{-1} $household^{-1}$	3.45	1.73	1.3	1.2
Average bean consumption	kg day^{-1} $household^{-1}$	0.62	0.35	0.8	0.7

[1] Household dependent members do not contribute to farm labour, but do consume household food resources.

In both countries maize and bean are grown as companion crops, however almost all farmers (94% of households) allocate smaller area to bean. Thus the bean area is assumed to be always cultivated in association with maize. In Nicaraguan diet, there is a smaller consumption of maize (Table 15) due to the greater consumption of rice and sorghum compared to Guatemalan one, and often sorghum is cultivated and consumed as a substitute of maize. For both countries we analyse the percentage of energy supplied by maize and bean and how, depending on land availability and crops allocation, the household is able to fulfil its energy needs.

To analyse how these changes affect the typical household welfare, we defined the following scenarios described in the next subsections: family size and composition, farm productivity; smallholder land size.

2.4.1 Simulating family size and composition

In this scenario, we firstly analyse the impact of family size on household food security and secondly the effect of family composition on smallholder welfare. In this first analysis, four different family sizes (3, 5, 7 and 13 people) are investigated in order to explore its effect in the household food security levels. The dependency ratios (children and elderly over the active people in the household), were kept constant for all cases. Energy requirements are calculated according to gender, height, weight and physical activity level of the family members. The average basal metabolic energy expenditure is adapted to the family size investigated as a ratio of the basal metabolic energy expenditure of the typical family composition in the region (Table 9). The physical activity level, is calculated as a function of the activities implemented. The rest of parameters, including labour equivalent force, and the number of farmers working off-farm were kept constant, *ceteris paribus*, during the simulation period with the values of the typical household, for all family sizes investigated. In the second analysis, family composition and dependency ratios vary with the time. The evolution of the family composition was evaluated for a five people and a seven people household during a 21-year simulation. For both cases, we assume a labour force equivalent to two men during the first seven years. Then, during the following five years, the labour force equivalent is increased to three men due to the full incorporation of one of the children to the farm labours. This also supposes an extra income derived from the off-farm labour of this person. During the following six years, one of the sons emancipates at the age of 24 years old (Marchionni et al., 2010) and another one starts farming full time so the labour force equivalent stays in three men. The last three years of the long term simulation, another son emancipates which reduces the labour force equivalent to the initial amount of two men. During all this simulation, the family size is considered constant assuming possible births, emancipations, and deaths.

2.4.2 Simulating farm productivity

In this section we analyse how household welfare is affected by farm productivities. This is undertaken exploring different yield combinations and yearly weather variability. The effect of yearly weather variability is explored on different types of farm productivity leading to different yield couples of staple crops. Farm productivity might emerge from climatic events, or be a consequence of agricultural management, or the access to very fertile land or on the contrary unsuitable soils, more suitable for perennial forestry than for agriculture. To analyse the influence of soil quality and its inherent properties in the household welfare levels, we divided the whole range of maize and bean yields observed in the region in seven intervals (Table 11 and Table 16), which leaded to 64 combinations of maize and bean yields. Average maize and bean yields were obtained from field surveys and are in agreement with other studies in the region (COSUDE-SICTA-IICA, 2012; FAO-WFP, 2010; INE, 2003; INIFOM–TGL–COSUDE, 2010). All 64 yield couples were analysed thought a MVSS in order to find the lower yield levels, within the 64 maize and bean couples, required to attain annual household consumption needs. Yield couples above that lower level were left out of the study for reaching annual food security. In the MVSS, yield couples are introduced externally to analyse their effect on the rest of variables. The rest of variables are simulated according to the normal functioning of the model.

Table 16. All 64 combinations of maize and bean yields (kg/ha) analysed to explore farm productivity effect on welfare of the typical Guatemalan and Nicaraguan household in the studied regions.

GUATEMALA

Maize / **Bean**	515	1056	1597	2137	2678	3219	3760	4300
193	Combination1	Combination2	……					
473	Combination9	Studied yield						
753	…..	couples						
1033								
1313				Annual food security				
1593								
1873								
2132								Combination64

NICARAGUA

Maize / **Bean**	260	509	757	1006	1254	1503	1752	2002
227	Combination1	Combination2	……					
443	Combination9							
658	…..	Studied yield		couples				
874								
1089				Annual food security				
1305								
1521								
1736								Combination64

The range interval in maize yields analysis is 541 (kg/ha) and in bean yields 280 (kg/ha) in Guatemala and 249 (kg/ha) and in bean yields 217 (kg/ha) in Nicaragua. The striped area represents the yield couples where the analysis was focused. The grilled area represents the yield couple with values closer to the average yields of the region. The flat grey area represents the yield couples resulting in all year-round food security fulfilment.

Subsequently, to focus on subsistence smallholders, we chose six couples of maize and bean yields around the average values of the studied region (1517 and 651 kg ha^{-1} respectively in Guatemala; 769 and 678 kg ha^{-1} in Nicaragua) to assess the effect in food security and household net cash income outputs (Table 16, grilled area). These six couples were chosen with approximately even yields intervals within each crop yield range, assuming that both companion crops respond similarly to the same external factors. As a consequence, we left out of the analysis, scenarios combining very high maize yields and very low bean yields and vice versa. The yield couples selected are represented in Table 16 within and striped square. A simulation was undertaken, for each of these selected yield combinations, keeping the rest of parameters constant with the values of the typical household.

The long term impact and inter-annual variability in household net cash income and food security levels for different yield combinations are explored. Net cash income is accounted on the beginning of July (doy=182) coinciding with the most critical period of food scarcity in these systems (Bacon et al., 2014). This allows investigation of the welfare situation at the critical period of food scarcity. Simulated results for the first year were not used in the analysis to avoid any influence from the initial conditions established in the model.

2.4.3 Establishment of smallholder land size threshold integrating regional factors

We adapted the size definition threshold to a regional context with subsistence and less than subsistence smallholders. Thus, we take into account not only farm size but other relevant characteristics such as landscape, weather, land uses, farm productivity, soil fertility (nitrogen levels), investment in inputs, equipment, household food consumption, household labour capacity, labour arrangements (i.e. "*mano vuelta*[2]") or relative shares of on-farm and off-farm labour. Therefore, to determine the sustainable size limits of the smallholder farms we assessed simultaneous variability in maize and bean area allocation and household labour capacity (labour force) keeping constant the rest of variables (with the average value of the region). The analysis is focused on area allocations where maize area is greater or equal than bean area. For these combination of areas, we established a hierarchy in welfare indicators. First, the combinations of areas leading to annual food security fulfilment were detected. For those areas, we identified the combination/s attaining higher annual cash flow. Then, for those areas meeting both criteria, we selected the one/s leading to smaller workload and determined the yields obtained under those conditions. This gives us an idea of the potential welfare parameters of smallholder farms of the region under the actual average conditions. Hereafter, we also calculated welfare parameters for the actual average farm size in the region, to increase knowledge of the actual situation.

A multivariate sensitivity simulation (MVSS) was run using SASHACA over a 21-year period to assess combinations of staple crop areas, by intervals of 0.2 ha, and household labour capacity ranging from two to four household labour force equivalent. Maize and bean areas were investigated from the minimum area of maize and bean to four ha in order to include the maximum area of each crop founded in both study cases. The welfare parameters analysed are: the average yield of the crops, farmers' workload, food security levels, and cash flow, for a long term simulation (21 years).

[2] Traditional practice which consists in lending a hand to relatives or farmers within the local community in their agricultural activities in exchange for a mutual collaboration.

3 RESULTS AND DISCUSSIONS

3.1 SASHACA model development

3.1.1 Model behavioural performance and sensitivity analysis

The model simulated realistic outputs and showed logical behavioural representation on all land and labour allocation parameters, management options, and incidence of food scarcity periods (Figure 6). Most of the activities are sensitive to the start time and volume of the rainy season. Actual timing for the main household activities and food scarcity periods (Figure 6a) are compared to the values of a virtual average smallholder in two extreme years within a 21 years Guatemalan weather dataset (INSIVUMEH, 2013): a year with heavy early rains (Figure 6b: year 1996) and a year with scarce late rains (Figure 6c: year 2002). The scarcity periods correspond to the yields and management activities of the previous year (Figure 6b and Figure 6c). Following heavy early rains, crops are sown early and the scarcity period for maize was shortened from late July to the middle of September (Figure 6b: year 1996), compared with the scarcity period after a year with scarce late rains which extended from April to November (Figure 6c: year 2002). In years with heavy early rains (Figure 6b), farmers sow earlier to make the most of initial rains, concentrating labour demand early in the season. Also, the following year presents shorter and milder food scarcity periods than years following seasons with limited late rain (Figure 6c). When comparing simulated outputs (Figure 6b and Figure 6c) with observed data (Figure 6a) all simulated activities are encompassed within the periods defined in the surveys. Sowing and harvest labours are simulated slightly ahead for the years with a heavy early rainy season. However, all these results are in accordance with the behavioural rules stated by the farmers for the early rainy season.

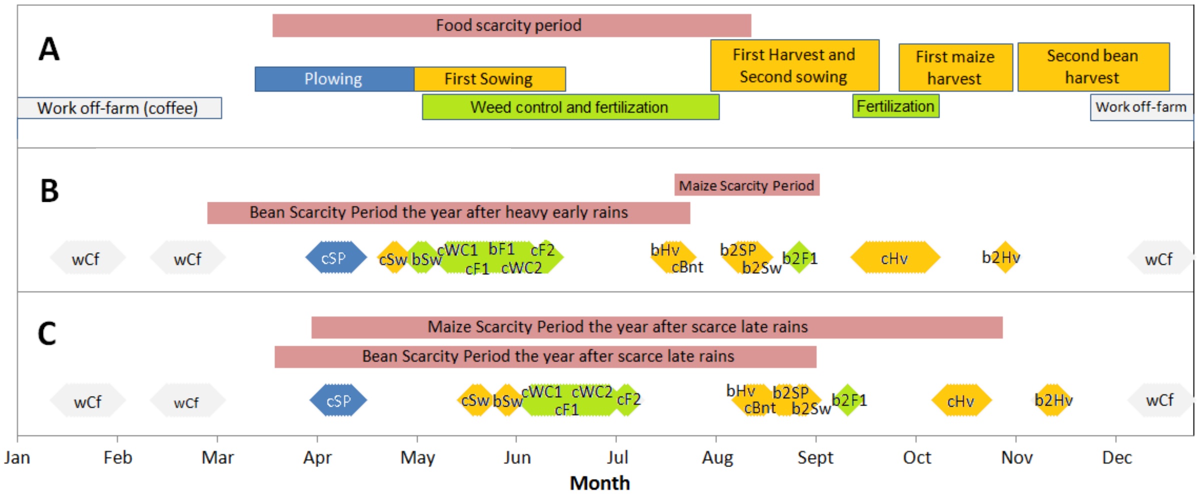


Figure 6. Representation of model behaviour reproduction for the main activities in staple crops, off-farm labour, and food scarcity periods. A) Actual timing for the main household activities (survey data) and food scarcity periods (MAGA, 2011). B and C) Values for a virtual average smallholder for: a year with heavy early rains (B: year 1996); and a year with limited late rains (C: year 2002). *Where: Garnet red: food scarcity period; grey: work off-farm; blue: plowing; orange: sowing and harvesting; green: weeding and fertilization; wCf: Work on coffee harvest out of the community; cSP: Soil Plowing; cSw: Maize sowing; bSw: Bean sowing; cWC1: Maize weed control; cF1: Maize fertilization1; bF1: Bean fertilization; cF2: Maize fertilization2; cBnt: Maize bending; b2SP: Soil plowing for second cycle bean crop; b2Sw: Second cycle bean sowing; b2F1: Second cycle bean fertilization; bHv: Bean harvest; bHv2: Second cycle bean harvest; cHv: Maize harvest.*

The univariate sensitivity analysis Table 17) results in values of up to 30% relative uncertainty in some of the output variables. Parameters among the ones with larger uncertainty include, the ratio of leaf mass to leaf area of both crops, the ratio of leaf mass to absolute crop mass from anthesis to maturity of maize, the mineralization rate, the nitrification rate, the percentage of energy derived from bean, and the wage of off-farm labour at coffee harvest. Individual changes in these parameters cause around 20-30% of uncertainty in the most affected output variable directly related with them. For nitrogen content in humus, the uncertainty of mineralization rate results in an error margin of about ±119 kg ha-1 year-1, 27% of the average value. Maize sale price, maize harvest labour productivity, journal hours and plant facility to absorb NH4+, are among the constants and parameters with less impact on the results for the ranges established according to the literature. The variability of maize sale price results in an uncertainty of roughly 13% of yearly cash flow. This is because during the 21-year simulation period for the sensitivity analysis, the household only sells maize a small number of years, when the yields are big enough to sell part of their production. Expected variability in journal hours, maize harvest labour productivity and technology factor do not greatly impact on total activity hours, due to sufficient workforce availability for the average scenario used for the sensitivity analysis. Variability on plant facility to absorb NH4+, results in an uncertainty of 5 to 7% of Nitrogen uptake for bean and maize, respectively. This might be a consequence of the low levels of this element available in the mountainous soils of the region.

The most sensitive parameters are maize and bean leaf mass to leaf area ratios, maize and bean leaf mass to absolute crop mass until anthesis ratios, bean leaf mass to absolute crop mass from anthesis to maturity ratio, and the daily wage for working off-farm. All of these parameters present a variation greater than 12% of the output variable directly related to them. The main output variables affected by these sensitive parameters are maize and bean yields, and cash flow, which also present high uncertainty values (ranging from 12-28%). The sensitivity of these parameters could result from the broad range of values investigated. Also, sensitivity of the model could be improved by incorporating knowledge of the distribution of different parameter values, and not just the range.

Table 17. Univariate sensitivity analysis and uncertainty expected in the main output variables of the SASHACA model for selected constants and parameter ranges.

Constant or parameter (name in model)	*Unit*	*Range*	*Main output variable*	*Unit*	*Sensitivity[a] (%)*	*Relative Uncertainty[b] (%)*
Grain filling rate of maize (cGrnfillr)	d.u.	0.30-0.54	Maize yield	*kg ha^{-1}*	0.9	15
Ratio of leaf mass to leaf area for maize (cSlm)	$kg_{leaf}\ ha_{leaf}^{-1}$	275-355	Maizeyield	*kg ha^{-1}*	3.7	21
Ratio leaf mass to absolute crop mass up to anthesis for maize (cLwr ant)	$kg_{leaf}\ kg_{crop}^{-1}$	0.2-0.3	Maizeyield	*kg ha^{-1}*	1.4	12
Ratio leaf mass to absolute crop mass from anthesis to maturity for maize (cLwr mat)	$kg_{leaf}\ kg_{crop}^{-1}$	0.1-0.2	Maize yield	*kg ha^{-1}*	0.3	6
Grain filling rate of bean (bGrnfillr)	d.u.	0.30-0.62	Bean yield	*kg ha^{-1}*	0.5	11
Ratio of leaf mass to leaf area for bean (bSlm)	$kg_{leaf}\ ha_{leaf}^{-1}$	196-270	Bean yield	*kg ha^{-1}*	3.1	22
Ratio leaf mass to absolute crop mass up to anthesis for bean (bLwr ant)	$kg_{leaf}\ kg_{crop}^{-1}$	0.5-0.7	Bean yield	*kg ha^{-1}*	1.4	12
Ratio leaf mass to absolute crop mass from anthesis to maturity for bean (bLwr mad)	$kg_{leaf}\ kg_{crop}^{-1}$	0.5-0.7	Bean yield	*kg ha^{-1}*	3.2	23
Journal hours (Journal h)	h	6,10, 1[c]	Maize yield	*kg ha^{-1}*	0.2	5
Journal hours (Journal h)	h	6,10, 1[c]	Bean yield	*kg ha^{-1}*	0.2	5
Technology factor (lTech)	d.u.	1-2	Farmer workload days	*day year^{-1}*	0.3	7
Harvest productivity (cTHvprod)	kg h^{-1}	4-10	Farmer workload days	*day year^{-1}*	0.03	1
Thickness of layer H0	cm	2.5-10	Evaporation	*mm year^{-1}*	0.2	13
Thickness of layer H0	cm	2.5-10	Maize yield	*kg ha^{-1}*	0.1	5
Thickness of layer H0	cm	2.5-10	Bean yield	*kg ha^{-1}*	0.03	3
Volumetric content of water at Wilting Point of layer H0 (WPH)	$m^3\ m^{-3}$	0.17-0.24	Evaporation	*mm year^{-1}*	0.5	6
Mineralization rate (Mineral rate)	d.u.	0.002-0.006	Nhumus	*kgN ha^{-1}*	0.73	27
Mineralization rate (Mineral rate)	d.u.	0.002-0.006	$NH4^+$ N	*kgN ha^{-1}*	0.1	5
Mineralization rate (Mineral rate)	d.u.	0.002-0.006	$NO3^-$ N	*kgN ha^{-1}*	0.1	4
Plant resistance/facility to absorb NH4 (plant NH4 resist)	d.u.	0.2-0.5	N uptake maize	*kgN ha^{-1}*	0.1	7
Plant resistance/facility to absorb NH4 (plant NH4 resist)	d.u.	0.2-0.5	N uptake bean	*kgN ha^{-1}*	0.2	5
Nitrification rate (Nitrifp rate1)	d.u.	0.04-0.08	$NH4^+$ N	*kgN ha^{-1}*	0.8	18
Diet kcal coming from maize (Percentage kcal from Corn)	%	50-85	Maize consumption	*kg year^{-1}*	0.6	10
Diet kcal coming from bean (Percentage kcal from bean)	%	6-15	Bean consumption	*kg year^{-1}*	0.7	19
Daily wage for a working day on coffee harvest out of the community (eDaily wage coffee)	€ h^{-1}	0. 56-0.70	Cash flow	*€ year^{-1}*	-13.5	24
Daily wage for a working day at the community (eDaily wage community)	€ h^{-1}	0.25-0.38	Cash flow	*€ year^{-1}*	-1.5	28
Price of selling maize (eCorn sellprice)	€ h^{-1}	0.2-0.3	Cash flow	*€ year^{-1}*	-0.2	3
Price of selling bean (eBean sellprice)	€ h^{-1}	0.55-0.65	Cash flow	*€ year^{-1}*	-2	13

Price of buying maize (eCorn buyprice)	*€ h^{-1}*	0.25-0.35	Cash flow	*€ $year^{-1}$*	-1.9	30
Price of buying bean (eBean buyprice)	*€ kg^{-1}*	0.65-0.95	Cash flow	*€ $year^{-1}$*	-0.9	14

[a] Output Sensitivity: Percentage of change for a 1% change in input.
[b] Relative uncertainty: Simulated SD/Simulated Mean.
[c] The probability distribution for all variables is Random Uniform, except journal hours where it follows a vector distribution going from six to ten hours by intervals of one unit. d.u.: Dimensionless units; Nhumus, Nitrogen content in humus; $NH4^{+}N$ Ammonium nitrogen, $NO3^{-}$ N nitrate nitrogen.

The relative uncertainty changes when the variability of several constants and parameters is taken into account concurrently. The highest uncertainty is caused by the ratio of leaf mass to leaf area of maize (53%). In the case of household cash flow, the MVSS (Table 18) shows a 48% relative uncertainty value. The reason for this uncertainty is the concurrent change in household incomes and expenditures. Small changes of just 5% in such variables can lead to large cumulative changes in household cash flow through the 21 years of simulation. For maize and bean yields, which are two of the most relevant model outputs, simultaneous variability of constants and parameters results in a variation of ±329 kg ha-1 and ±111 kg ha-1 respectively, which is about 32% of the average maize yield and 23% of the average bean yield resulting from the MVSS during the simulation period. In general terms, overall uncertainty increases with MVSS, although this analysis might lead to some loss of physiological or social meaning (i.e. a ten hours working day might happen concurrently with high labour cost, while this combination is quite unlikely).

Table 18. Multivariate sensitivity simulation (MVSS) and uncertainty expected in the main output variables of the SASHACA model for the selected constants and parameter ranges.

Constant	***Unit***	***Range***	***Output Variable***	***Unit***	***Output sensitivity range***	***Relative Uncertainty (%)***
Salary wages Off farm coffee (eDaily wage coffee)	€ day^{-1}	0.56-0.69	Cash flow	€ $year^{-1}$	12-910	48
Salary wages Off farm community (eDaily wage community)	€ day^{-1}	0.25-0.38				
Ratio of leaf mass to leaf area for maize (cSlm)	$kg_{leaf}\, ha_{leaf}^{-1}$	275-355	Nuptake corn	kgN ha^{-1}	4-136	53
Ratio of leaf mass to leaf area for bean (bSlm)	$kg_{leaf}\, ha_{leaf}^{-1}$	196-270	Nuptake bean	kgN ha^{-1}	13-86	37
Volumetric content of water at Wilting Point of layer H0 (WPH0)	$m^3\, m^{-3}$	0.17-0.24	Evaporation	mm $year^{-1}$	205-481	15
Thickness of layer H0 (ThicknessH0)	cm	2.55-10	Maize yield	kg ha^{-1}	165-1734	32
			Bean yield	kg ha^{-1}	245-731	23
Mineralization rate (Mineral rate)	d.u.	0.002-0.006	N Humus	kgN ha^{-1}	81-697	35
Plant resistance/facility to absorb NH4 (plant NH4 resist)	d.u.	0.2-0.5	$NH4^{+}$ N	kgN ha^{-1}	9-55	26
Nitrification rate (Nitrifp rate1)	d.u.	0.02-0.04	$NO3^{-}$ N	kgN ha^{-1}	12-54	22
Diet kcal coming from maize (Percentage kcal from Corn)	%	70-85	Maize consumption	kg $year^{-1}$	47-169	18
Diet kcal coming from bean (Percentage kcal from bean)	%	6-14	Bean consumption	kg $year^{-1}$	14-30	17

The probability distribution for all variables is Random Uniform; d.u.: Dimensionless units; Nhumus, Nitrogen content in humus; $NH4^{+}N$ Ammonium nitrogen, $NO3^{-}$ N nitrate nitrogen.

3.1.2 Model calibration to actual farmer conditions

Within the observed calibration and evaluation data sets, the variable presenting the widest variation was total energy expenditure of the household (TEE), followed by maize yield, maize consumption and household cash flow (Figure 7). The average simulated TEE ranges from 2736 kcal day-1 person-1 during very active periods (crops season, work off-farm) to 2089 kcal day-1 person-1 during periods with lower activity. The means of both simulated and observed variable values are similar and within the range of 25th and 75th percentiles for most of the output variables. The only variable with a mean falling slightly out of this interval was bean sales (Figure 8). The skewed distribution is due to the large number of farmers that are not able to sell bean and so do not receive any income from bean sales. A similar result occurred with maize sales, where only four farmers acknowledge selling part of their maize production (Figure 8). Predicted maize yield includes daily consumption before harvest, which can be up to 25% of total maize production in years with low yields. Predicted maize yield is underestimated for the evaluation set. This might be a consequence of the skewed distribution of this variable in the evaluation set. Annual expenses in nitrogen fertilization (Cost N) are also slightly underestimated. This underestimation derives from the assumption that farmers try to fertilize the average amount used in the region. However, if they do not have enough time or money to perform any of the fertilizations, they would not expend that money on fertilizer and thus the annual nitrogen application and in turn the expenses in nitrogen fertilizer would be reduced.

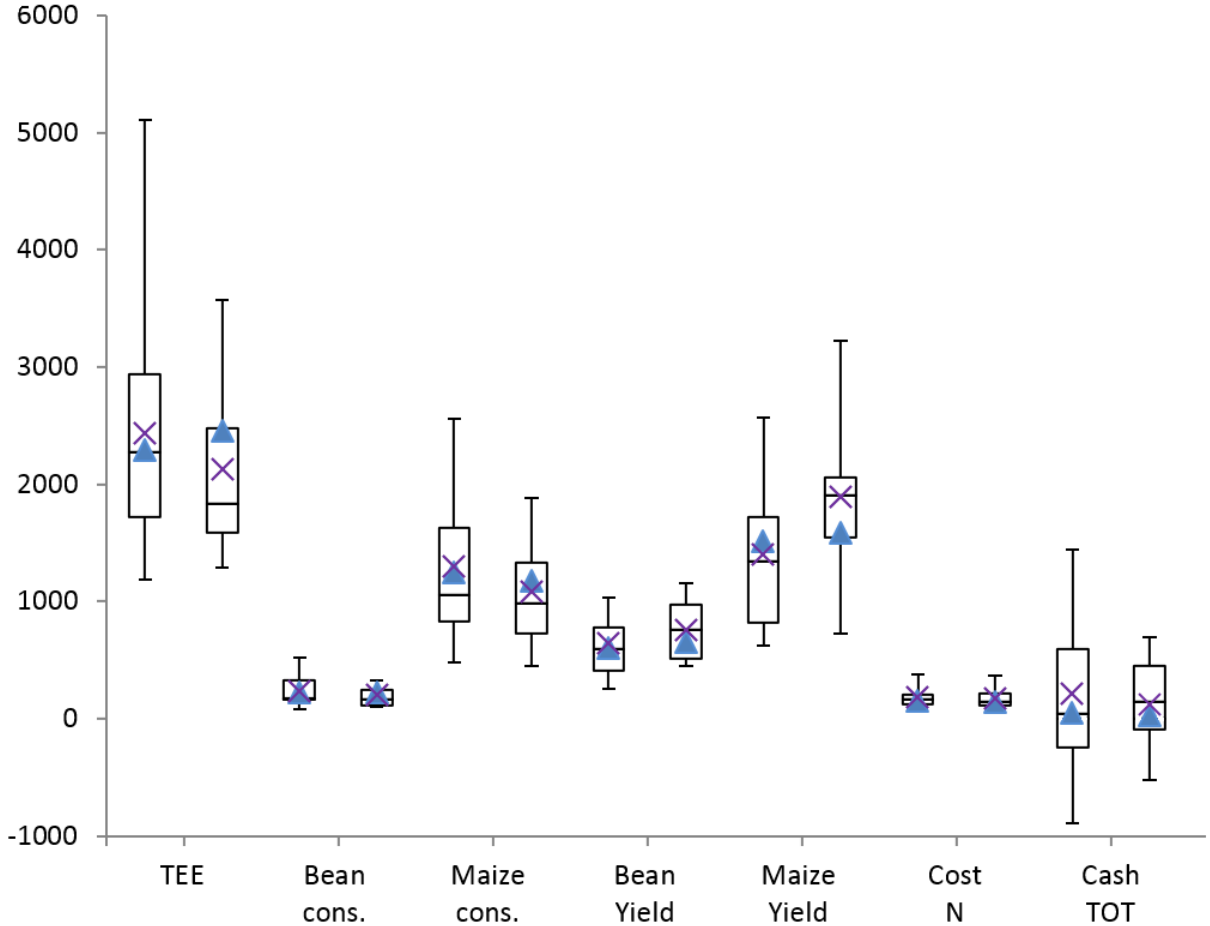


Figure 7. Box plots (5th, 25th, 50th, 75th, and 95th percentile) of the observed data for the main output variables assessed in the model. The means of observed data are represented with crosses, and the predicted values for a virtual representative household are represented by triangles. For each variable the box on the left shows values for the calibration dataset and the box on the right shows values for the evaluation data set. *TEE (Total Energy Expenditure of the household, kcal/day), Bean cons. (Household bean consumption, kg/day), Maize cons. (Household maize consumption, kg/day), Bean Yield (kg/ha), Maize Yield (kg/ha), Cost N (*Annual expenses in nitrogen fertilizer, *€/year), Cash TOT (Annual cash flow of the household, €/year).*

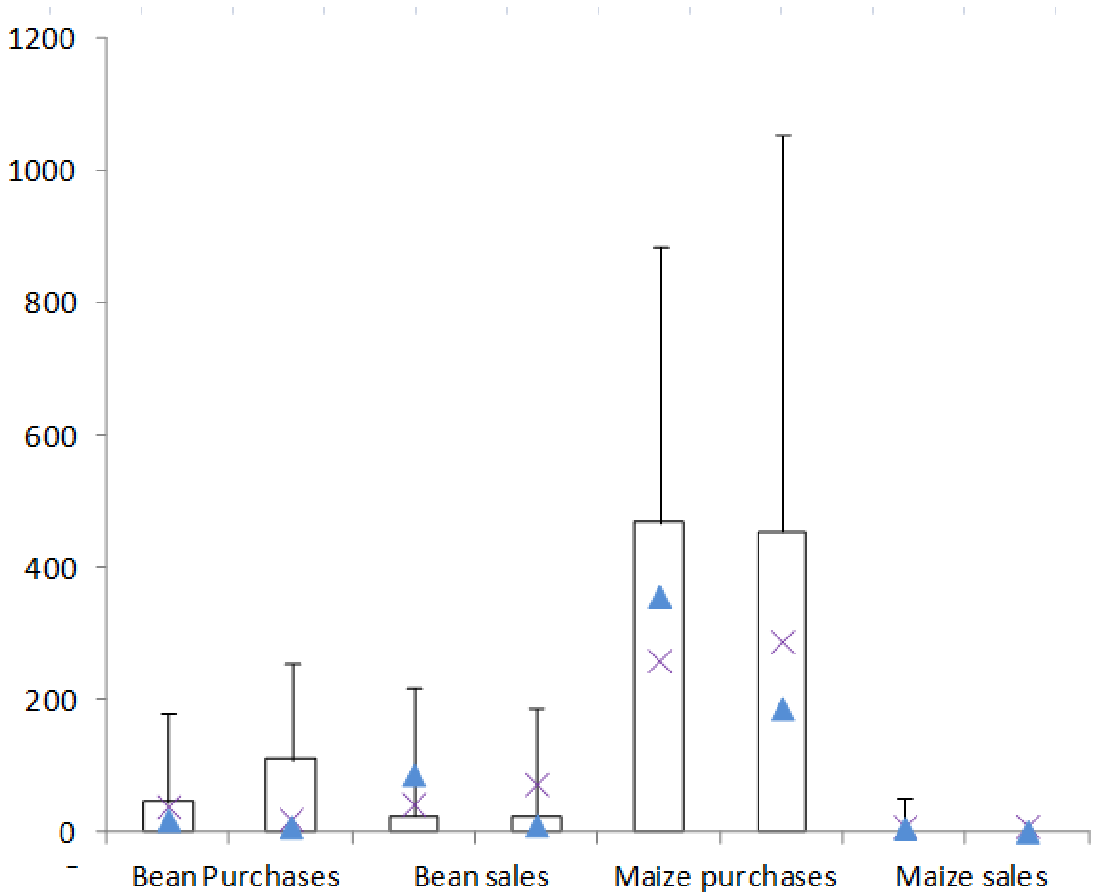


Figure 8. Box plots (5th, 25th, 50th, 75th, and 95th percentile) of the observed data for the main output variables assessed in the model. The means of observed data are represented with crosses, and the means of predicted values are represented by triangles. For each variable the box on the left shows values for the calibration dataset and the box on the right shows values for the evaluation data set. *Bean purchases (kg/year), Bean sales (€/year), Maize purchases (kg/year), Maize Sales (€/year).*

These results involve comparing the average value of a 21-year simulation for a virtual smallholder with the average value of the observed dataset gathered from farmer estimations in a specific year. Thus, it is not surprising that the accuracy of predictions is smaller than if they would be compared with a 21-year observation dataset, which unfortunately is typically not available in developing countries. Also, all variables evaluated exhibited wide variation in both calibration and evaluation sets (Table 19). Thus, the expected accuracy in model simulations cannot be very high. However, the aim of the model was not to make exact predictions, but to increase the knowledge of the system and analyse the trends of the impact of smallholder endowments and critical leverage points.

All confidence intervals for both, calibration and evaluation sets include the average value of the simulated output variables (Table 19). For example, for the observed calibration data set, the average total energy expenditure of the household is 2433 kcal day-1 person-1. A 95% confidence interval for the proportion in the whole population having the same average total energy expenditure on the survey is 2142-2724 kcal day-1 person-1 (Table 19). This means that there is a 95% probability that the calculated confidence interval from some future simulation encompasses the true value of the population parameter.

Table 19. Main model output variables (average of the simulated values and observed data, and confidence intervals) for the calibration and evaluation datasets.

Variable	Unit	Calibration dataset			Evaluation dataset		
		Simulated[a]	Observed[b]	Confidence Interval[c]	Simulated[a]	Observed[b]	Confidence Interval[c]
Annual fertilizer expenses	*€ year^{-1}*	155	179	137-220	*144*	*162*	*124-279*
Bean consumption rate	*kg year^{-1}*	229	232	194-270	227	202	153-250
Bean purchases	*kg year^{-1}*	18	31	0-62	*8*	*19*	*0-58*
Bean sales	*€ year^{-1}*	87	76	19-134	*11*	*72*	*0-168*
Bean yield	*kg ha^{-1}*	602	650	547-753	*659*	*758*	*592-923*
Household cash flow	*€ year^{-1}*	55	120	6-234	*32*	*122*	*-109-352*
Average Energy Expenditure	*kcal day^{-1} person^{-1}*	2288	2433	2142-2724	*2454*	*2128*	*1707-2550*
Maize consumption rate	*kg year^{-1}*	1247	1304	1123-1485	*1181*	*1082*	*812-1352*
Maize purchases	*kg year^{-1}*	356	259	150-368	*187*	*288*	*60-515*
Maize sales	*€ year^{-1}*	6	9	0-20	*1*	*9*	*0-27*
Maize yield	*kg ha^{-1}*	1514	1401	1190-1612	*1591*	*1889*	*1449-2330*

[a] *Average simulated value over 21 years for the average household.*
[b] *Average actual data derived from surveys (2013) for the average household.*
[c] *95% confidence interval of the survey (observed). All values are expressed for household, except average energy expenditure which is the average value of all members of the household.*

3.1.3 Comparing Simulated Results with the Literature

Long term simulated maize yield outputs (around 1500-1600 ± 560 kg ha-1) are similar to those reported in the literature for the region of study (1632 kg ha-1 (INE, 2003); 1900-2400 kg ha-1 (COSUDE-SICTA-IICA, 2012)). Similarly, simulated bean yield values (around 600-650 ± 278 kg ha-1) also match data from literature (199-265 kg ha-1 (MAGA, 2012); 250-910 kg ha-1 criollo bean (IICA, 2008); 331 kg ha-1 (INE, 2003); 593-800 kg ha-1 (FAO-WFP, 2010); 900 kg ha-1 (COSUDE-SICTA-IICA, 2012). TEE simulated values (2300-2450 ± 203 kcal day-1person-1) are also in agreement with the values reported by FAO for dietary energy consumption in Guatemala (1808-2098 kcal day-1 person-1 (FAO, 2014); and 2440 kcal day-1 person-1 for rural areas in Guatemala (FAO, 2008b).

Maize sale price produces low uncertainty in the model (Table 17), due to the fact that the model is built according to household behaviour. De Janvry and Sadoulet (2000) note that about 60% of farm households in Nicaragua and Mexico never sell any of their production. Also, these farm households diversify their income sources, and there is a large proportion of households (73% in Mexico and 34% in Nicaragua) that rely on off-farm activities for more than half of their income. On the other hand, maize and bean purchase prices have a major impact, because as showed in the long term simulation, the scarcity period must be covered purchasing staple food. WFP (2008) report purchase to consumption rates ranging from 25 to 85% on white maize and from 40 to 90% for black bean. The simulated scarcity period extends from April to October depending on rain timing and abundance. Bacon et al. (2014) report scarcity periods extending from April to October, with the most critical period from June to August. The percentage of energy intake from maize and beans varies hugely with location and the urban or rural nature of the area, and determines household consumption values. Pfister et al. (2005) reported a large degree of uncertainty (25%) in consumption of staples. They attributed this uncertainty to the adaptation of consumption patterns to the size of the food stocks, which are reduced in scarcity periods. This variation in consumption along with food availability is also reflected in the outputs of our model (around 1200 ± 423 kg year-1 for maize and 230 ± 73 kg year-1 for bean). Other studies in the area report similar average consumption values of maize: 1452 kg year-1 (MAGA, 2012); 1648 kg year-1 (Serrano and Goñi, 2004); 861-1722 kg year-1 (ICTA, 2002) and beans: 164 kg year-1 (IICA, 2008); 318 kg year-1 (MAGA, 2012).

3.2 SASHACA model application in Guatemala: Impacts of smallholder endowments on their welfare in highland areas of Central America

The consequence of changes in smallholder endowments expresses the importance of delineating thresholds in endowments that allow households to escape from poverty and food insecurity.

3.2.1 Effect of changes in land availability and crop area allocation on smallholder welfare

The effect of changes in land availability and crop area allocations are shown for the range of values found in the region of study. These effects are shown through annual and long term variability.

3.2.1.1 Inter-annual variability in household food security levels

Maize food security shows similar variability regardless of the simulated maize area (Figure 9a). This variability only changes for a very small area of 0.05 ha. In some of the years of low rainfall (1993, 1994, 1998, 2001-2004), the food security levels of the typical household decrease, for all simulated maize areas. Bean areas smaller than 0.61 ha show a similar trend as for maize (Figure 9b). However, bean areas above 0.61 ha reach food security for all simulated years.

As the managed area increases, higher levels of food security might be expected. However, for any area allocation above 0.55 ha of maize and 0.25 ha of beans, food security levels do not continue increasing with area (note trends in Figure 9). This is due to a drop in yields due to inadequate management caused by lack of labour at specific moments, leading to yearly average maize shortfall periods of around a month and a half. Furthermore, the model assumes higher food needs and input expenses as the cropped areas are increased, which in the case of maize prevents total food security fulfilment. This effect on food security is more noticeable on years of adverse climatic events (1994, 1998, 2001-2004), where the investment in agricultural inputs does not translate into higher yields. In the case of bean crop, its higher market value and smaller consumption level allow selling bean surplus which improves smallholder welfare. Food security is achieved with area allocations larger than 0.61 ha of beans and 0.57 ha of maize for the typical household surveyed (Figure 9b).

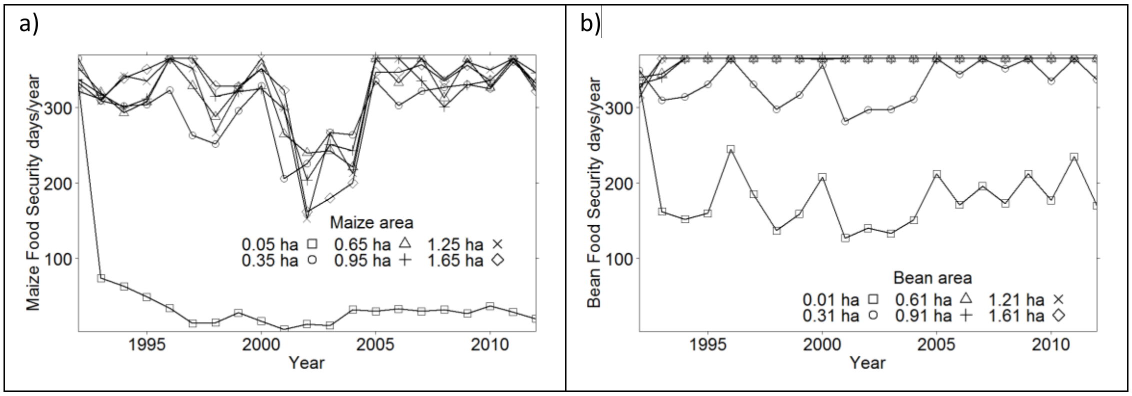


Figure 9. Annual food security days for (a) 0.05-1.65 ha of maize area allocation and 0.25 ha of bean, (b) 0.01-1.61 ha of bean area allocations and 0.57 ha of maize

Due to the existence of two bean cycles, simulated bean production is more regular and not so dependent on sporadic adverse climatic events. However, in practice the second bean cycle is often not grown as a polyculture[3], which sometimes leads to lower yields as a consequence of greater pest and diseases impacts (Altieri et al., 1978; Fininsa, 1996; Francis et al., 1975, 1977; Van Rheenen et al., 1981), an effect not included in the model. Thus, risk reduction might be one of the reasons why farmers in the region allocate bigger areas to maize production despite the highest bean market value.

Bean food security is strongly influenced by bean area. This is due to the lower value of maize grain which does not allow purchasing enough beans to avoid scarcity periods. Also, because maize is the main food item in the diet, farmers prioritize maize needs fulfilment over bean needs (Schoonhoven and Voysest, 1991) and so the model does also.

The joint analysis of maize and bean allocation and the impact on food security suggests that the minimum area needed to satisfy yearly food requirements of a typical household in the region would be about 0.61 ha of maize and beans grown in polyculture. Myers (1999) wrote: "It is realistic to suppose that the absolute minimum of arable land to support one person is a mere 0.07 of a hectare and this assumes a largely vegetarian diet, no land degradation or water shortages, virtually no post-harvest waste, and farmers who know precisely when and how to plant, fertilize, irrigate, etc.". This estimation, which is based on attainable yields (since expected yields in mountain areas of Central America are not the same than in flat rainy and fertilized areas of northern Europe or North America), would be equivalent to 0.49 ha for a family of seven people. Thus, it seems realistic that the model-generated requirement of

[3] Polycultures are defined as systems in which two or more crops are simultaneously planted within sufficient spatial proximity to result in interspecific competition and complementation (Altieri et al., 1978).

0.61 ha of maize and beans sown in polyculture, complemented with essential off-farm incomes would be able to provide yearly round food requirements to an average household in the region.

3.2.1.2 Average long term variability in smallholder welfare

Land availability and crop area allocations around the average values of the region show higher cash flow increase with bean area than it does with maize area allocation (Figure 10a). This is due to the higher market sale price of beans compared to maize grain. If we read Figure 10 as a topographic map where the altitude lines would be the variable defined on the top, we observe a greater slope in the bean area allocation (topography lines closer; Figure 10a). This suggests an advantage in increasing bean area at the expense of maize area allocation to maximize cash. However, as the second cycle of beans is much more affected by diseases and pests than maize this option is inherently riskier. Also, maize is the most consumed product and almost all farmers allocate bigger areas to maize than beans.

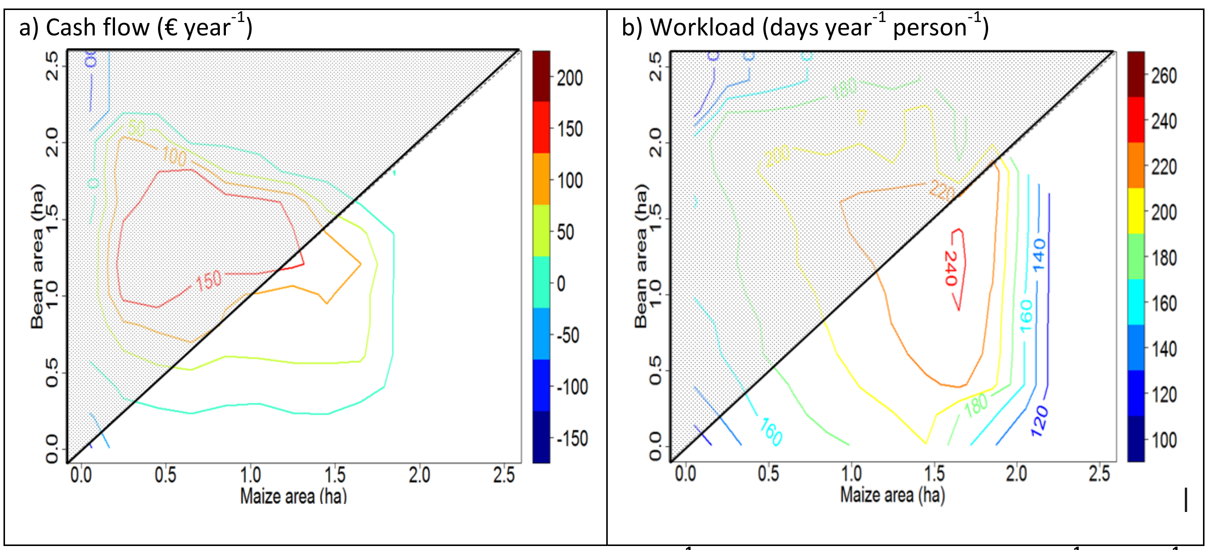


Figure 10. Simulation results for (a) household cash flow (€ year^{-1}), (b) farmer workload (days year^{-1} person^{-1}) for a 21-year period considering a typical household with an equivalent labour force of two men. The analysis was focused on maize and beans combinations mostly found in the region (where maize area allocation is equal or greater than bean area allocation). This corresponds to the area underneath the bisector line

Maize and bean intercrop areas greater than 0.75 ha demand larger quantities of labour (Figure 10b) than the capacity of the typical household with an equivalent labour force of two men (which equals to a workload capacity of 180 days year^{-1} person^{-1}). Intercropping increases utilization of labour resources, allowing bean to benefit from some of the activities implemented for maize (Thayamini and Brintha, 2010). This makes maize management appear more labour intensive than beans (Figure 10b). Consequently, if bean was sown as a sole crop its management would likely be more labour intensive than modelled here as a companion crop.

Simulated maize yields start decreasing when area increases above approximately 0.5 ha (Figure 11a). Above 0.75 ha of maize and bean intercrop, inadequate management causes yield reductions of 13% in maize and 21% in beans (Figure 11). As stated above this is a direct consequence of the deficient labour force to undertake management of those land areas.

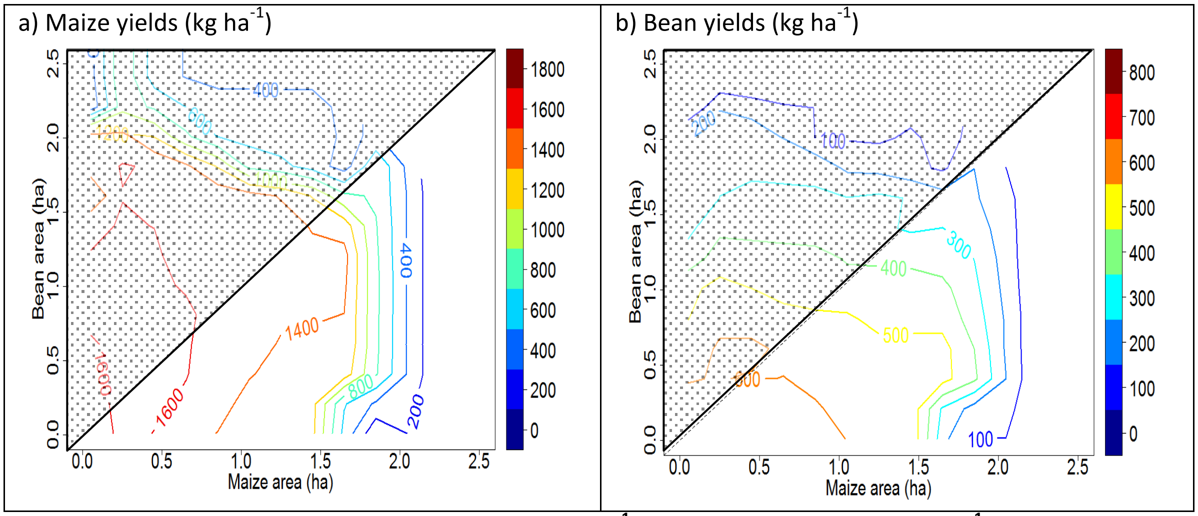


Figure 11. Simulation results for (a) maize yields (kg ha^{-1}) and (b) bean yields (kg ha^{-1}) for a 21-year period considering a typical household with an equivalent labour force of 2 men in Guatemala. The analysis was focused on maize and beans combinations mostly found in the region (where maize area allocation is equal or greater than bean area allocation). This corresponds to the area underneath the bisector line.

The model shows that the observed typical household works around 180 days a year, from which about 80 man-days are devoted to staple crops management and 100 man-days to off-farm labour. Jansen et al. (2006) reported similar distribution of working time allocation for the hillside areas of Honduras. Other authors in smallholder farming systems, also reported similar workload values for the management of one hectare of maize monoculture (32-86 man-days a year in Venezuela FAO, 1974; 78-124 man-days a year in Mozambique Howard et al., 1998; Uaiene, 2004). Furthermore, the upper limit of workload for the simulated typical household was found to be 244 man-days a year and is reached for areas of 1.65 ha of maize and 1.41 ha of bean. Larger areas (up to 2.05 ha, simulated upper limit) showed a decrease of workload due to inadequate time to properly cover farm management (Figure 10b). In that situation, some agricultural management activities cannot be done because labour is not available when that activity needs to be performed.

Our simulations indicate that maize area allocation primarily affects maize food security, and bean area allocation primarily affects bean food security (Figure 12). A minimum area allocation of 0.45 ha of each crop notably improves household food security (338 and 341 days of full maize and bean supply respectively). In contrast, a maize allocation of 0.45 ha with just 0.01 ha of beans lead to 232 days of maize supply. The average food scarcity period during a 21-year simulation is less than twenty days for area allocations equal or bigger than 0.65 ha of maize and 0.41 ha of bean (Figure 12), and the household is completely food secure when maize and bean areas are around 0.6 ha each.

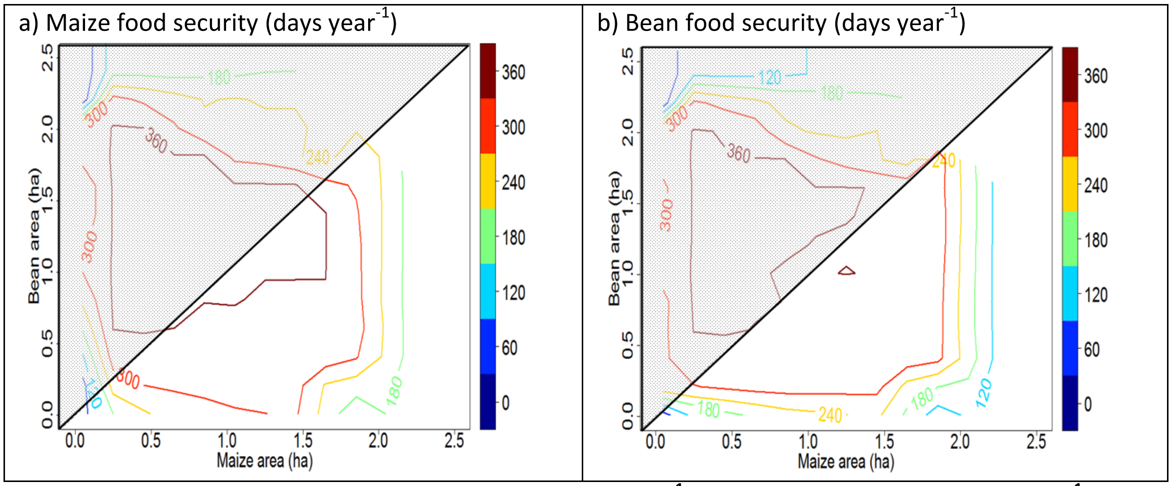


Figure 12. Simulation results for (a) maize food security (days year^{-1}), (b) bean food security (days year^{-1}) for a 21-year simulation considering a typical household with a labour force equivalent to two men.

Results suggest that there is a substantial improvement in household welfare for staple area allocations above the average of the region. However, shortage in labour availability at certain moments of peak workloads prevents achievement of higher yield values for area allocations larger than 0.75 ha of maize (Figure 11). Thus, both labour force and land availability interact, constraining household welfare. This is in agreement with the results of Leonardo et al. (2015) who highlighted the importance of labour force availability to increase smallholder productivity and achieve food self-sufficiency in maize-based farming systems in Mozambique. In our study, in a mountainous area where land is scarcer, land availability has a greater impact than labour force on poverty and food security. To fulfil food security, maize and bean area allocations should range from 0.55 to 0.75 ha. In this situation cash flow is not maximized but farmers have enough time to work off-farm (from 40 to 50 days year^{-1} person^{-1})

3.2.2 Effects of off-farm labour opportunities on smallholder welfare

The simulations show that pure on-farm labour household is on average food secure in maize for six and a half months and in beans for ten months (Table 20), which implies a debt accumulation of about 257 € year^{-1}. Pure on-farm households and producers with the least resources cannot afford to purchase food when harvests fail (IFAD-UNEP, 2013). Previous research in the region also reported that many farmers in Nicaragua (97% of households, n=229) bought a portion of their basic grains, and that, the use of credits to buy basic foods is one of their coping mechanisms during the lean months (Bacon et al., 2014; HLPE, 2013). This is the case in years with high incidence of pests or plagues (as the Coffee Rust in 2012; WFP, 2015b) or droughts (e.g. in 2001/2002, 2009/2010, and 2014; UNOOSA, 2012; WFP, 2015b) which reduces off-farm employment opportunities and so also the income during lean months. Hellin et al. (2017) report an average maize food secure period of 6.9 months a year in five communities in the maize-growing highlands of Guatemala.

Table 20. Simulation results for the three off-farm opportunity scenarios analysed for the typical household in highland areas of Guatemala.

Off-farm opportunities scenarios	Cash flow (€ $year^{-1}$)	Maize food security (month $year^{-1}$)	Bean food security (month $year^{-1}$)
Pure on-farm labour	-257	6.5	10.0
Average off-farm labour [a]	-7	10.3	10.5
Plentiful off-farm labour	684	12.0	12.0

[a] Value calculated using an off-farm labour force equivalent to two men. Cash flow at 31st December.

Households relying their livelihood on their own crops and working off-farm 2.2 months a year (average off-farm labour opportunity scenario) results in maize and bean security for 10.3 and 10.5 months respectively, with an average yearly negative cash flow of -7 € $year^{-1}$. Similar shortfall periods to the ones simulated here for hillside areas in Guatemala, were found by Bacon et al. (2014) in hillside areas of Nicaragua, where the average period of seasonal hunger lasted about three months. Also, Fujisaka (2007) reported three to four months of food scarcity suffered by the majority of farmers they interviewed in Guatemala. Generally, the income that smallholders earn from engagement in off-farm work and self-employment complements smallholder agriculture, allowing them to maintain its cultivation despite low returns that otherwise would often be insufficient to sustain all family members (Isakson, 2009). Jansen et al (2006) in Honduras also observed that subsistence households following a mixed basic grains/off-farm labour livelihood strategy, can earn significantly higher incomes than pure basic grains farmers.

Households in the third scenario (plentiful labour), are food secure all year long and are able to save up to 684 € $year^{-1}$ on average (Figure 13). This confirms that households with off-farm work opportunities can earn higher incomes than households relying just on on-farm basic grain farming. De Janvry and Sadoulet (2000) found that 73 % and 34 % of households in Mexico and Nicaragua respectively, derived more than half of their income from off-farm labour. It's estimated that around 75 % of smallholder farmers live below the national poverty line in Guatemala. In addition, the average smallholder farmer has to earn 40 % of their income from off-farm employment (Align, 2021a). In Nicaragua, when comparing the estimated rural living wage (232 €) and the agricultural minimum wage (103 €), the agricultural minimum wage is just enough to cover 44 % of the basic costs of living (Align, 2021b).

The situation of no off-farm opportunities, shows how households face months of food scarcity, forcing them into dietary changes, food rationing, and using credit to buy basic foods during the lean months (Bacon et al., 2014). Also, smallholders often cannot afford waiting for a better price or more profitable markets to sell their product. The need for immediate cash (e.g. for school fees) may require smallholders to sell their harvest at low prices, which may force them into a poverty trap (Deaton 1991). In the case of off-farm employment shortfall, only households with large areas of land would avoid food scarcity periods (as explained in 3.2.1.2 Average long term variability in smallholder welfare). The simulated results show that most households in the region rely partly on off-farm labour incomes for subsistence and are unable to achieve food security without this extra source of revenue as a complement to their harvest. Thus, in our study region, the minimum threshold of off-farm labour is 1 month per year working on coffee harvest and 1.3 months per year working on other farms within the community. Beyond this threshold, the household is able to increase its savings. However, there must be a limit for this increase in income when the farmer disregards the management of its own farm for working off-farm. Saqalli et al. (2010) reported values ranging from 80 to 240 man-days a year working off-farm according to the family responsabilities and duties of the farmer in Niger. This deficient management can be observed when farmers increase the amount of hours working on other farms within the community (Figure 13a). There is a turning point (50 $day.year^{-1}.person^{-1}$ of labour opportunity in the community) where the slope of cash flow reduces its increasing rate. This indicates that farmers are not managing their fields efficiently, which leads to drops in yields and thus in cash flow. The time spent working on coffee farms (late November to March) affects management in a smaller amount because this labour generally occurs after smallholder farmers have finished their own harvest (from August to November). Also, bigger labour opportunities at coffee farms provide such a good source of incomes that allows a growth on cash flow even deserting their own farms. However, there would be cultural reasons why farmers would prefer not to abandon their farms and work entirely off-farm, such as pride, long-term perceived risk management (Isakson, 2009). Saqalli et al. (2010) found that the percentage of adults that migrate to work off-farm in Niger depends on the opportunities that their village offers for extra-agricultural income generation, which reduce the need for migration.

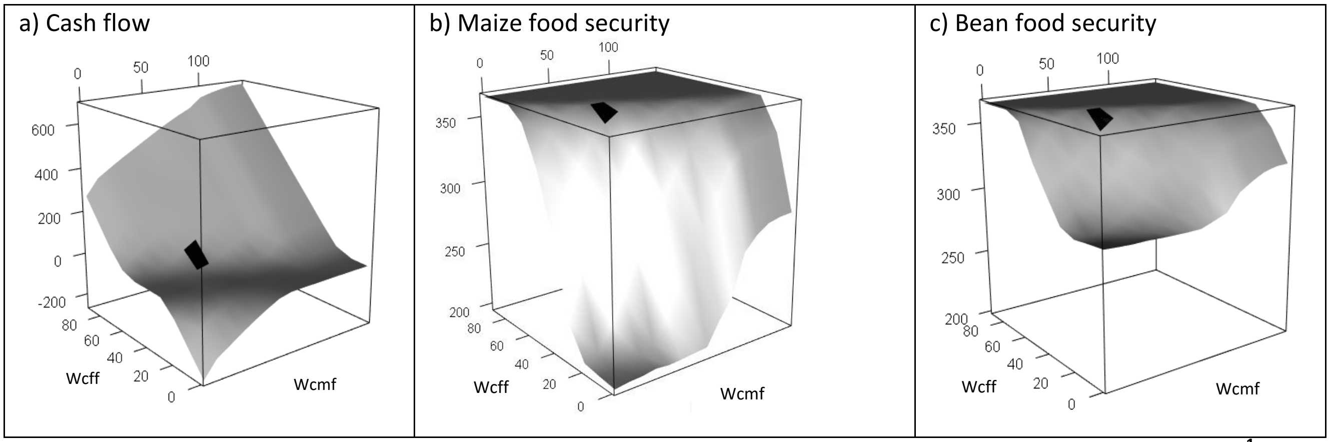


Figure 13. Welfare results from different off-farm work opportunities combinations. (a) Cash flow (€ year^{-1}), (b) maize food security (days year^{-1}), and (c) bean food security (days year^{-1}). Black area represents the average off-farm work situation in the region. Wcff: work on coffee farms opportunities (day.year^{-1} person^{-1}); Wcmf: work on other people's farms within the community opportunities (day.year^{-1}person^{-1}).

Other research in Honduras showed that income generated through engagement in off-farm wage and self-employment strongly enhances household food security levels and also allows farmers to purchase external agricultural inputs to improve yields and labour productivity (Ruben and Van Den Berg, 2001; Hellin et al., 2017). In Guatemala, the income received by an agricultural employee corresponds to 1.8 poverty lines, which represent the amount that a person needs to cover their basic expenses (Baumeister, 2013). Thus, a household consisting of a family equivalent to 6.5 people would need 3.6 permanent agricultural employees to cover the basic goods and services needed for the household without any off-farm income (Baumeister, 2013; CEPAL, 2011). In our simulation with a labour force equivalent to two permanent agricultural employees, they need off-farm work equivalent to 1.6 permanent agricultural employees to cover basic household expenses (6-7 hours of off-farm).

3.2.3 Effects of purchased inputs on smallholder welfare

Maize and beans are sown as companion crops, with a mutually beneficial relationship. Results of different nitrogen applications and weeding treatments are show in the following sections.

3.2.3.1 Nitrogen application

Although the bean crop provides a considerable amount of nitrogen to the soil, there is an increase in maize yields with nitrogen application (70-N, 126-N, and 155-N) compared to no nitrogen (0-N) application (Figure 14a). Tukey's HSD test shows significant differences between no nitrogen application (0-N) and all nitrogen applications (70, 121, and 155-N) for maize yields for both household land sizes (Figure 14a). This indicates that maize lacks sufficient nitrogen when the only supply comes from the previous bean crop. While applying 70 kgN ha^{-1} (70-N) increases maize yields compared to no nitrogen application (0-N), there are not significantly higher yields with greater nitrogen application rates (121 or 155 kgN ha^{-1}) (Figure 14a). This suggests that greater nitrogen applications than 70 kgN ha^{-1} do not further increase maize yields for either of the two farm sizes investigated. Vieira et al. (1998) in their guide for fertility management in hillside areas proposed an average nitrogen application of 86 kg ha^{-1} as the nitrogen rate leading to economic response of maize for soils with low fertility levels and low management technology. Household net cash income variability for the average area of the region arises from the weather variability rather than from the different nitrogen applications evaluated. The existence of food scarcity periods in most years throughout the simulation makes households prioritize food purchase over savings. For households managing areas of double the average area of the region there is significantly higher net cash income with application rates of 70 kgN ha^{-1} (Figure 14b).

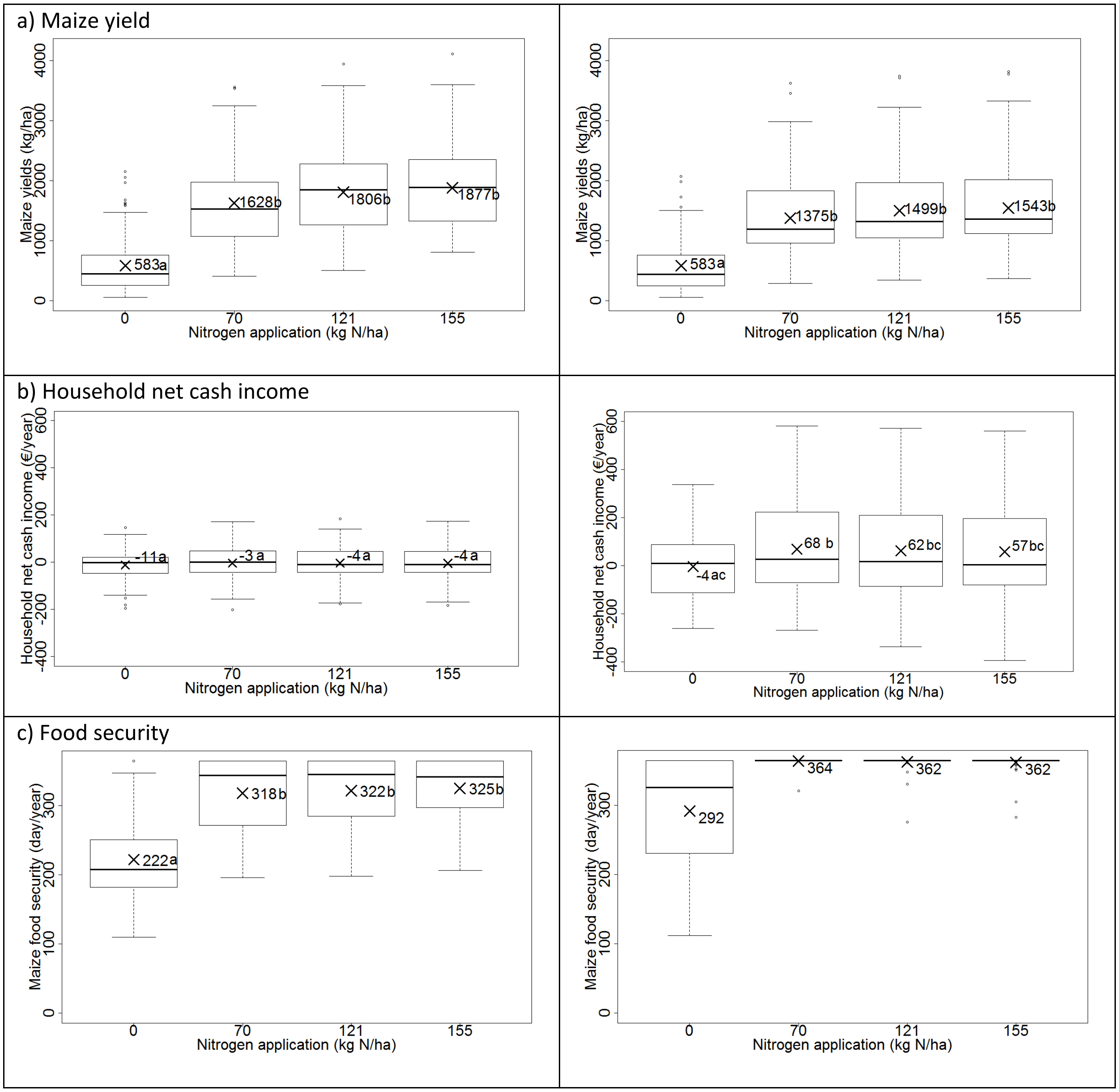


Figure 14. Box plots (25th, 50th, 75th percentiles) of maize yield (a), household net cash income (b), and food security (c) estimates of a long term (21 years) simulation in SASHACA for a typical household with the average land size (left side plots), and for a typical household with double the average land size (right side plots). The whiskers denote the most extreme data point which is no more than 1.5 times the interquartile range from the box. Black crosses show the mean value, and black points the values of any data points which lie beyond the extremes of the whiskers. Means marked with different letters represent significant differences with a confidence level of 95% using Tukey's HSD test

The results of the Tukey's HSD test for food security constitute a statistical significant difference between nitrogen application and no nitrogen application in the case of average-sized farms (Figure 14c left side plot). The box plots also depict the distribution of simulated outputs, all of them presented greater variability with nitrogen applications than with no nitrogen application, although the higher N rates do not change the means. This is a consequence of weather variability; a high nitrogen rate may result in a high income in rainy years or in a big loss in dry years due to the risk of investing in fertilizers, and the consequent effect on maize yields, household net cash income, and food security levels (Figure 14). Bacon et al. (2014) reported that they could not find any evidence of corn yield benefits associated with extra investments in basic grain production in Nicaragua. Morris et al. (2013) found that farmers in El Salvador exacerbated the lean months by using credits to buy chemical inputs for maize and bean production instead of food.

3.2.3.2 Weeding

Welfare outputs do not substantially change with the use of chemical weeding for households managing areas about the average land size of the region, apart from the labourer's workload which is reduced ten days a year on average for each family labourer (Figure 15). Nevertheless, chemical weeding improves all welfare parameters for households managing double land size. In this case, manual weeding results in deficient crop management, which reduces yields (about 16%). The increase in maize yields when using herbicides enables the typical household to achieve complete food security and more than double the household net cash income in comparison to the manual weeding management (Figure 15). The range from minimum to maximum workload is wider with manual weeding, which is attributed to its more tedious and time consuming process.

The use of herbicides appears to be a good option, significantly reducing workload for the average areas and increasing all welfare parameters for greater areas. Parsons et al. (2009, 2011b) found the potential for large increases in yield with a combination of manure and effective chemical weed control.

According to our surveys and interviews (Marín-González et al., 2018), many farmers use herbicides if they can afford them, because it reduces the workload, leaving more spare time for other activities such as off-farm employment, gathering wood, or repairing fences. However, about 60% of farmers prefer doing manual weeding, which despite being more labour intensive does not require any investment in external inputs. Furthermore, there is also the possibility that herbicides can damage the companion bean crop.

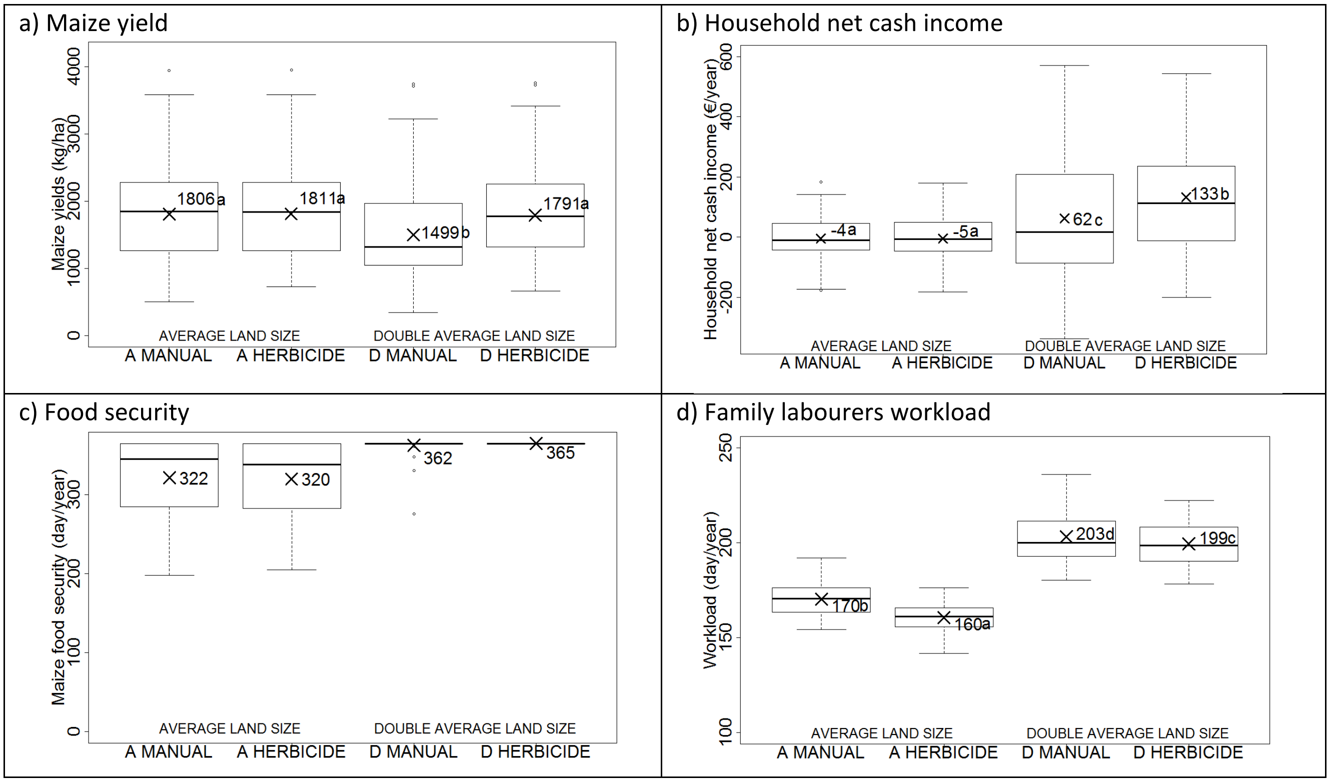


Figure 15. Box plots (25th, 50th, 75th percentiles) of maize yield (a), household net cash income (b), food security (c), and family labourers workload (d) estimates of a long term (21 years) simulation in SASHACA for the typical household with the average land size, and for a typical household with double the average land size using manual weeding (MANUAL) or chemical weeding (HERBICIDE). Whiskers denote the most extreme data point which is no more than 1.5 times the interquartile range from the box. Black cross points show the mean value and black points the values of any data points which lie beyond the extremes of the whiskers.

3.3 SASHACA model application in Guatemala and Nicaragua: Family farming definition adapted to regional context with a focus on subsistence or near-subsistence smallholders

3.3.1 Effects of family size and composition

Simulated results for a typical Guatemalan household of 7 family members and with the typical family composition of the region, faces an average annual food shortage of 2.23 and 1.77 months a year of maize and bean respectively with peak periods of up to 5.40 and 3.50 months (obtained in the 10th year of simulation). A typical Nicaraguan household of 7 family members faces an average annual food shortage of 2.63 and 0.63 months a year of maize and bean respectively with periods of up to 7.53 and 2.53 months in the 6th year of simulation (Figure 16). A typical Guatemalan household of 5 family members copes with a shorter scarcity period, being the average lean period of maize grain 0.23 months and 0.13 months a year for bean. For this household, the longest maize and bean shortfall periods were 1.73

and 1.13 months respectively (happening in the 11th and 12th years of simulation). In the case of Nicaragua, the typical household deals with an average maize shortfall period of 0.3 months a year and no bean shortfall. The same household composed by 3 family members do not face any scarcity period in neither Guatemala or Nicaragua. Nevertheless, a thirteen family members household with a labour force equivalent to two men copes with a shortfall periods of 6 and 5 months of maize and bean on average in Guatemala (Figure 16 left side). In Nicaragua these shortfall periods would extend to 7 and 4 months for maize and bean respectively (Figure 16 right side).

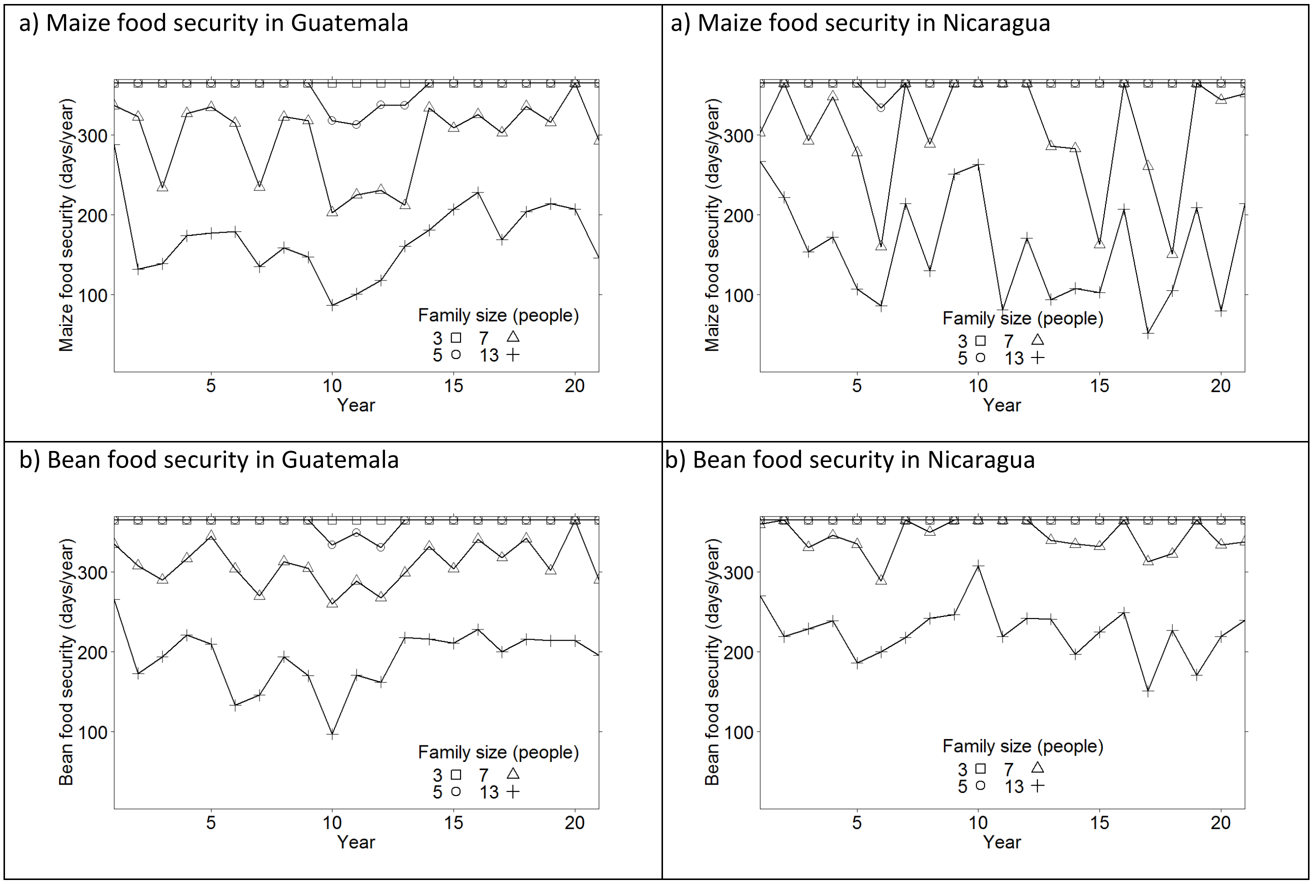


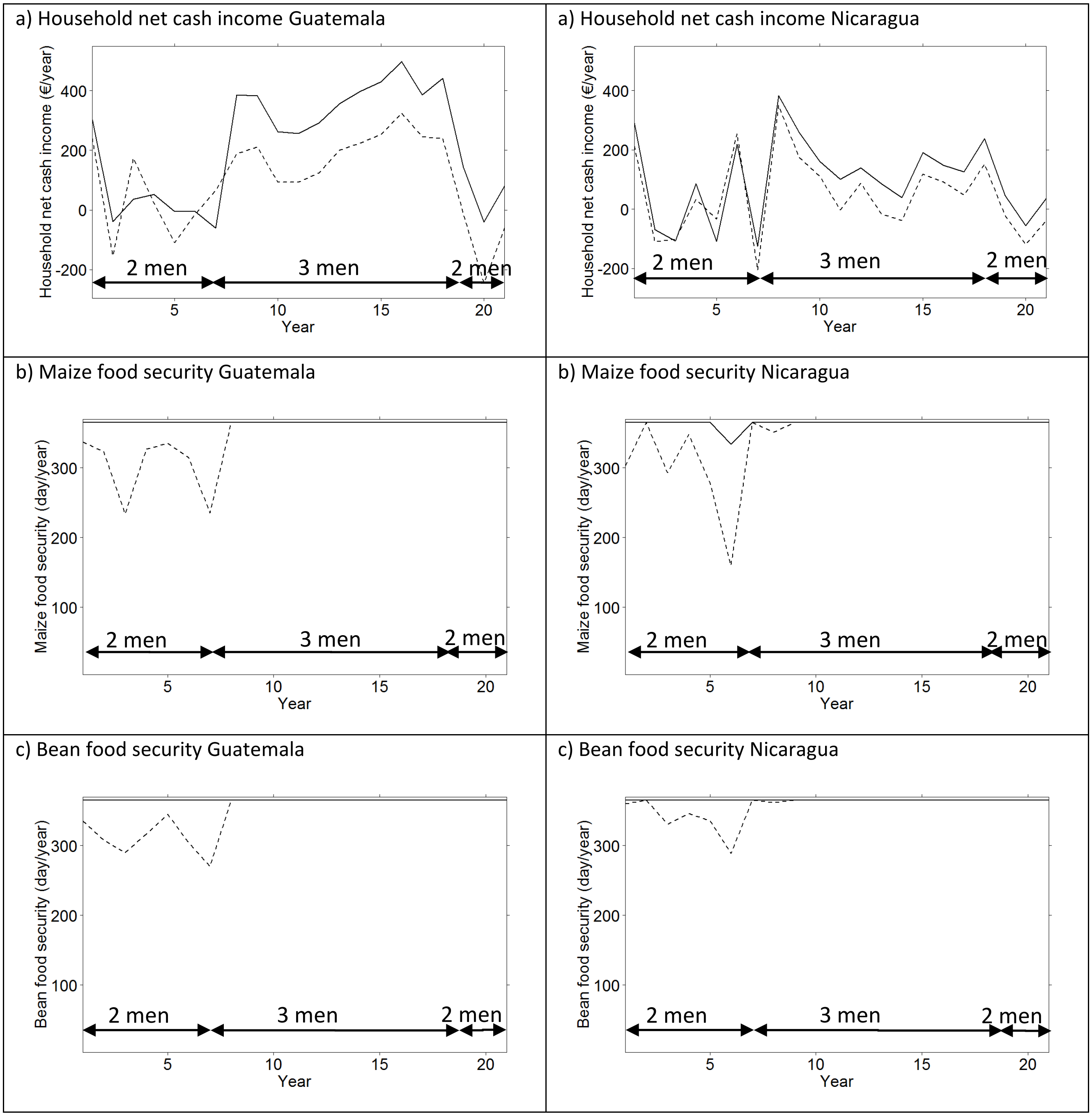
Figure 16. Maize (a) and bean (b) food security days a year for different family sizes of the average typical household in Guatemala (left side) and Nicaragua (right side).

Results from the analysis of changes in family composition and dependency ratios show how the evolution of labour force equivalent of two or three people, depending on age, affects differently a five people and a seven people household (Figure 17).

In terms of food security, in the Guatemalan case, the household with 5 members does not incur a food shortfall, whereas the household with 7 members incurs food shortfall during the 8 first years of simulation facing an average annual food shortage for the 21-year period of 0.7 and 0.6 months a year of maize and bean respectively with periods of up to 4.4 and 3.2 months respectively, obtained in the 3rd and 7th years of simulation. After that first period of scarcity, households are able to save enough money to purchase food in years with smaller incomes reaching complete food security. In the case of Nicaragua a typical household of 5 members has to cope with a month of maize food shortfall during the 21-years simulation. In the other hand, the 7 members household copes with an average period of 1.9 months of maize shortfall and 0.7 months of bean shortfall, taking place during the first 8 years (Figure 17 b and c).

In Guatemala, during the first 7-year period of simulation the number of years with a positive net cash income is similar for both household family sizes, however the 7 people household presents a wider variability, which might be a consequence of a narrower dependency on yearly weather. The following 11 years, with a labour force equivalent to 3 men, the household with 5 family members reaches a net cash income ranging from 256 to 498 € year^{-1} due to the extra income obtained from the off-farm labour of this third worker. The household with 7 family members has to face a larger food demand, which allows net cash incomes rising from 93 to 323 € year^{-1}. The last 3 years the household net cash income drops as a consequence of the emancipation of one of the sons, which reduces the household labour force equivalent to 2 men. In the case of Nicaragua, both household sizes present a similar behaviour, however most of the years the net cash incomes are higher for the household with 5 family members (reaching a maximum of 383 € year^{-1}) (Figure 17a).

Figure 17. Household net cash income (a), maize (b) and bean (c) food security days a year for a 5 members family size (solid line) and 7 members family size (dash line) varying family composition with the time. The double arrows indicate the labour force equivalent.



Although the household family size and composition is not perceived as an important issue for the local population, there is a relation between family size and food security; the larger the family size the smaller food availability to each person within the household. In Central America (Menchu and Mendez, 2012, 2011a, 2011b; World Bank, 1998) and in other developing regions (Muche et al., 2014; Olayemi, 2012; Rahim et al., 2011 in Ethiopia, Nigeria, and Iran respectively) has been probed that large family size has a negative impact on household food security. This might indicate that, most of the family members belong to dependent age groups, not contributing for production but consuming food stocks. When variation of the number of active members in the household is studied over a long term period (for 5 and 7 family members households), the typical household is able to achieve annual food security and increases its net cash incomes with just one extra family labourer (Figure 17). This suggests that, at least for family sizes close to the average size of the region (5 and 7 family members), the food security status varies according to the evolution of the dependency ratio of the family (which changes with marriages, age of the family members, births and deaths). Supposing the same evolution of dependency ratios for different family sizes, larger families present worse food security levels. Our simulations show better welfare results when family work capacity increases and is preserved in the household. However, most studies analyse family size in a static way, which does not show its real importance. It would be interesting to further investigate on the effect of the evolution of dependency ratios of different family sizes over time on smallholders welfare parameters.

3.3.2 Effects of farm productivity

From the yield combinations evaluated, the best long term maize food security results were achieved for the combination of 1033 kg ha^{-1} of bean and 1597 kg ha^{-1} of maize in Guatemala and 1089 kg ha^{-1} of bean and 757 kg ha^{-1} of maize in Nicaragua (Figure 18). A typical household obtaining these yields would incur in maize shortfall during less than 0.3 months a year on average and 0.4 months a year on bean in both studies Guatemala and Nicaragua. The longest shortfall period faced by a typical household in Guatemala (Yield combination: 473 kg ha^{-1} of bean and 1056 kg ha^{-1} of maize) over a period of 21 years last 2.9 months for maize and 1.53 months for bean on average. In Nicaragua (Yield combination: 658 kg ha^{-1} of bean and 509 kg ha^{-1} of maize) the longest average shortfall period is 6.3 months of maize and 2.1 months of bean (Figure 18). The most similar yield combination to the average yields found in Guatemala study case (651 kg ha^{-1} of bean and 1517 kg ha^{-1} of maize) is the one obtaining 753 kg ha^{-1} of bean and 1597 kg ha^{-1} of maize which leads to an average of 1.16 and 2.3 months a year of maize and bean shortfall respectively. In the case of Nicaragua (769 kg ha^{-1} of bean and 678 kg ha^{-1} of maize), the typical household, combining 874 kg ha^{-1} of bean and 757 kg ha^{-1} of maize (similar to the yields found in the region), is maize food insecure during 2.5 months a year on average and bean food insecure during 1.2 months a year on average (Figure 18). All these average scarcity periods obtained for different yield combinations in Guatemala and Nicaragua are within the same order of magnitude than the three to five months reported on literature of those countries (Fujisaka, 2007; Bacon et al., 2014; and Hellin et al., 2018)

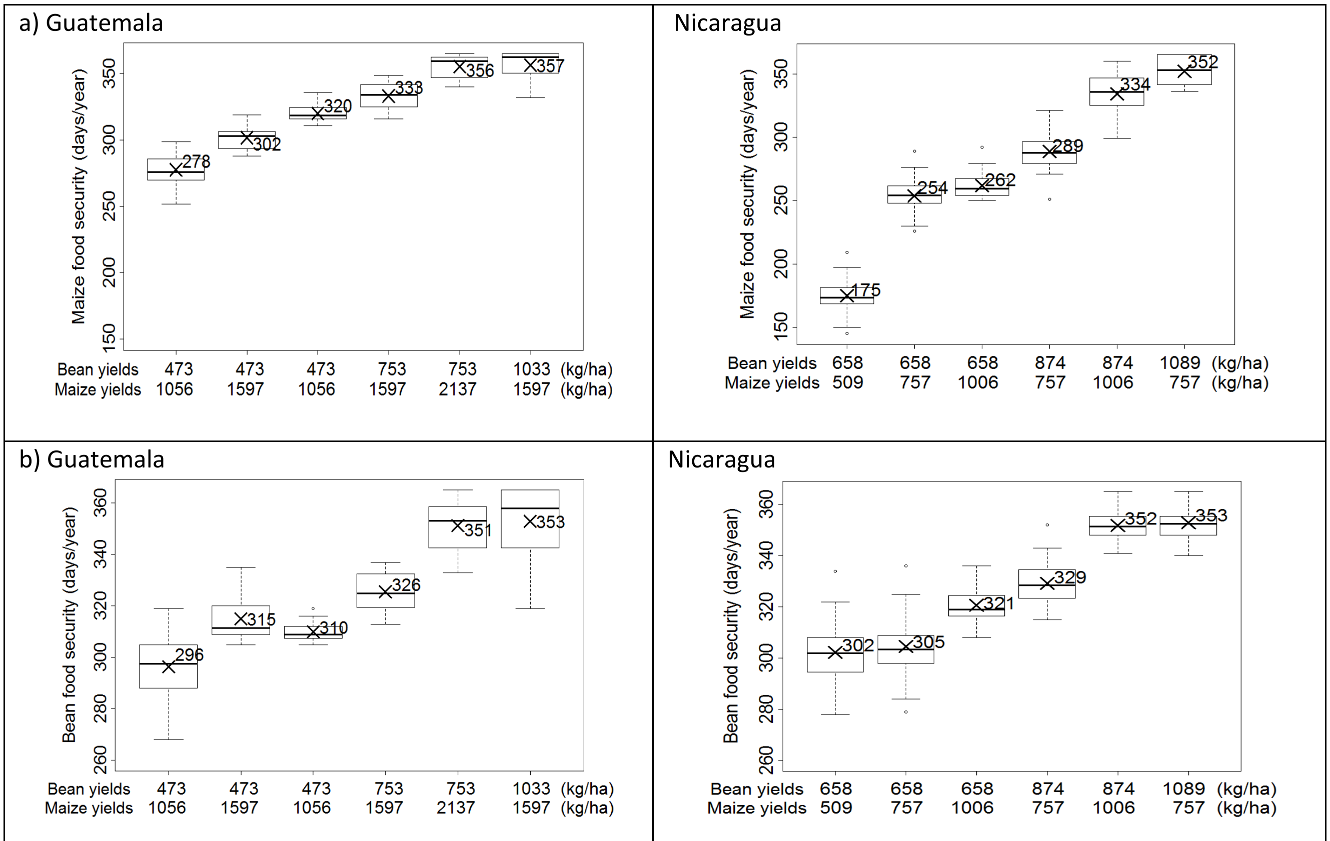


Figure 18. Farm productivity box plots (25th, 50th, 75th percentile) of the simulated maize a) and bean b) food security resulting from each combination of maize and bean yields around the average yield values of the Guatemalan and Nicaraguan studied areas during a 21-year simulation. *The whiskers denote the most extreme data points which are no more than 1.5 times the interquartile range from the box. Black points denote the values of any data points which lie beyond the extremes of the whiskers. Crosses indicate the average of the 21-year simulation for a yield combination.*

None of the yield combinations provides a surplus of net cash income at the beginning of July (the time of biggest scarcity, in which yearly net cash income is calculated) in any of the study cases, apart from a yield combination in Nicaragua obtaining values slightly above cero (Figure 19). By that time of the year, the typical household has usually depleted its food stocks, and if they had any cash available they use it to purchase staple grains, which most of the years, results in no cash availability or even indebtedness. This is in agreement with literature in the region, indicating that many farmers buy a portion of their basic grains after depleting their stock and often they use credit for subsistence food purchases which can contribute to debt accumulation (Bacon et al., 2014; Maxwell et al., 1999). In Guatemala, it appears a larger variability in net cash income with higher yield simulated combinations. This variability might result from changes in farmer's workload, work efficiency and timing on labours at each moment and its evolution during the time, which are directly related to yearly weather variability. All these variables have an effect on food consumption and stocks which consequently affect to net cash income. Thus, farm productivity but also weather variability influence the situation in which the household has to cope the lean episode (Figure 19a). In Nicaragua the largest variability in net cash income results from low yield simulated combinations and their average value is biased towards negative values indicating how severe the indebtedness can be and how can it be aggravated depending on yearly weather variability (Figure 19b). This low yield combinations might result from climatic hazards or be a consequence of a sub optimal agricultural management or the use of unsuitable soils, more suitable for perennial forestry than for agriculture. The HLPE (2013) found that the high risk incidence and low resource availability imply expenditures that can trigger an impoverishment spiral of smallholders. Also, they found that smallholders use their income to firstly feed the family and repay loans or debts, which reduces surplus and cash incomes and in turn farm investments.

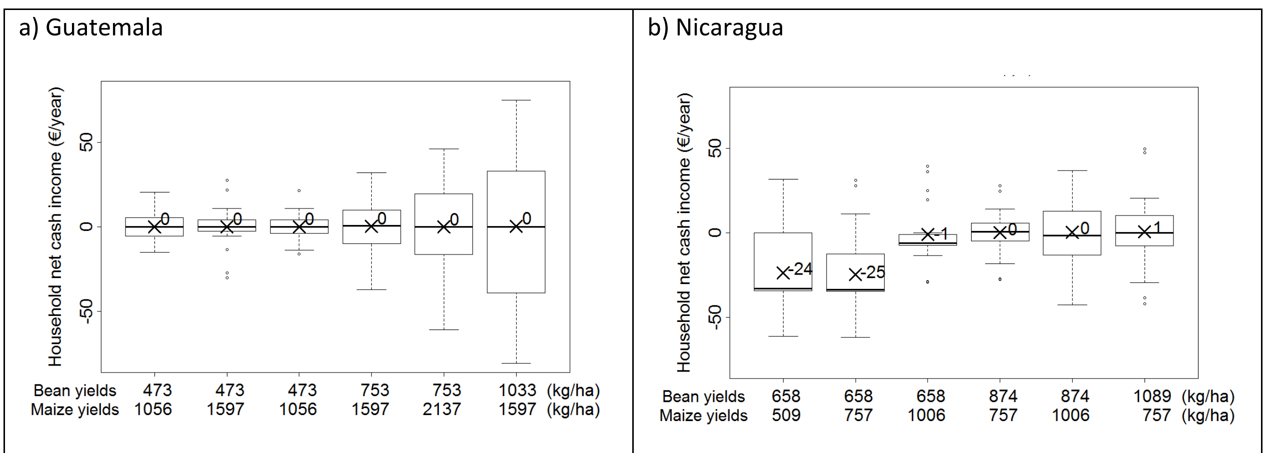


Figure 19. Farm productivity box plots (25th, 50th, 75th percentiles) of simulated net cash income at the critical food scarcity period (*first July*) for different combinations of maize and bean yield values around the average yield of the region. The whiskers denote the most extreme data point which is no more than 1.5 times the interquartile range from the box. Black points denote the values of any data points which lie beyond the extremes of the whiskers. Crosses indicate the average of the 21-year simulation for a yield combination.

The results showed that household welfare dynamics depend not only on the variability of farm productivity of the fields managed by each household but the inter-annual weather variability. The analyses showed how different yield levels of the staple crops can lead to scarcity periods of different intensity and how weather variability affects differently depending on farm productivity scenario and welfare level derived from it. This is in line with Scoville (1947) argument that "no size of farm is large enough to ensure profit" and that incomes will vary even between different farms of the same size, which supports our effort of determining a desirable size adapted to the local conditions. Furthermore, analysing different farm productivity combinations we found that household welfare dynamics depend not only on yields obtained by a farmer's management or access to a better soil, but they are also influenced by seasonal weather variability which affects timing and workload of some activities (e.g. sowing, weeding), work management efficiency, household food consumption, and food stocks, determining household welfare trajectory. Leonardo et al. (2015) in Mozambique also reported that better yields in maize and revenues were achieved by smallholder farms combining better crop management and productivities. The application of CERES-Maize model to a mid-altitude zone of central Malawi also revealed substantial regional variability in self-sufficiency maize production, which was attributed to a combination of farm productivity and weather effects (Thornton et al., 1995). There has not being a large rise in productivity of maize and bean in the last 14 years in Guatemala and Nicaragua (FAOSTAT, 2020), this is specially manifest in Nicaragua where the average national maize yield stayed around 1264 kg ha^{-1} during the 2000-2020 period. Management and policies aimed to increase these productivities appear as a good effort to tackle food security problems of this countries and specially the most needed subsistence and near-subsistence smallholder farms in less favoured mountainous areas.

3.3.3 Establishing of smallholder land size threshold adapted to regional context.

According to the simulations (Figure 20), a typical household in Guatemala with a labour force equivalent to two men, would achieve complete annual food security on maize and bean for areas of maize within the range 0.65-1.65 ha and areas of bean within the range 0.61-1.41 ha. The highest cash flow (160 € year^{-1}), allowing annual household food security, is reached for maize and bean area allocations of 1.25 and 1.21 ha respectively. For these area allocations there is a workload of 226 days person^{-1} year^{-1}, and yield drops of 12 % and 41 % on maize and bean crops respectively. In Nicaragua, farmers allocate smaller areas of bean than maize. A typical household in Nicaraguan study case with an equivalent labour force of two men achieves full annual food security for areas of maize within the range 0.85-2.45 ha and areas of bean within the range 0.41-1.21 ha. The highest cash flow (117 € year^{-1}), allowing annual food security, is reached for maize and bean area allocations of 2.05 and 1.21 ha respectively. For these area allocations there is a workload of 223 days person^{-1} year^{-1} and yield drops of 10 % and 58 % on maize and bean crops respectively.

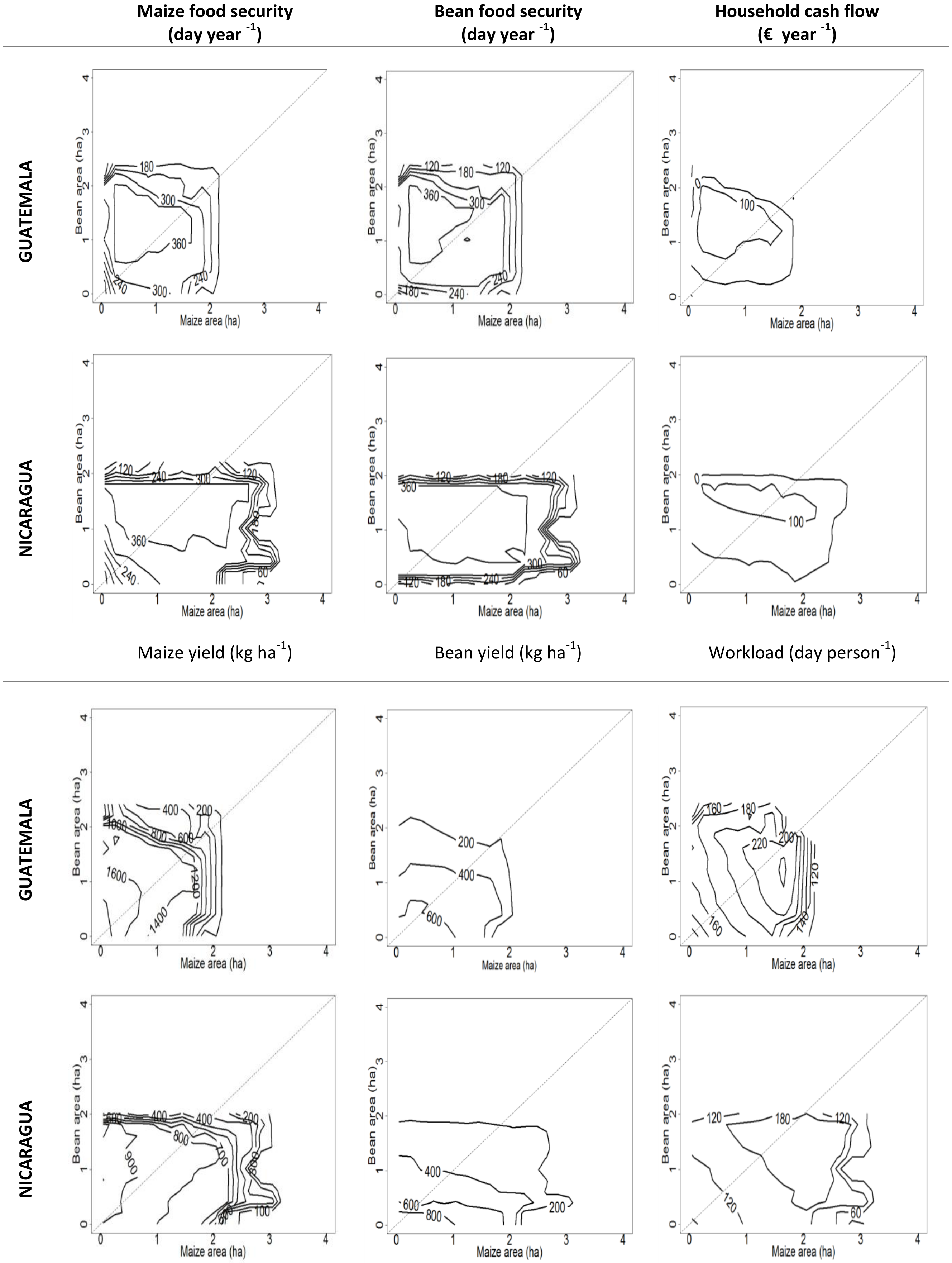
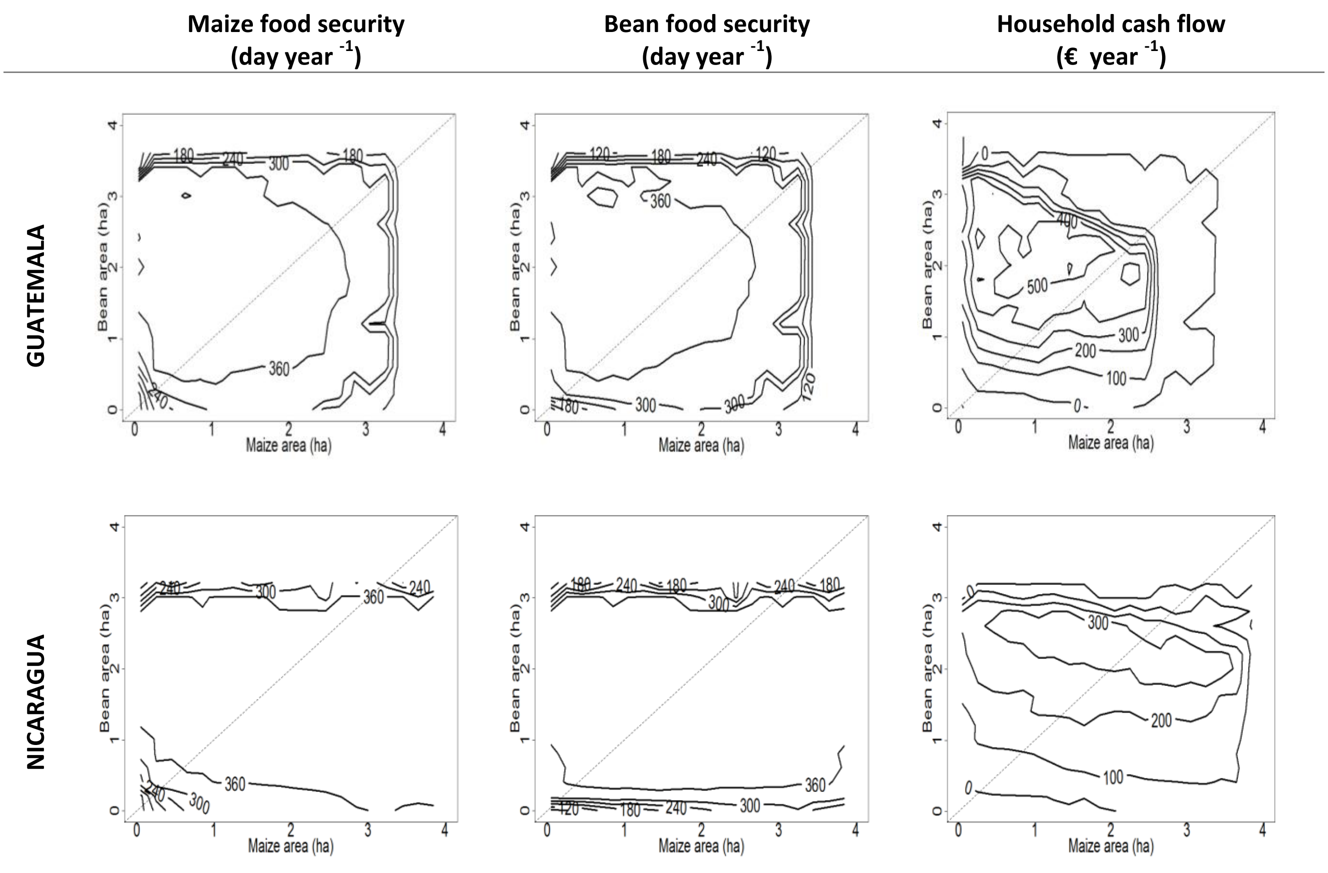


Figure 20. Welfare parameters (maize and bean food security and household cash flow, maize and bean yields, activity hours) change with crops area allocation for a typical household in Guatemala and Nicaragua with a labour force equivalent to two men.

A typical household in Guatemala with a labour force equivalent to three men (Figure 21) would be food secure all year long when managing areas within 0.65 ha and 2.65 ha of maize and 0.41 ha and 2.61 ha of bean. This household satisfies annual household food needs and reaches the highest cash flow (538 € $year^{-1}$) for maize and bean area allocations of 2.25 and 1.81 ha respectively. For these area allocations the workload attains 239 days $person^{-1}$ $year^{-1}$, and there are yield drops of 11% and 40% on maize and bean crops respectively. In Nicaraguan study case, a typical household with an equivalent labour force of three men achieves full annual food security for areas of maize within the range 0.65-2.85 ha and areas of bean within the range 0.41-3.01 ha. The highest cash flow (376 € $year^{-1}$), allowing annual food security, is reached for maize and bean area allocations of 3.05 and 2.21 ha respectively. For these area allocations there is a workload of 231 days $person^{-1}$ $year^{-1}$ and yield drops of 9% and 61% on maize and bean crops respectively.



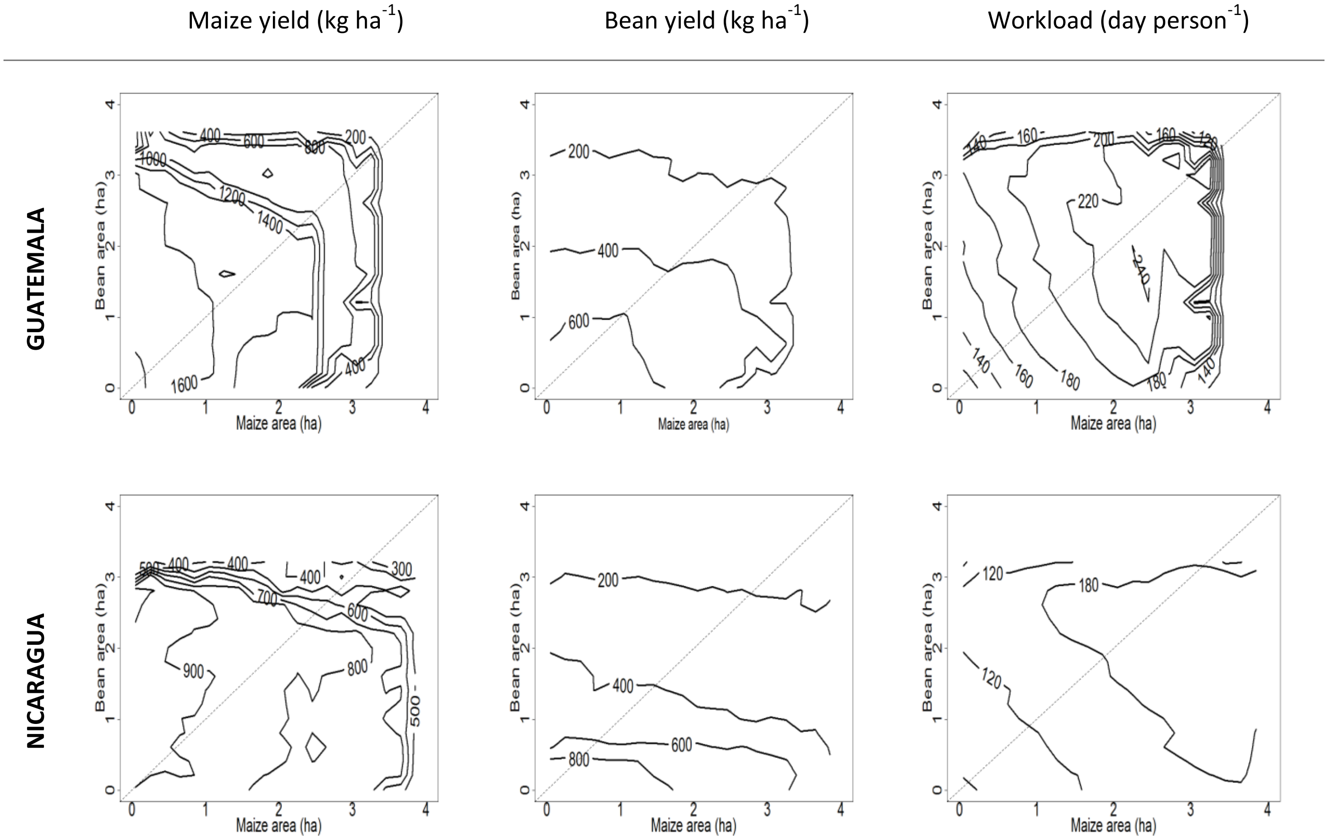


Figure 21. Welfare parameters (maize and bean food security and household cash flow, maize and bean yields, activity hours) change with crops area allocation for a typical household in Guatemala and Nicaragua with a labour force equivalent to three men.

In the case that a typical household in Guatemala had a labour force equivalent to four men (Figure 21), it would be food secure all year long for maize areas within 0.65 ha and 3.85 ha of and 0.41 ha and 3.81 ha of bean. This household satisfies annual household food needs and reaches the highest cash flow (902 € year^{-1}) for maize and bean area allocations of 3.05 and 2.41 ha respectively. For these area allocations the workload attains 240 days person^{-1} year^{-1}, and there are yield drops of 12% and 40% on maize and bean crops respectively. In Nicaraguan study case, a typical household with an equivalent labour force of four men achieves full annual food security for areas of maize within the range 0.45-3.85 ha and areas of bean within the range 0.21-3.81 ha. The highest cash flow (564 € year^{-1}), allowing annual food security fulfilment, is reached for maize and bean area allocations of 3.25 and 3.01 ha respectively. For these area allocations the household workload is 209 days person^{-1} year^{-1}, and there are yield drops of 8% and 62% on maize and bean crops respectively.

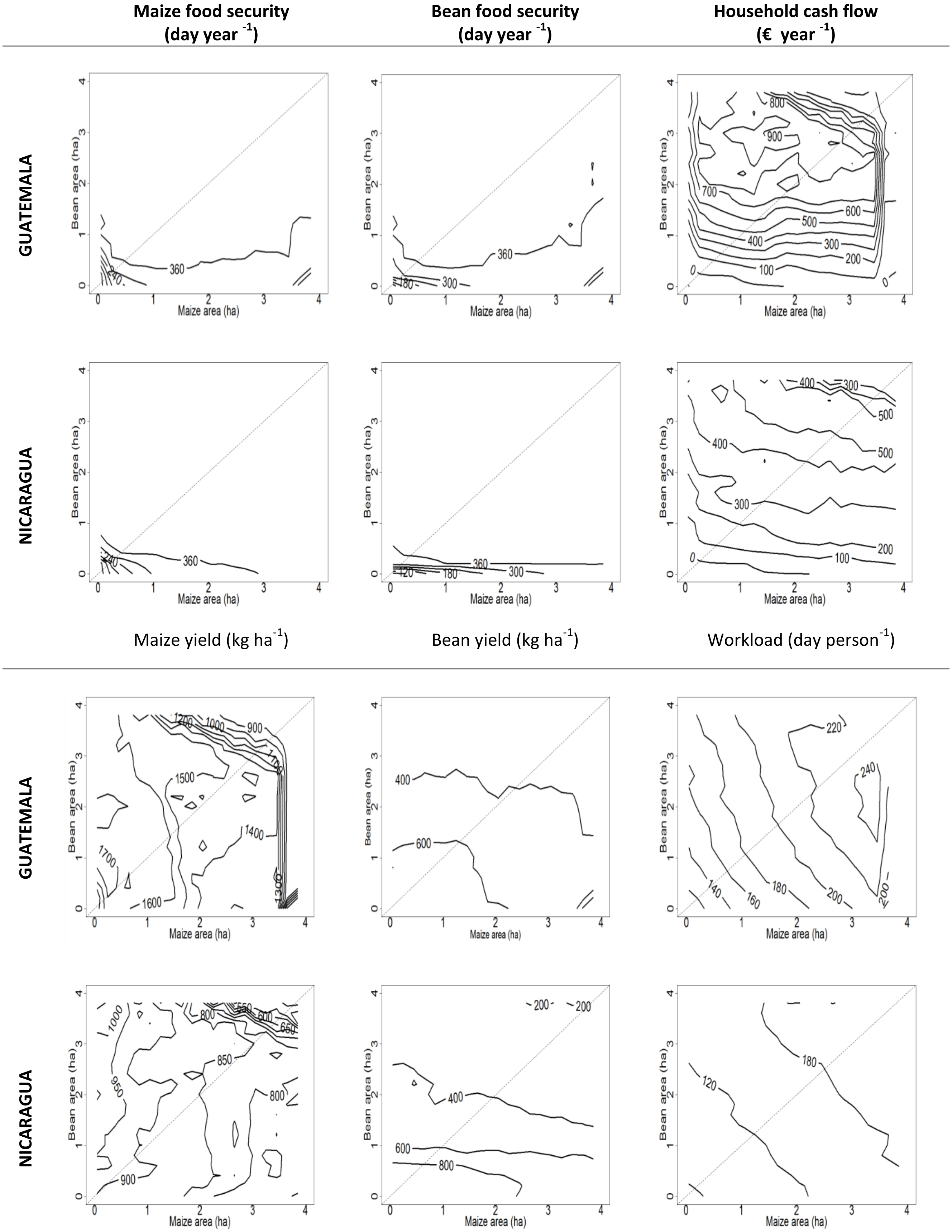


Figure 22. Welfare parameters (maize and bean food security and household cash flow, maize and bean yields, activity hours) change with crops area allocation for a typical household in Guatemala and Nicaragua with a labour force equivalent to four men.

To summarize, the welfare situation of a typical household varies with the household labour force equivalent and the area and crop allocation managed (Figures 5-7). In both countries, all parameters related to household welfare improve along with the household labour force. Both, labour force and land availability interact constraining household welfare. This is in line with the results of Leonardo et al. (2015) who emphasized the importance of labour availability to increase smallholder productivity and achieve food self-sufficiency in maize-based farming systems in Mozambique. In our study, in a mountainous area where land is scarce, land availability has a greater impact than labour force in poverty and food security.

We simulated (following the hierarchy specified in 2.4.3 Establishment of smallholder land size threshold integrating regional factors), the desirable farm size to achieve subsistence and sustainable food security with the smaller household workload. The desirable farm size varies, according to the household labour force availability. In highlands of Guatemala, it ranges from 1.25 ha of maize (of which 1.21 ha are associated with bean as companion crop), to 3.05 ha (2.41 ha associated with bean), for a labour force equivalent to two and four men respectively. In the case of Nicaraguan study case, the desirable farm size ranges from 2.05 ha of maize (of which 1.21 ha are associated with bean) to 3.25 ha (of which 3.01 ha are associated with bean), with a labour force equivalent to two and four men respectively. While other authors defend a 2 ha threshold to define smallholder farms (Hazell et al., 2010; IFAD and UNEP, 2013; Nagayets, 2005), our results show that the 2 ha threshold does not capture the actual characteristics of the farm, such as performance of producers, potential production or environmental factors that might affect productivity and as a consequence the carrying capacity of those 2 ha.

Following a definition of smallholder, based on farm size in terms of what the smallholder family can care for (Scoville, 1947), the desirable farm size for subsistence smallholder farms in the highlands of Guatemala would be established in the range 1.25-3.05 ha, and in 2.05-3.25 ha for the Nicaraguan context depending on the household labour force. These values are within the second category purposed by Fradejas and Gauster (2006) as 'subsistence' (0.7-7 ha, 2.5 ha on average) farms in Guatemala and also within the second category purposed by Soto Baquero et al. (2007) for Nicaragua at a national level; 'transition family agriculture[4]' (average area of 4 ha).

[4] Transition agriculture: Depends on its own production (sales and self-consumption), satisfies requirements for family reproduction, but has difficulties to generate surplus allowing reproduction and development of the production unit.

So far we identified the desirable farm size for three household labour force scenarios (ranging from two to four household farmers) to reach sustainable food security and the higher cash flow. This is useful to know the potential of the smallholder farms of the region under the actual average conditions and to set a desirable goal to aim for. However, in mountainous areas, land availability is frequently a constraint (Wymann von Dach et al., 2013) and farmers are forced to subsist with the scarce land they have available. Altieri (2004) identified inequality and access to land as one of the major threats to food security. Thus, it is also important to know what is the situation of the smallholder welfare parameters for the average areas managed in the study regions (Table 21) which are not expected to increase but instead split among household's members, often into plots too small to feed a large family (Morris et al., 2013) unless government policies take action.

According to the simulation results, a typical household in Guatemala managing the average land size and crop allocation of the region, 0.57 ha of maize and 0.25 ha of bean sown in association with it, would be included within the first category purposed by Fradejas and Gauster (2006) for Guatemala; 'less than subsistence[5]' (<0.7 ha) farms. Supposing that this typical household has a labour force equivalent ranging from two to four men, it would not be able to reach annual food security levels and would accumulate debts every year, getting trapped in a poverty circle (Table 21). This is consistent with Fradejas and Gauster (2006) who stated that farms within this category would not even fulfil subsistence levels by themselves. Morris et al. (2013) highlighted the high cost of food and farm inputs along with the seasonal nature of farm income as some of the main causes of household vulnerability to food in El Salvador. Isakson (2009) found that most subsistence-oriented maize farmers in Guatemala broke even in monetary terms or even incurred losses (some of them quite substantial), and none incurred significant gains. However many farmers do not evaluate the decision of cultivating maize in strictly monetary terms (Isakson, 2009), there are other factors (joys of family, fresh air, integration in the community, and fulfillment) are non-pecuniary and outside the realms of market logic. Isakson (2009) writes of Guatemalan peasants: 'By planting corn, a family might assure itself of poverty, and possibly even hunger – but it will not face starvation'.

Similarly to the Guatemalan study case, a typical household in Nicaraguan study case managing the average land size and crop allocation of the region, 0.93 ha of maize and 0.36 ha of bean grown as an intercrop, would be included

[5] This category, is in an unstable situation with respect to production and depends on public support to facilitate technological innovations and access to credit and markets (Soto Baquero et al., 2007)

within the first category purposed by Soto Baquero et al. (2007) for Nicaragua at a national level; 'subsistence family agriculture' (average area around 1 ha). Supposing that this typical household has a labour force equivalent to two men, it has to get indebted (-3 € year^{-1}) to produce its own food (Table 21). Under this conditions there is a 5% maize yield drop and a 23% bean yield drop of the potential simulated yields. However, when the labour capacity of the household increases (labour force equivalent to three or four men), these yield drops are reduced to below 3% for both crops and the household cash flow achieves positive values (32 and 45 € year^{-1} respectively). In these last two scenarios, the typical household has enough labour force to undertake an adequate land management and sufficient off-farm labour to save some money by the end of a 21 years simulation run.

Table 21. Welfare indicator results for a typical household with the average crop allocation and a labour force equivalent from two to four men in Guatemala and Nicaragua study cases.

Welfare indicator	GUATEMALA			NICARAGUA		
	Labour force equivalent					
	2 men	3 men	4 men	2 men	3 men	4 men
Maize food security *(days year^{-1})*	306	318	319	329	350	355
Bean food security *(days year^{-1})*	317	322	322	357	362	364
Maximum cash flow *(€ year^{-1})*	-3	-2	-2	-3	32	45
Workload *(days year^{-1} person^{-1})*	170	149	137	131	99	92
Maize yield *(kg ha^{-1})*	1577	1629	1632	864	898	901
Bean yield (*kg ha^{-1}*)	652	669	663	643	821	837

The typical household in Guatemala study case, managing the average area of staples of the region (0.57 ha of maize and 0.25 ha of bean) and with a labour force equivalent to two men, would incur two months of average maize shortfall and 1.6 months of average bean shortfall. In Nicaragua study case, a typical household managing the average area of staples of the region (0.93 ha of maize and 0.36 ha of bean) and with a labour force equivalent to two men, copes with an average maize shortfall of one month and 0.25 months of bean shortfall. Previous research reports food scarcity lasting from 3 to 4 months in Guatemala (Fujisaka, 2007) and 3.15 months of seasonal hunger in Nicaragua (Bacon et al., 2014).

4 CONCLUSIONS

System dynamics are a useful approach for assessing complex interactions between the environmental system and smallholder decision making, and identifying potential critical issues. By developing SASHACA, we have a model that can be used to gain insight into the functioning of smallholder agricultural systems of highland Central America. Also, we improved understanding of development and evaluation of dynamic models in regions with data scarcity. We combined the adaptation of established crop, soil, and weather models with the development of food security and nutrition, labour availability and smallholder cash flow models to address the study aims.

We analysed the model for its application within the Guatemalan context. The SASHACA model performed well in all tests undertaken for assessment of dynamic models, including extreme conditions testing. Furthermore, our intention was to develop a simple model, requiring low data inputs to ease its use in developing countries where data are usually scarce. Further development of the model could include slope and soil quality, and improve cash flow sub-model, given its importance in smallholder food security. Based on the model assessment, we conclude that the SASHACA model is an adequate tool for assessing the impact of smallholder endowments on their food security and welfare and identifying critical leverage points of these agricultural systems. The SASHACA model could be applicable to simulate a wide range of smallholder agricultural systems in highland areas of Central America. Also, after a specific parameterisation, calibration and validation it could be useful to simulate smallholder agricultural systems in other developing regions worldwide.

Using the SASHACA dynamic bio-economic model of smallholder systems in highlands of Central America, we explored interactions and feedbacks between household endowments and characteristics and their poverty and food insecurity levels. Also, we delineated thresholds allowing or preventing to escape from those undesirable situations. Initial assets, endowments, or household characteristics and their interactions have a strong influence on the long-term household livelihood and welfare status. For example, management of large areas increases production but also food energy consumption and expenses in inputs, which in turn affects food security levels and economic welfare. This is more notable in years of adverse climatic events (such as droughts or pests incidence), where the investment in agricultural inputs does not translate into higher yields. Bean area allocations can have a big impact on food security because of its higher market price and smaller consumption compared to maize. However, risk aversion of farmers usually results in smaller areas of beans than the more secure maize crop. The findings of the study of different crop area allocations revealed that a typical household in the region would need an area of 0.6 ha of maize and bean intercrop complemented with around two months of off-farm labour to securely meet yearly food requirements.

The results of the analysis of off-farm labour impact suggest that a typical household relies on off-farm labour incomes, and is unable to reach food security without it. A typical household working on-farm and engaged in the average number of days of off-farm labour (average off-farm labour opportunity scenario) still does not achieve full year food security and would experience a nearly even cash flow balance. A scenario with plentiful off-farm opportunities is needed to reach year round food security and a positive cash flow balance.

The welfare outputs resulting from analysing purchased agricultural inputs suggest that the high nitrogen rates used by some of the farmers of the region are too high and the yield increase resulting from them does not justify the extra expense in nitrogen fertiliser. The companion bean crop provides a considerable amount of nitrogen to the soil, reducing the need of external nitrogen supply. It would be desirable to adapt nitrogen application to the agronomic conditions and nitrogen budget (determined from yields) obtained in the region. This is important to avoid misuse and associated economic and environmental risks which may be occurring nowadays. The results suggest that there is no economic benefit of using herbicides for small land sizes. However, some farmers (about 40%) prefer the use of herbicides because of the reduced workload and drudgery of manual weeding. Larger farms can increase their food security and welfare levels with the use of herbicides and fertilizer.

The only scenarios able to generate an average annual income above the extreme poverty line of 503 Euros per capita a year[6] are scenarios where the smallholder farm relies partly on off-farm revenues and/or has a sufficient area for cultivating staple crops. Our findings underscore how certain smallholder endowment levels such as land availability, crop allocation, off-farm availability or use of external inputs can lead to food unsecure and poverty situations. Thus, considering that Guatemala has the largest population and the third population growth rate in Central America (UNICEF 2015, World Bank, 2021) it seems likely that food security will continue to be an issue in highland Guatemala, and may even deteriorate due to land pressure and a growing population. In this context, it would be important to

[6] using USD 1.9 day^{-1} and exchange rate of USD per EUR of 1.33 in 2013 (ECB, 2015)

include this farm size constraint on public policies avoiding a further reduction of their size, which could trap smallholders in a poverty cycle.

Using SASHACA system dynamics bio-economic model of smallholder agricultural systems in highlands of Central America, we explored how different factors absent in the size-definition of family farm affect smallholders´ welfare with the aim of guiding food security and nutrition programmes and policies helping subsistence and near-subsistence smallholders to escape from poverty and food insecurity circle.

Family nature of the labour force and the no or limited non-family hired labour, are generally accepted characteristics of smallholder farms, however there is more discrepancy on whether and which other factors might be included. Here, we analysed how some of these factors affect household welfare trajectory and included them in a contextualized definition of a desirable smallholder size in terms of labour capacity. While the household size and dependency ratios are not perceived as an important issue for the local population, the results showed its influence on the food security levels of the household. A typical household composed by seven people and with the typical family composition of the region (in terms of age and gender), faces more than two months of food shortfall compared to a lean period shorter than a week for a five people household in both study cases. When variation of household dependency ratios is studied over time, the typical household improves its welfare levels achieving annual food security. The study suggests the importance of family planning and government promotion of adequate family size in rural areas. However, we found a research gap and suggest further investigation on the effect on food security of the evolution of dependency ratios of different family sizes over time.

The results also showed how securing an adequate level of yields on the staple crops can lead to different scarcity periods in terms of timing, length and intensity. A typical household managing the average land size in Guatemala and Nicaragua study cases, would need to increase its crops productivity to ensure a maximum average long term shortfall period of two weeks. The wealth level of the household (at the beginning and during the course of each cropping season), derived from different productivity scenarios, also affects the work efficiency, household food consumption and staple grains stocks, and therefore household welfare trajectory.

Although there are many characteristics defining family farms, farm size has been the most popular and practical criterion to define family farm. However, we think that it must be used in terms of what the smallholder family can care for allowing an efficient use of the family labour force, an acceptable welfare and must be adapted to the specific socioeconomic, biophysical and cultural characteristics of the region. The household labour force equivalent determines the area that the household is able to manage without major implications on the farm efficiency and productivity, which in turn establishes the household welfare situation. For a household available workforce ranging from two to four people, these size threshold varies from 1.25 to 3.05 ha of staple crops for a typical household in Guatemala study case and from 2.05 to 3.25 ha of staple crops for a typical household in Nicaragua study case.

Nevertheless land availability constraints force farmers to make their living with smaller plots, sometimes not able to sustain a family. According to the simulation results, a typical household in Guatemala managing the average land size and crop allocation of the region (0.57 ha of maize and 0.25 ha of bean), would not be able to reach annual food security levels and would accumulate debts at long term, getting trapped in a poverty circle. Similarly a typical household in Nicaragua has to get indebted to produce its own food or incur modest gains (32 and 45 € $year^{-1}$ for a labour force equivalent to three and four men respectively). An important responsibility of countries is to promote equitable rural development. Subsistence smallholder farms in highland agricultural systems are one the most needed groups in developing countries, with about 70% the world's mountain people experiencing or at risk of hunger (FAO, 2011). Nevertheless, they have a key role for sustainable food, nutrition security and poverty reduction (IAASTD, 2009; FAO, 2012). Thus it is useful to identify them, their actual situation, and their potential, for the purpose of designing and implementing development strategies, policies and programs. The use of dynamic simulation models such as SASHACA seem to be a good tool to gain knowledge and help to refine smallholder farm concept facilitating integration of the local specificities.

5 THESIS PUBLICATIONS AND CONTRIBUTIONS

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Publication in JCR journal

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7 SUPPLEMENTARY MATERIAL

7.1 General tests for assessment of dynamic models

The first test conducted was the study of model boundary adequacy. This test examines whether the selected model frontier is adequate for the model purpose. To this end, revision of endogenous structure was done together with evaluation of potentially important feedbacks omitted from the model. The structure includes crop growth, soil nitrogen and water content, family food availability, labour allocation, and cash flow.

Even though some sub-models were adapted from existing models (Connor et al., 2008; Connor and Fereres, 1999; O'Leary and Connor, 1996) we undertook partial model tests to evaluate the rationality of decision rules of each sub-model through structure assessment test. Partial models were also evaluated to avoid violation of physical laws such as conservation of energy or matter. Additionally, we checked equations for the presence of first-order negative feedback loops to avoid negative stocks. Irrational assumptions were inspected, such as actions happening when there are not sufficient resources. The only variable that is allowed to be negative is cash flow, to represent households' indebtedness over certain periods of the year. We also investigated the aggregation level of some sub-model structures. More detailed model structures were developed when needed and outputs were compared. Throughout the model development process, we examined the model in response to changes in constants and parameters over a realistic range, including zero values (extreme condition testing). The ranges used for this examination were through reference to the literature (Supplementary material Table 3).

System dynamic models are a combination of differential equations solved by numerical integration. Thus, selection of the correct integration method and time step is important to avoid introduction of misleading dynamics into the model. Both the time unit and time step of the model were equal to one day. However, we reviewed time constants to guarantee that they were at least twice the time step in order to reduce integration error problems (Ford, 1999). Dimensional consistency was also checked to ensure unit errors were correct. This test for assessment of dynamic models involves inspection of model equations for suspect parameters, and checking for dimensional errors among the units of each variable in the model. For this test, we used the dimensional analysis tools included in Vensim® DSS.

After several iterative loops of model development, testing, and correcting errors we considered the model adequate to assess the impacts of smallholder endowments on food security in Agricultural Systems in Highland Areas of Central America. Model boundary and aggregation level were judged adequate since they encompass the main variables, interactions and feedbacks for the ultimate purpose of the model. The fact that the model includes discontinuous events, makes it difficult to test with higher-order integration methods that may average out sporadic changes. Nevertheless, for models that include social and human systems where a high accuracy is not the main goal, the Euler integration used in our model is generally the correct integration method (Sterman, 2000). We ensured that unit errors were correct and the model presented dimensional consistency. The model also passed the rationality test, avoiding violation of physical laws such as conservation of energy and matter.

Supplementary Materials Table 1. Factorial calculations of total energy expenditure (TEE) for a typical family in Guatemalan highlands.

Main daily activities	Time allocation (h)	Energy cost PAR[a]	Time × energy cost	Mean PAL[b]	BMR (kcal day^{-1})	TEE (kcal day^{-1})
Sedentary or light activity lifestyle of a (<3 years, 8 kg)						
Sleeping	8	1.0	8			
Eating	3	1.5	4.5			
Sitting	8	1.5	12			
Walking at varying paces without a load	5	3.2	16			
Total	24		40.5	**1.69**	435.5	**734.9**
Sedentary or light activity lifestyle (3-10 years, 20 kg)						
Sleeping	8	1.0	8.0			
Personal care (dressing, showering)	1	2.3	2.3			
Eating	1	1.5	1.5			
Cooking	1	2.1	2.1			
Sitting (office work, selling produce, tending shop)	8	1.5	12.0			
General household work	1	2.8	2.8			
Walking at varying paces without a load	1	3.2	3.2			
Low intensity aerobic exercise (playing…)	3	4.2	12.6			
Total female	24		44.5	**1.85**	892.2	**1654.3**
Total male	24		44.5	**1.85**	958.4	**1777.1**
Active or moderately active lifestyle (30-60 years, 50kg)						
Sleeping	6	1.0	6.0			
Personal care (dressing, showering)	1	2.3	2.3			
Eating	1	1.5	1.5			
Standing, carrying light loads (waiting on tables)	6	2.2	13.2			
Walking at varying paces without a load	5	3.2	16			

Low intensity aerobic exercise	2	4.2	8.4			
Light leisure activities (chatting)	3	1.4	4.2			
Total	24			**1.90**	1446.7	**2748.7**
Active or moderately active lifestyle (18-30 years, 50kg)						
Sleeping	7	1.0	7.0			
Personal care (dressing, showering)	1	2.3	2.3			
Eating	1	1.5	1.5			
Standing, carrying light loads or non-mechanized domestic chores	6	2.3	13.8			
Walking at varying paces without a load	4	3.2	12.8			
Collecting water/wood	3	4.4	13.2			
Light leisure activities (chatting)	2	1.4	2.8			
Total	24		53.4	**2.23**	1227.5	**2731.3**
Vigorous or vigorously active lifestyle (18-30 years, 60kg)						
Sleeping	7	1.0	7.0			
Personal care (dressing, bathing)	1	2.3	2.3			
Eating	2	1.4	2.8			
Cooking	0	2.1	0.0			
Non-mechanized agricultural work (planting, weeding, gathering)	7	4.1	28.7			
Collecting water/wood	1	4.4	4.4			
Walking at varying paces without a load	3	3.2	9.6			
Low intensity aerobic exercise (football)	3	3.5	10.5			
Total	24		58.3	**2.43**	1595.6	**3875.9**
Vigorous or vigorously active lifestyle (10-18 years, 50kg)						
Sleeping	7	1.0	7.0			
Personal care (dressing, bathing)	1	2.3	2.3			
Eating	2	1.4	2.8			
Cooking	0	2.1	0.0			
Non-mechanized agricultural work (planting, weeding, gathering)	7	4.1	28.7			
Collecting water/wood	1	4.4	4.4			
Walking at varying paces without a load	3	3.2	9.6			
Low intensity aerobic exercise (football)	3	3.5	10.5			
Total	24		58.3	**2.43**	1542.5	**3747.1**
AVERAGE FAMILY				**2.05**	1156.9	**2467.0**

[a] *Energy costs of activities, expressed as multiples of basal metabolic rate, or PAR are based on Annex 5 of the consultation's report (WHO, 1985)*

[b] *multiple of 24-hour BMR*

[c] *Reference values of population* (FAO, 2008)

Supplementary Materials Table 2. Selected parameters for each labour derived from surveys.

Crop	Activity	Farmers (number)	Farmer (%)	Length ($h\ ha^{-1}\ person^{-1}$)	Product ($kg\ ha^{-1}$)	Cost (€ kg^{-1})	Speed ($km\ h^{-1}$)
Maize	Manual ploughing	60	98	270	2.5	4.9	0.046
	Chemical ploughing	2		198			0.063
Bean 1&2	Manual ploughing	18	66	263	3.1	5.0	0.048
	Chemical ploughing	11		79			0.157
Maize	Manual weeding[1]	30	79	284	4.3	4.3	0.044
	Chemical weeding[1]	20		82			0.153
Bean 1&2	Manual weeding[1]	18	59	276	3.6	14.4	0.045
	Chemical weeding[1]	3		48			0.259
Maize	Fertilization 1 (15/15/15) [1]	59	94	87	264	0.5	0.145
	Fertilization 2 (Urea) [1]	53	84	63	198	0.6	0.197
Bean 1&2	Fertilization 1(15/15/15) [1]	29	67	63	103	0.4	0.197
	Fertilization 2 (Urea) [1]	13	29	56	5.2	2.1	0.222

Bean 1&2: Average value from the two seasons of bean and all tasks involved in the activity; [1]: Average value for all tasks involved in the activity (e.g. in maize there are up to three weeding tasks). Farmers (%): Percentage over total farmers sowing the crop. Source: Surveys to farmers.

Supplementary Materials Table 3. Table summary of the values retained for the main parameters and constants of the model and literature sources from which they were derived.

Variable name	Variable description	Units	Value or range	Ref. Value or Range	References
WEATHER					
	Constants				
doy	Days of the year	day	365	365	
CROP DYNAMICS SECTION					
	Maize Constants				
cArea	Area of maize	ha	0.09-1.6	0.09-1.6	(Fieldwork, 2013)
cEtg (Adjust function)	Base temperature for development	ºC	10	8-10	8 (Streck et al., 2008); 10 (Díaz-ambrona et al., 2013); 10 (Tsubo et al., 2005)
cEtg (Adjust function)	Optimum temperature for development	ºC	24-30	25-35	25-35 (Bellido, 1991); 28 (Streck et al., 2008)
cEtg (Adjust function)	Upper temperature for development	ºC	37	30-41	30 (Tsubo et al., 2005); 30 (Díaz-ambrona et al., 2013); 36 (Streck et al., 2008); 41 (Yan and Hunt, 1999)
ctt1	Thermal time from emergence to flowering	ºC day	698	629-898	500-1100 (sowing-anthesis)(López, 2002); 629 (Tsubo et al., 2005); 898 (Díaz-ambrona et al., 2013)
ctt2	Thermal time from flowering-maturity	ºC day	771	500-900	500-900 (Fuentes López, 2002); 744 (Tsubo et al., 2005); 771 (Díaz-ambrona et al., 2013)
ck_{ext}	Canopy extinction coefficient	Dimensionless	0.5	0.43-0.66	0.432 (Tsubo et al., 2005); 0.66 (FAO, 2006b)

cRue	Radiation use efficiency	$g\ MJ^{-1}$	3.1	3.0-4.0	3 (Tsubo et al., 2005); 3 (Díaz-ambrona et al., 2013); 3.1-3.2 (Connor et al., 2011); 3.5-4.0 based on Cropsyst documentation, (Stöckle et al., 2001)
cSLM	Ratio leaf mass to leaf area	$kg_{leaf}\ ha_{leaf}^{-1}$	275	275-363	275 (Amanullah et al., 2007)
cLwr ant	Minimum ratio leaf mass to absolute crop mass to anthesis	$kg_{leaf}\ kg_{crop}^{-1}$	0.25	0.194	0.194 Average plant Lwr (Amanullah et al., 2007)
cLwr mat	Minimum ratio leaf mass to absolute crop mass to maturity	$kg_{leaf}\ kg_{crop}^{-1}$	0.1	0.194	0.194 (Amanullah et al., 2007)
cLAI max	Maximum leaf area index maize for Hi max	$m^2\ m^{-2}$	5.8	2.4-7	2.4-5 (Amanullah et al., 2007); 5 (Díaz-Ambrona et al., 2013); 4-7 (Stockle and Nelson, 2001)
cSenes rate	Senescence rate of CORN BIO	Dimensionless	0.008	0.005-0.006	0.005 (Bellido, 1991); 0.006 (Barrios et al., 2013)
cGrnfillr	Rate of grain filling from cTGW	Dimensionless	0.3	0.39-0.54	0.39 (IICA-PROCIANDINO, 1993); 0.54 (Vargas et al., 2007)
cRgrowth	Root growth rate	$mm\ day^{-1}$	8	3-13	(Bellido, 1991)
cRdepthmax	Max rooting depth	m	1.2	0.8-2.0	0.8 (Díaz-ambrona et al., 2013), 1.5-2.0 (Stockle and Nelson, 2001)
TSW	Thousand seeds weight	$Kg\ 1000seeds^{-1}$	0.3	0.3	0.34 (Carrasco et al., 2009) trabajo graduación
	Bean Constants				
bArea	Area of bean	ha	0.01-1.5	0.09-1.5	(Fieldwork, 2013)
bEtg (Adjust function)	Base temperature for development	ºC	8	2-10	2 (Scully and Waines, 1988); 3 in Nicaragua (Díaz-ambrona et al., 2013); 4.2 in Portugal (Ferreira et al., 1997); 7.1-13.2 in Africa (Smithson and Summerfield, 1998) 10 (Tsubo et al., 2005); 7 Dapaah et al. (1999); 8 (Balasubramanian, 2002); 8-10 (Hall, 2001) 10 Kapitsimadi (1988)
bEtg (Adjust function)	Optimum temperature for maize development	ºC	21-30	18-29	18-22 (Balasubramanian, 2002); 20.4-23.3 (Smithson and Summerfield, 1998); 24.2 (Ferreira et al., 1997); 29 (Yan and Hunt, 1999)
bEtg (Adjust function)	Upper temperature for development	ºC	37	22-39.3	22 (Díaz-ambrona et al., 2013); 28.4-33.4 (Yoldas and Esiyok, 2009); 29.1-40.2 (Smithson and Summerfield, 1998); 30 (Tsubo et al., 2005); 39.3 (Yan and Hunt, 1999)
btt1	Thermal time from emergence to flowering	ºC day	500	484.8-1000	484.8-497.1 (Balasubramanian, 2002); 564 (Tsubo et al., 2005); 895.3 (Yoldas and Esiyok, 2009); 1000 (Díaz-ambrona et al., 2013);
btt2	Thermal time from flowering-maturity	ºC day	900	494.1-958.7	494.1 (Balasubramanian, 2002)583 (Tsubo et al., 2005); 604.7 (Díaz-ambrona et al., 2013); 958.7 (Yoldas and Esiyok, 2009);

bk_{ext}	Canopy extinction coefficient	Dimensionless	0.6	0.618	(Tsubo et al., 2005)
bRue	Radiation use efficiency	g MJ^{-1}	1.8	1.2-2.0	2 (Tsubo et al., 2005); 2 (Díaz-ambrona et al., 2013); 1.2-1.9 (Connor et al., 2011)
bSLM	Ratio leaf mass to leaf area	kg_{leaf} ha_{leaf}^{-1}	205	196-346	196.07-269.54 in (Boutraa, 2009); 207-346 (White and Montes-R, 2005)
bLwr ant	Minimum ratio leaf mass to absolute crop mass to anthesis	kg_{leaf} kg_{crop}^{-1}	0.50	0.59-0.69	0.59-0.69 (Gebeyehu, 2006); 0.585 (Trindade et al., 2010)
bLwr mat	Minimum ratio leaf mass to absolute crop mass to maturity	kg_{leaf} kg_{crop}^{-1}	0.50	0.59-0.69	0.59-0.69 (Gebeyehu, 2006); 0.585 (Trindade et al., 2010)
bLAI max	Maximum leaf area index at max high (LAI max)	m^2 m^{-2}	3.3	3-6	3-4 (Stockle and Nelson, 2001); 5 (Díaz-ambrona et al., 2013); 3-6 (Ghamari and Ahmadvand, 2013)
bSenes rate1	Senescence rate of CORN BIO from phenostage 1.6-2.1	Dimensionless	0.012	0.016-0.026	(Barrios et al., 2013)
bSenes rate2	Senescence rate of CORN BIO from phenostage ≥2.2	Dimensionless	0.02	0.016-0.026	(Barrios et al., 2013)
bGrnfill	Rate of grain filling from cTGW	Dimensionless	0.33	0.51-0.62	0.51-0.62 (Vargas et al., 2007)
bRgrowth	Root growth rate	mm day^{-1}	14	12-28.8	12-28.8 (Souda et al., 1990)
cRdepthmax	Max rooting depth	m	1.5	0.9-1.5	1.5 (Díaz-ambrona et al., 2013); 0.9-1.3 (Stockle and Nelson, 2001);
TSW	Thousand seeds weight	Kg $1000seeds^{-1}$	0.35	0.15-0.6	0.15-0.6 Singh (1992); 0.25-0.4 (Ulloa et al., 2011)**)**
LABOUR					
	Constants				
Journal h	Total hours worked a day	h	8	6-10	6-10 (Field observation)
	Parameters				
Distance between furrows in maize	Distance between furrows in maize	m	0.8	0.8	(Fieldwork, 2013); 0.75-1 (Tsubo et al., 2005); 0.8 (Fuentes López, 2002) 0.9 (Soplin, 1993); 1 (Carrasco et al., 2009)
Distance between maize plants	Distance between maize plants	m	0.6	0.6	(Fieldwork, 2013); 0.4 (Carrasco et al., 2009); 0.5 (Fuentes López, 2002); 0.6 (Soplin, 1993)
Distance between furrows in bean	Distance between furrows in bean	m	0.80	0.60-1.10	0.60-1-1.1 (Tsubo et al., 2005); 0.8 (Hunsaker-Alcântara et al., 2007; Hunsaker-Alcântara et al., 2010)
Distance between bean plants	Distance between bean plants	m	0.30	0.30	0.30 (Tsubo et al., 2005)
cSPspdMAN	Speed of manual soil preparation maize	m h^{-1} $person^{-1}$	46	46	27-116 for wheat (Frank, 2000)
bSPspdMAN	Speed of manual soil preparation bean	m h^{-1} $person^{-1}$	48	48	(Fieldwork, 2013)

bSPspdPROD	Speed of soil preparation with herbicide in pre-emergence	$m\ h^{-1}\ person^{-1}$	147	147	(Fieldwork, 2013)
cTSowspd	Speed of sowing labour	$m\ h^{-1}\ person^{-1}$	139	139	0.22-0.54 for wheat (Frank, 2000)
cWCspdMAN	Speed of manual weed control 1 and 2	$m\ h^{-1}\ person^{-1}$	44	44	0.027-0.116 for wheat (Frank, 2000)
cWCspdPROD	Speed of weed control 1 and 2 with herbicide	$m\ h^{-1}\ person^{-1}$	153	153	(Fieldwork, 2013)
cF1spdT15	Speed of maize fertilization 1	$m\ h^{-1}\ person^{-1}$	145	145	(Fieldwork, 2013)
cF1spdUr	Speed of maize fertilization 2	$m\ h^{-1}\ person^{-1}$	197	197	(Fieldwork, 2013)
bF1spdT15	Speed of bean fertilization 1	$m\ h^{-1}\ person^{-1}$	209	209	(Fieldwork, 2013)
cBentspd	Speed of maize bending	$m\ h^{-1}\ person^{-1}$	125	125	(Fieldwork, 2013)
cHvprod	Harvest productivity maize	$kg\ h^{-1}$	4.22	4.22	(Fieldwork, 2013)
bHvprod	Harvest productivity bean	$kg\ h^{-1}$	2.98	2.98	(Fieldwork, 2013)
Total days with weed favourable conditions during Wcontrol2 period	Conditions for weed development, days with SAW > SAW threshold for weed development *from cWC1 and cWC2*	day	>6	>6	Panel consensus (Bontkes and Van Keulen, 2003)
Effect of weeds on 1st period of maize growth	Maize losses consequence of weeds 1st period incidence	%	0.25	0.25	Panel consensus(Bontkes and Van Keulen, 2003)
Effect of weeds on 2nd period of maize growth1	Maize losses consequence of weeds 2nd period incidence	%	0.2	0.2	Panel consensus (Bontkes and Van Keulen, 2003)
Effect of weeds on 2nd period of maize growth2	Maize losses consequence of weeds 2nd period incidence	%	0.1	0.1	Panel consensus (Bontkes and Van Keulen, 2003)
lTechf	Technology factor	Dimensionless	1	1	Panel consensus
Yearly worked days offered at Coffee farms	Days worked at coffee farms off-farm	$days\ year^{-1}$	51	0-150	(Fieldwork, 2013)
Yearly work days offered at the Community per household	Days worked at community off-farm	$days\ year^{-1}$	45	0-208	(Fieldwork, 2013)
Delay labour	Delay to accomplish the labours	day	7	7-14	(Fieldwork, 2013)

SOIL WATER					
	Constants				
	Soil type	Type	Inceptisol	Inceptisol	Inceptisol (IICA, 1992); Inceptisol (Raun and Barreto, 1995)
	Texture	Type	Sandy clay loam	Sandy clay loam	Sandy clay loam (IICA, 1992); sandy-loam (Hunsaker-Alcântara et al., 2010);
ThicknessH0	Horizon 0 thickness	m	0.027	0.027	Field observation
ThicknessH1	Horizon 1 thickness	m	0.12	0.12	0.12-0.33 (IICA, 1992)
ThicknessH2	Horizon 2 thickness	m	0.23	0.23	0.33-0.46 (IICA, 1992)
FCH	Field Capacity	$m^3\ m^{-3}$	0.37	0.3-0.37	0.37 FAO, 2006a; 0.30-0.37 (Stockle and Nelson, 2001)
WPH	Permanent Wilting Point	$m^3\ m^{-3}$	0.19	0.17-0.24	0.19 FAO, 2006a; 0.17-0.24 (Stockle and Nelson, 2001)
DensApH0	Bulk density	$g\ cm^{-3}$	1.35	1.25-1.35	1.25-1.35 (Stockle and Nelson, 2001)
SAW condition	Soil available water threshold for weed development	%	39	39	
ASWD	Allowable soil water depletion	Dimensionless	0.6	0.6	0.8 (Connor and Fereres, 1999)
	Parameters				
Irrigation	Irrigation	mm	0	0	(Fieldwork, 2013)
SOIL NITROGEN					
	Constants				
HumificationK1 rate	Humification rate of Nfresh organic matter	Dimensionless	0.021	0.021	Panel consensus
Mineralization rate	Mineralization rate of NHumus	Dimensionless	0.004	0.004	Panel consensus
Volatp	Volatilization rate of $NH4^+$	Dimensionless	phvol/100	phvol/100	Panel consensus
Nitrifp	Nitrification rate of $NH4^+$	Dimensionless	0.02-0.04	0.02-0.04	Panel consensus
Inmovp	Immobilization rate of $NO3^-$	Dimensionless	0.008	0.008	Panel consensus
Denitrifp	Denitrification rate of $NO3^-$	Dimensionless	0.01-0.001	0.01-0.001	Panel consensus
Plan NH4resist	Plant resistance to absorbe $NH4^+$	Dimensionless	0.25	0.25	Panel consensus
	Parameters				
StrawResidue	Ratio of straw left on field	Dimensionless	90/100	90/100	(Fieldwork, 2013)
cNBiomass	Ratio of N in the maize biomass	Dimensionless	2.5/100	0.025	(Skowronska and Filipek, 2010)
bNbiomass	Ratio of N in the bean biomass	Dimensionless	3.5/100	0.035	(Waddington, 2003)
Manure N	Nitrogen from manure application	$Kg^{-1}\ ha^{-1} day^{-1}$	0	0	(Fieldwork, 2013)
FRESH OMinit	Initial Fresh Organic matter nitrogen	$kg\ ha^{-1}$	41.24	41.24	Panel consensus
NHumusi	Initial Humus nitrogen	$kg\ ha^{-1}$	150	150	Panel consensus
$NH4_i^+$	Initial amount of	$kg\ ha^{-1}$	40	40	Panel consensus

	$NH4^+$ on soil				
$NO3_i^-$	Initial amount of $NO3^-$ on soil	*$kg\ ha^{-1}$*	10	10	Panel consensus
Type of fertilizer1 maize	Type of first fertilization of maize	*type*	15/15/15	15/15/15	(Fieldwork, 2013)
cF1 product	Dose of product for first fertilization of maize	*$kg\ ha^{-1}$*	234	234	(Fieldwork, 2013)
cF1 pNH4, bF1 pNH4	Percentage of $NH4^+$ into product for first fertilization of maize and bean	%	10.3	10.3	(Fieldwork, 2013)
cF1 pNO3, bF1 pNO3	Percentage of $NO3^-$ into product for first fertilization of maize and bean	%	4.7	4.7	(Fieldwork, 2013)
Type of fertilizer2	Type of second fertilization of maize	*type*	Urea	Urea	(Fieldwork, 2013)
cF2 product	Dose of product for second fertilization of maize	*$kg\ ha^{-1}\ day^{-1}$*	178	178	(Fieldwork, 2013)
cF2 pNH4	Percentage of $NH4^+$ into product for second fertilization of maize	%	46	46	(Fieldwork, 2013)
Type of fertilizer1 bean	Type of first fertilization of bean	*type*	15/15/15	15/15/15	(Fieldwork, 2013)
bF1 product	Dose of product for first fertilization of bean	*$kg\ ha^{-1}$*	39	39	(Fieldwork, 2013)
FOOD					
	Constants				
fMaize Nutrient Database	Energy in white maize	$kcal\ kg^{-1}$	3410	3410	FAO INFOODS (2010)
fBean Nutrient Database	Energy in black bean	$Kcal\ kg^{-1}$	3320	3320	FAO INFOODS (2010)
	Parameters				
Maize consumption reduction	Level of stock to reduce maize consumption	kg	45	45	(Fieldwork, 2013)
Bean consumption reduction	Level of stock to reduce bean consumption	kg	8	8	(Fieldwork, 2013)
cPurchase quantity1	Minimum level of stocks to purchase maize 1	kg	45.36	45.36	(Fieldwork, 2013)
cPurchase quantity2	Minimum level of stocks to purchase maize 2	kg	90.72	90.72	(Fieldwork, 2013)
bPurchase quantity	Minimum level of stocks to purchase	kg	3	3	Half a week family needs of bean (Fieldwork, 2013)

	bean				
Maize storage	Amount of maize stored annually	kg	900	670-970	Panel consensus
Bean storage	Amount of bean stored annually	kg	110	83-171	Panel consensus
No bw	Number of people <3yr	people	1	0.4-1	0.4-1 PNUD (2011)
No Chm	Number of men 3-10yr	people	1	1-2.2	1-2.2 PNUD (2011)
No Chw	Number of women 3-10yr	people	1	1-2.2	1-2.2 PNUD (2011)
No tm	Number of men 10-18yr	people	1	1-1.7	1-1.7 PNUD (2011)
No Am	Number of men 18-30yr	people	1	1.2-2	1.2-2 PNUD (2011)
No Aw	Number of women 18-30yr	people	1	1.2-2	1.2-2 PNUD (2011)
No Em	Number of people 30-60yr	people	1	1.54-2	1.54-2 PNUD (2011)
INPUT Fsize	Family size	people	6.5	6.5	6.5 MAGA (2012)
Family labour	Number of family members working at community off-farm	people	2	1-4	1-4 (Fieldwork, 2013)
Percentage kcal from Bean	Percentage of TEE main food items from Bean	%	14	6.1	6.1 (Serrano and Goñi, 2004), 14 (Saenz de Tejada and Ramírez, 2013)
Percentage kcal from Maize	Percentage of TEE main food items from Maize	%	83	50-70	50 (Mazariegos et al., 2006); 70 (Alarcón and Adrino, 1991); 85 (Arnés et al., 2015)
cpercent loss	Percentage of losses in maize storage	%	25	25	25 (Panel consensus)
bpercent loss	Percentage of losses in bean storage	%	15	15	15 (Panel consensus)
CASH FLOW					
	Parameters				
eScoffee for CASH FLOW	Fraction of total salary from coffee harvest invested into food and agricultural inputs	%	100	1-100	(Oxfam, 2009)
eScommunity for CASH FLOW	Fraction of total salary from community work invested into food and agricultural inputs	%	100	1-100	(Oxfam, 2009)
eDaily wage coffee	Daily wage for a working day on coffee harvest off-farm	€ h^{-1}	0.61375	0.56-0.69	0.56-0.69 (Fieldwork, 2013)
eDaily wage	Daily wage for a	€ h^{-1}	0.3109	0.25-0.36	0.25-0.36 (Fieldwork, 2013))

community	working day at the community off-farm				
fNfarmers coffee	Number of family members working at coffee harvest off-farm	people	1.5	0-4	0-4 (Fieldwork, 2013)
fNfarmers community	Number of family members working at community off-farm	People	1.1	0-4	0-4 (Fieldwork, 2013)
eOther incomes	Incomes from other off-farm activities	€ h^{-1}	226	0-1437	0-1437 (Fieldwork, 2013)
eOther expenditures	Other expenditures	€ h^{-1}	567	5-2751	5-2751 (Fieldwork, 2013)
ecF1pprice	Average cost of fertilizer F1 maize	€ kg^{-1}	0.48	0.48	0.48 (Fieldwork, 2013)
ecF2 pprice	Average cost of fertilizer F2 maize	€ kg^{-1}	0.55	0.55	0.55 (Fieldwork, 2013)
ebF1 pprice	Average cost of fertilizer F1 bean	€ kg^{-1}	0.48	0.48	0.48 (Fieldwork, 2013)
eCorn buyprice	Maize purchase price (function of time, Eq. 150)	€ kg^{-1}	0.29-0.35	0.29-0.37	0.29-0.37 (Fieldwork, 2013); 0.288-0.308 (COSUDE-SICTA-IICA, 2012)
eCorn sellprice	Maize sale price (function of time, Eq. 154)	€ kg^{-1}	0.24- 0.30	0.25-0.31	0.25-0.31 (Fieldwork, 2013)
eBean buyprice	Bean purchase price (function of time, Eq. 151)	€ kg^{-1}	0.68-0.95	0.68-0.95	0.71-0.99 (Fieldwork, 2013)
eBean sellprice	Bean sale price (function of time, Eq. 155)	€ kg^{-1}	0.62-0.87	0.62-0.87	0.62-0.87 (Fieldwork, 2013)

Supplementary Materials Table 4. Model equations used in the Vensim™ submodels. Prefix c (maize) and b (bean). Just fundamental equations are described in this table and some intermediate equations needed for the complete understanding of the model functioning.

Eq.	Units	Equation
	WEATHER	
1	*mm day^{-1}*	***ETP*** *= (1.26*0.8*sora XLS*Units m2 mm by MJ/2.442)*(0.45+0.01*tav XLS*Units day by ºC)*
2	*mm day^{-1}*	***Maximum Evaporation under field conditions (Ec)*** *= MAX (0 , (sqrt(Dsr)-sqrt(MAX(0,Dsr-1)))*(ETP-Trc))*
3	*mm day^{-1}*	***Maximum Transpiration of Maize under standard conditions (cTrc)*** *= ETP*(1-exp(-cKext*cLai))*
4	*mm day^{-1}*	***Maximum Transpiration of Bean under standard conditions (bTrc)*** *= (ETP-cTrc)*(1-exp(-*

		bkext*bLai)) taking into account the fraction of IPAR partitioned to the crop (bR)
5	*mm day^{-1}*	***Actual Evapotranspiration (ETc Dsr)*** *= Ec+Trc*
6	*day*	***No rain counter (wf1)*** *= IF THEN ELSE(Rain XLS=0, 1 , 0)*
7	*day*	***Restart counter if rain (wf2)*** *= IF THEN ELSE(Rain XLS>0, WS1-1 , 0)*
8	*day*	***Days since last rain (Dsr)*** *= wf1-wf2*
9	*day*	***Days of the year (doy)*** *= MODULO(Time, 365) + 1*

CROP DYNAMICS

10	*kg ha^{-1} day^{-1}*	$\boldsymbol{Total\ Growth\ rate\ (TGW)} = rue\ x\ 10\ x\ 0.45x\ Srad\ x\ \left[1 - e^{(-klc\ x\ LAI)}\right] x \min(ETG, EWG, EWDG, ENG)$
11	*none*	$\boldsymbol{Effect\ of\ water\ on\ Growth\ (Ewg)} = \ \forall\, Tr_0 > 0;\ Ewg = \dfrac{Tr}{Tro}\ \ ELSE;\ Ewg = 1$
12	*none*	***Effect of temperature on Growth (Etg)*** *= WITH LOOKUP (tav_XLS,([(0,0)(60,1)],(10,0),(12,0.143),(14,0.286),(16,0.429),(18,0.571),(20,0.714),(22,0.857),(24,1),(26,1),(27,1),(29,1),(30,1),(32,0.7143),(34,0.4286),(37,0),(43,0)))*
13	*none*	***Effect of weeds on growth (Ewdg)*** *= 1-(lc EFFECT OF WEEDS ON GROWTH1+lc EFFECT OF WEEDS ON GROWTH2)*
14	*none*	***lc EFFECT OF WEEDS ON GROWTH1****= lcWC1efy-Reset wc1efy*
15	*dmnl*	***lc EFFECT OF WEEDS ON GROWTH2*** *= lcWC2efy-Reset wc2efy*
16	*dmnl*	***Effect of Nitrogen on maize growth (cEng)*** *= IF THEN ELSE(cPNUp>0 :AND: CPhenstage deriv>0 :AND: NUPTAKEc>0.02 , MIN (1 , MAX(0.4 , NUPTAKEc/cPNUp)) , 1)*
17	*kg*	***Maize potential N uptake (cPNUp)*** *= WITH LOOKUP (MAIZE BIO, ([(0,0)-(9320,100)],(0,0),(1150,11.5), (2330,23),(4660,46),(6990,69),(9320,92))*
18	*none*	$\boldsymbol{Leaf\ area\ index\ (LAI_i)} = \dfrac{CROP\ BIOxLwr}{SLM}$
19	*none*	$\boldsymbol{Ratio\ leaf\ mass\ to\ absolute\ crop\ mass\ (Lwr)} = \ \forall\ \mathrm{PhSTAGE} < 1 : OR: PhSTAGE > 3\ \mathrm{Lwr} = 0;\ \forall\ \mathrm{PhSTAGE} < 2\ \ \mathrm{Lwr} = 1 - (1 - Lwr_{ant})\ x\ (CORN\ PhSTAGE - 1);\ \forall\ PhSTAGE\ < 3; Lwr = Lwr_{mad} x\ (3 - PhSTAGE) + (Lwr_{ant} - Lwr_{mad})$
20	*kg ha^{-1}*	***Accumulated Biomass (CROP BIO)*** *= INTEG (cTGW-cGrnfill-cSenes ,* $\frac{Plantation\ density\ x\ TSWx\ number\ of\ seeds\ per\ hole}{3}$ *)*
21	*none*	***CROP PhSTAGE*** *= (IF THEN ELSE(sow end= 1 :AND: CROP PhSTAGE=0, 1 , 0))+ cf5 - (IF THEN ELSE(CORN PhSTAGE>=3 :AND: CORN DRYING=0 :AND: Deriv cDried cHarvest begin tag<0 , CORN PhSTAGE/dt , 0))*

22	*none*	***BEAN PhSTAGE*** *= (IF THEN ELSE(sow end= 1 :AND: CROP PhSTAGE=0, 1 , 0))+ cf5 - (IF THEN ELSE(BEAN PhSTAGE>=3 :AND: BEAN RIPENING=0 :AND: bHarvest end=1 , BEAN PhSTAGE/dt , 0)*
23	*none*	$\boldsymbol{Phenostage\ rate\ (cf5)} = \forall PhSTAGE = 0 : OR: PhSTAGE > 3\ \ cf5 = 0;\ \forall\ PhSTAG < 2\ \ cf5\ = \frac{MAX\ (0, MIN\ (tav\ XLS, ctxs) - ctb1)}{ctt1};\ \forall\ PhSTAGE < 3\ cf5 = \frac{MAX\ (0, MIN\ (tav\ XLS, ctxs) - ctb2)}{ctt2}$
24	*kg ha^{-1}*	***Grain Yield*** *= IF THEN ELSE(cPhend > 0 , CROP GRAIN/dt , IF THEN ELSE(CROP PhSTAGE>= 3 , IF THEN ELSE(CROP GRAIN/dt > fCROP intake*Units by ha , fCROP intake*Units by ha , 0) , 0))*
25	*kg ha^{-1} dia^{-1}*	$\boldsymbol{Rate\ of\ grain\ filling\ (Gmfill)}\ = \forall\ PhSTAGE > 2 : AND: PhSTAGE < 4; Gmfill = TGW\ x\ 0.3\ \ \ ELSE;\ Gmfill = 0$
26	*mm day*	$\boldsymbol{Root\ penetration\ rate\ (Rpen)} = \ \forall\ PhSTAGE < 1\ Rpen = 0;\ 1 < PhSTAGE < 4 : AND: ROOT\ DEPTH < Rdepthmax;$ $Rpen = Rgrowth;\ ELSE\ Rpen = 0$*; parameters specific for each crop*
27	*kg ha^{-1} dia^{-1}*	***Maize residues and senescence (cSenes) =*** *IF THEN ELSE(cPhend > 0 , (CORN BIO-((cPlDens *TSW*3)/3))/dt , IF THEN ELSE(CORN PhSTAGE>1.6 :AND: CORN PhSTAGE<2.2 , CORN BIO/dt*cSenes rate , IF THEN ELSE(CORN PhSTAGE>=2.2 , CORN BIO/dt*cSenes rate , 0)))*
28	*kg ha^{-1} dia^{-1}*	***Bean residues and senescence (bSenes) =*** *IF THEN ELSE(bPhend delay > 0 , (BEAN BIO-(bPlDens* (bTSW)*4/3))/dt , IF THEN ELSE(BEAN PhSTAGE>1.6 :AND: BEAN PhSTAGE<2.2 , BEAN BIO/dt* bSenes rate1, IF THEN ELSE(BEAN PhSTAGE>=2.2 , BEAN BIO/dt*bSenes rate2 , 0)))+ bTGW*leafsteam ratio*
29	*kg ha^{-1} dia^{-1}*	***Bean nitrogen fixation (bNfix)****=IF THEN ELSE(NTOT inorganic in soil<77, bPNUp*"%Ndfa" , MAX(0,"%Ndfa"*bPNUp*(1-B Sensibility of BNF to Soil N*NTOT inorganic in soil/Units N)))*
30	*dmnl*	***Effect of Nitrogen on bean growth (bEng)*** *= IF THEN ELSE(bPNUp>0 :AND: b Phstage deriv>0 :AND: NUPTAKEb>0.02 , MIN (1 , MAX (0.25 , (bNfix+NUPTAKEb)/bPNUp)) , 1)*
31	*kg*	***Bean potential N uptake (bPNUp)*** *= WITH LOOKUP (BEAN BIO, (([(0,0)-(2500,60)],(0,0),(60,0.1), (125,3.5), (250,4),(450,4),(600,13), (1600,30), (1750,42), (2325,58),(2500,60))*
LABOUR		
32	*h*	***Labour length ª*** $= \frac{Area\ (ha)\ x\ 10000(\frac{m^2}{ha})}{Distance\ furrows\ (m)\ x\ Labour\ Speed\ (\frac{m}{h})}$
33	*h*	$\boldsymbol{Harvest\ length} = \frac{Area\ (ha)\ x\ Crop\ yield\ (kg/ha)}{Wproductivity\ (kg/h)}$
34	*Km.h^{-1}*	***Labour speed =*** *fNfarmers x fwEffTOT x Speed MANUAL Labour (km/h) :OR: Speed PRODUCT Labour (km/h)*
Seed bed preparation		

35	*h*	***Seed bed preparation of maize workload (cSoilp length pulse)*** *= IF THEN ELSE(doy = 95 :AND: LABOUR AVAILABILITY POOL+Max delay labour h >0 ,IF THEN ELSE(cTSP length<400 , cTSP length , 0),0)*
36	*h*	***LABOUR AVAILABILITY POOL*** *=[IF THEN ELSE(LABOUR AVAILABILITY POOL/dt<-Journal h, Journal h , IF THEN ELSE(LABOUR AVAILABILITY POOL/dt>-Journal h :AND: LABOUR AVAILABILITY POOL/dt<Journal h, Journal h-LABOUR AVAILABILITY POOL/dt , 0))]- [cSoilp length pulse+Csow length pulse+cWC1 length pulse+cWC2 length pulse+cF1 length pulse+cF2 length pulse+cBent length pulse+cHarvest length pulse+bHarvest length pulse+bsow length pulse+bF1length pulse+wCoffe length pulse+wCommunity length pulse+cTom irrig labour+b2Soilp length pulse]*
37	*h*	***Seed bed preparation of bean workload (b2Soilp length pulse)****=IF THEN ELSE(bSoilp reset >0 :AND: LABOUR AVAILABILITY POOL+Max delay labour h >0 , IF THEN ELSE(bTSP length<300 , bTSP length , 0), 0)*
38	*day*	***bSoilp reset*** *= IF THEN ELSE(BEAN SOILP START = 1 , BEAN SOILP START*cBent end1 , BEAN SOILP START*(cBent end2-cBent end2a))*
Sowing		
39	*day*	***cBent end1*** *= DELAY FIXED (bSoilp start , 5 , bSoilp start)*
40	*day*	***cBent end2*** *= DELAY FIXED (bSoilp start , 15 , bSoilp start)*
41	*storms*	***Count 3 storms between 1 April-15 May (Stormcount****) = IF THEN ELSE (90 < doy :AND: doy < 136 :AND: Rain XLS > 6.6 :AND: Nstorms<3 , 1, IF THEN ELSE(135 < doy :AND: Rain XLS > 6.6 :AND: Nstorms <3 , 3 , 0))*
42	*storms*	***Storms to sow*** *= IF THEN ELSE(DNstorms3>0, 1 , 0)*
43	*dmnl*	***Maize sow restriction (lScrestrict)*** *= IF THEN ELSE(CSOW PERIOD=1 :AND: LABOUR AVAILABILITY POOL+Max delay labour h>0, 1 , 0)*
44	*h*	***Sowing of maize workload (Csow length pulse)=****IF THEN ELSE (lDeriv Csow begin tag>0 :AND: LABOUR AVAILABILITY POOL+Max delay Sow labour h>0, IF THEN ELSE(cTSow length<100 , cTSow length , 0),0); cTSow length = bArea m2/(Distance between furrows * bSwspd actual*
45	*day*	***Delay to Bsow*** *= DELAY FIXED (Csow end , 5 , Csow end)*
46	*h*	***Sowing of bean workload (bsow length pulse)=****IF THEN ELSE((Delay to bsow1 tag>0 :OR: b2Sow begin tag>0) :AND: LABOUR AVAILABILITY POOL+Max delay Sow labour h>0 , IF THEN ELSE(bTSow length<250 , bTSow length , 0) , 0); bTSow length =bArea m2/(Distance between furrows * bSwspd actual*
Weeding and fertilization		
47	*h*	***Maize Weed Control1 workload (cWC1 length pulse)****=IF THEN ELSE(Der cWC1 begin tag<0 :AND: LABOUR AVAILABILITY POOL+Max delay labour h>0, cTWC1length , 0); cTWC1length=cArea m2/ (Distance between furrows * cWC1spd actual*

48	*day*	***Adequate period for maize weed control 1 (cWC1 begin) =****IF THEN ELSE(1.28<=Round CPhStage :AND: Round CPhStage<=1.31 , 1 , 0)*
49	*dmnl*	***Begining of maize weed control 1(Der cWC1 begin tag)*** *=firstderiv(cWC1 begin, dt)*
50	*h*	***Maize Weed Control2 workload (cWC2 length pulse)=****IF THEN ELSE(Der cWC2 begin tag<0 :AND: LABOUR AVAILABILITY POOL + Max delay labour h>0 :AND: Total days with weed favourable conditions during Wcontrol2 period > 6 :OR: NoWC1>0 , cTWC2 length , 0); cTWC2 length = cArea m2/ (Distance between furrows * cWC2spd actual*
51	*day*	***Adequate period for maize weed control 2 (cWC2 begin)*** *= IF THEN ELSE(1.63<=Round CPhStage :AND: Round CPhStage<=1.66 , 1 , 0)*
52	*dmnl*	***Begining of maize weed control 2 (Der cWC2 begin tag) =****firstderiv(cWC2 begin, dt)*
53	*dmnl*	***Total days with weed favourable conditions during Wcontrol2 period****=IF THEN ELSE(Der cWC2 begin tag<0, CUMULATION OF WEED FAVOURABLE CONDITIONS DAYS DURING WCONTROL2 PERIOD/dt ,0)*
54	*day*	***CUMULATION OF WEED FAVOURABLE CONDITIONS DAYS DURING WCONTROL2 PERIOD****= INTEG (Days with favourable conditions for weed development during WC2 period-Total days with weed favourable conditions during Wcontrol2 period , 0)*
55	*dmnl*	***Days with favourable conditions for weed development during WC2 period****=IF THEN ELSE (WCONTROL2 PERIOD>0 :AND: SAW>85, 1 , 0)*
56	*day*	***WCONTROL2 PERIOD*** *=INTEG(IF THEN ELSE(Der cWC1 begin tag<0, 1 , 0)- IF THEN ELSE(Der cWC2 begin tag<0, WCONTROL2 PERIOD/dt , 0) , 0)*
57	*h*	***Weed control 1 did not take place (NoWC1) =****IF THEN ELSE(cWC1 onoff<1 :AND: LABOUR AVAILABILITY POOL +56>0 :AND: Der cWC2 begin tag<0, 1 , 0)*
58	*day*	***cWC1 onoff =****IF THEN ELSE(cWC1 length pulse>1,1 , 0)- IF THEN ELSE(Der cWC2 begin tag<0, cWC1 onoff/dt , 0)*
59	*dmnl*	***Weed incidence if no weed control 1 (lcWC1efy)*** *= IF THEN ELSE(cWC1 length pulse<1 :AND: Der cWC1 begin tag<0, Effect of weeds on 1st period of corn growth , 0)*
60	*dmnl*	*Reset wc1efy = IF THEN ELSE(cWC2 length pulse>0, lc EFFECT OF WEEDS ON GROWTH1/dt , IF THEN ELSE(Deriv cRipe>0, lc EFFECT OF WEEDS ON GROWTH1/dt , 0))*
61	*dmnl*	***Weed incidence if no weed control 2 (lcWC2efy)*** *= IF THEN ELSE(cWC2 length pulse<1:AND:cWC2 tag>0 :AND: lc EFFECT OF WEEDS ON GROWTH1/dt < Effect of weeds on 1st period of corn growth, Effect of weeds on 2nd period of corn growth1 , IF THEN ELSE(cWC2 length pulse<1:AND:cWC2 tag>0 , Effect of weeds on 2nd period of corn growth2 , 0))*
62	*dmnl*	*Reset wc2efy = IF THEN ELSE(Deriv cRipe>0, lc EFFECT OF WEEDS ON GROWTH2/dt , 0)*
63	*h*	***Maize fertilization1 workload (cF1 length pulse)*** *= IF THEN ELSE(Der F1 begin tag<0 :AND: LABOUR AVAILABILITY POOL+112>0, cTF1 length , 0); cArea m2/(Distance between furrows * cF1spd actual*

64	*day*	***Adequate period for maize first fertilization (cF1begin) =*** *IF THEN ELSE(1.4<=Round CPhStage :AND: Round CPhStage<=1.43 , 1 , 0)*
65	*dmnl*	***Begining of maize first fertilization (Der F1 begin tag) =****firstderiv(cF1 begin, dt)*
66	*h*	***Maize fertilization2 workload (cF2 length pulse)*** *= IF THEN ELSE(Der F2 begin tag<0 :AND: LABOUR AVAILABILITY POOL+112>0, cTF2 length , 0); cTF2 length= cArea m2)/(Distance between furrows * cF1spd actual*
67	*day*	***Adequate period for maize second fertilization (cF2 begin)*** *= IF THEN ELSE(2.04<=Round CPhStage :AND: Round CPhStage<=2.07 , 1 , 0)*
68	*dmnl*	***Begining of maize second fertilization (Der F2 begin tag) =****firstderiv(cF2 begin, dt)*
69	*h*	***Bean fertilization workload (bF1length pulse)*** *= IF THEN ELSE(Der bF1 begin tag<0 :AND: LABOUR AVAILABILITY POOL+56>0, bTF1 length , 0); bTF1 length= bArea m2/(Distance between furrows * bF1spd actual*
70	*day*	***Adequate period for bean fertilization (bF1begin)*** *= IF THEN ELSE(1.38<=BEAN PhSTAGE :AND: BEAN PhSTAGE<=1.42 , 1 , 0)*
71	*dmnl*	***Begining of bean fertilization (Der bF1 begin tag) =****firstderiv(bF1begin, dt)*

7.1.1.1.1 Maize defoliation, bending and harvest

72	*h*	***Bending workload (cBent length pulse)*** *= IF THEN ELSE(Deriv cRipe>0 :AND: LABOUR AVAILABILITY POOL+Max delay labour h>0, cTBent length , 0); cTBent length= cArea m2/(Distance between furrows * cBentspd actual*
73	*day*	***cRipe****= IF THEN ELSE(CORN PhSTAGE>=3, 2 , 1)*
74	*dmnl*	***Begining of bean fertilization (Deriv cRipe)*** *=firstderiv(cRipe , dt)*
75	*h*	***Harvest workload (cHarvest length pulse)*** *= IF THEN ELSE (Deriv cDried cHarvest begin tag<0 , cTHv length , 0); cTHv length =cAREA ha*cYield pulse)/cHvprod actual*
76	*day*	***MAIZE DRYING*** *= INTEG (IF THEN ELSE (CORN PhSTAGE>= 3 :AND: CORN DRYING=0 :AND: cHarv period<1, 60, IF THEN ELSE(Time=0, 60 , 0))- IF THEN ELSE(CORN PhSTAGE>=3 :AND: doy=335 , CORN DRYING/dt , IF THEN ELSE(CORN PhSTAGE>=3 :AND: CORN DRYING>0, 1 , 0)),0)*
77	*day*	***Maize drying period (cDried period)=*** *IF THEN ELSE(CORN DRYING>1, 1 , 0)*
78	*dmnl*	***Begining of maize harvest (Deriv cDried cHarvest begin tag) =****firstderiv(cDried period, dt)*

7.1.1.1.2 Off-farm labour

79	*h*	***Working periods off-farm in Coffee harvest (wCoffe length pulse)****=IF THEN ELSE(LABOUR AVAILABILITY POOL/dt>=Journal h, IF THEN ELSE(BEAN PhSTAGE<1 :AND: doy=349 :OR: BEAN PhSTAGE<1 :AND: doy=15 :OR: BEAN PhSTAGE<1 :AND: doy=46, Off farm Journal h*Yearly worked days offered at Coffee farms/3 , 0), 0)*

80	h	***Working periods off-farm at the community (wCommunity length pulse) =*** IF THEN ELSE(doy>91 :AND: doy<334 , wCommunity max , 0)
81	day	***Maximum days worked Outfarm at the community (wCommunity max) =*** IF THEN ELSE(LABOUR AVAILABILITY POOL/dt>= Journal h :AND: OFFFARM COMMUNITY LABOUR REMAINING/dt<(Off farm Journal h*Monthly work days offered at the Community per household), Off farm Journal h , 0)
		SOIL WATER AND NITROGEN
82	$mm.d^{-1}$	***Water content in layer H0 (WATER H0)*** = INTEG (Rain water+Irrigation-bTrH0-cTrH0-Ea-Infiltration H0 H1, 0)
83	$mm.d^{-1}$	***Water content in layer H1 (WATER H1)*** = INTEG (Infiltration H0 H1-cTrH1-bTrH1-Infiltration H1 H2 , 21.6)
84	$mm.d^{-1}$	***Water content in layer H2 (WATER H2)*** = INTEG (Infiltration H1 H2-cTrH2-bTrH2-Drainage, 41.4)
85	$mm.d^{-1}$	***Actual Maize transpiration in layer H0 (cTrH0) =*** MAX (0 , MIN(WATER H0+Rain XLS ,cTrH0Calc))
86	$mm.d^{-1}$	***Actual Maize transpiration in layer H0 calc (cTrH0Calc)*** = IF THEN ELSE(WATER H0>0 :AND: CORN ROOT DEPTH>0,IF THEN ELSE(WATER H0> SAWmaxH0,MIN(MIN(CORN ROOT DEPTH/ThicknessH0,1)*SAWmaxH0/dt* sqrt(MIN(1,MAX(0,(WATER H0/SAWmaxH0))*Units sqrt correction mm/(SAWmaxH0*ASWD))), cTrc),MIN(MIN(CORN ROOT DEPTH/ThicknessH0,1)*WATER H0/dt *sqrt(MIN(1,MAX(0,(WATER H0/SAWmaxH0))*Units sqrt correction mm/(SAWmaxH0*ASWD))),cTrc)),0)
87	$mm.d^{-1}$	***Actual Bean transpiration in layer H0 (bTrH0) =*** MAX (0 , MIN(WATER H0+Rain XLS-cTrH0Calc , bTrH0Calc))
88	$mm.d^{-1}$	***Actual Bean transpiration in layer H0 calc (bTrH0Calc)*** = IF THEN ELSE(WATER H0>0 :AND: BEAN ROOT DEPTH>0,IF THEN ELSE(WATERH0>SAWmaxH0, MIN(MIN(BEAN ROOT DEPTH/ThicknessH0,1)*SAWmaxH0/dt*sqrt(MIN(1,MAX(0,(WATER H0/SAWmaxH0))*Units sqrt correction mm/(SAWmaxH0*ASWD))),bTrc),MIN(MIN(BEAN ROOT DEPTH/ThicknessH0,1)*WATER H0/dt *sqrt(MIN(1,MAX(0,(WATER H0/SAWmaxH0))*Units sqrt correction mm/(SAWmaxH0*ASWD))),bTrc)),0)
89	$mm.d^{-1}$	***Actual Maize transpiration in layer H1 (cTrH1) =*** MIN(WATER H1+Infiltration H0 H1 ,cTrH1Calc)
90	$mm.d^{-1}$	***Actual Maize transpiration in layer H1 calc (cTrH1Calc)*** = IF THEN ELSE(WATER H1>0 :AND: CORN ROOT DEPTH>ThicknessH0 :AND: cTrc>cTrH0, IF THEN ELSE(WATER H1>SAWmaxH1 , MIN(MIN((CORN ROOT DEPTH-ThicknessH0)/ThicknessH1 , 1)*SAWmaxH1/dt *sqrt(MIN(1,MAX(0,(WATER H1/SAWmaxH1))*Units sqrt correction mm/ (SAWmaxH1 *ASWD))) , cTrc-cTrH0) , MIN(MIN((CORN ROOT DEPTH-ThicknessH0)/ThicknessH1 , 1)*WATER H1/dt*sqrt(MIN(1,MAX(0,(WATER H1/SAWmaxH1))*Units sqrt correction mm/ (SAWmaxH1*ASWD))) , cTrc-cTrH0)) , 0)
91	$mm.d^{-1}$	***Actual Bean transpiration in layer H1 (bTrH1) =*** MIN(WATER H1+Infiltration H0 H1-cTrH1Calc , bTrH1Calc)
92	$mm.d^{-1}$	***Actual Bean transpiration in layer H1 calc (bTrH1Calc)*** = IF THEN ELSE(WATER H1>0 :AND: BEAN ROOT DEPTH>ThicknessH0 :AND: bTrc>bTrH0, IF THEN ELSE(WATER H1>SAWmaxH1 , MIN(MIN((BEAN ROOT DEPTH-ThicknessH0)/ThicknessH1 , 1)*SAWmaxH1/dt *sqrt(MIN(1,MAX(0,(WATER

		H1/SAWmaxH1))*Units sqrt correction mm/ (SAWmaxH1*ASWD))) , bTrc-bTrH0) , MIN(MIN((BEAN ROOT DEPTH-ThicknessH0)/ThicknessH1 , 1)*WATER H1/dt*sqrt (MIN(1,MAX (0,(WATER H1/SAWmaxH1))*Units sqrt correction mm/(SAWmaxH1*ASWD))) , bTrc-bTrH0)) , 0)
93	$mm.d^{-1}$	**Actual Maize transpiration in layer H2 (cTrH2) =** MIN(WATER H2+Infiltration H1 H2 ,cTrH2Calc)
94	$mm.d^{-1}$	**Actual Maize transpiration in layer H2 calc (cTrH2Calc)** = IF THEN ELSE(WATER H2>0 :AND: CORN ROOT DEPTH>ThiknessH0H1 :AND: cTrc>cTrH0+cTrH1 , IF THEN ELSE(WATER H2>SAWmaxH2 , MIN(MIN((CORN ROOT DEPTH-ThiknessH0H1)/ThicknessH2 ,1)*SAWmaxH2/dt *sqrt(MIN(1,MAX(0,(WATER H2/SAWmaxH2))*Units sqrt correction mm/(SAWmaxH2*ASWD))), cTrc-cTrH0-cTrH1) , MIN(MIN((CORN ROOT DEPTH-ThiknessH0H1)/ThicknessH2 , 1)*WATER H2/dt *sqrt(MIN(1,MAX(0,(WATER H2/SAWmaxH2))*Units sqrt correction mm/(SAWmaxH2*ASWD))) , cTrc-cTrH0-cTrH1)) , 0)
95	$mm.d^{-1}$	**Actual Bean transpiration in layer H2 (bTrH2) =** MIN(WATER H2+Infiltration H1 H2-cTrH2Calc , bTrH2Calc)
96	$mm.d^{-1}$	**Actual Bean transpiration in layer H2 calc (bTrH2Calc)** = IF THEN ELSE(WATER H2>0 :AND: BEAN ROOT DEPTH>ThiknessH0H1 :AND: bTrc>bTrH0+bTrH1 , IF THEN ELSE(WATER H2>SAWmaxH2 , MIN(MIN((BEAN ROOT DEPTH-ThiknessH0H1)/ThicknessH2,1)*SAWmaxH2/dt *sqrt(MIN(1,MAX(0,(WATER H2/SAWmaxH2))*Units sqrt correction mm/(SAWmaxH2*ASWD))), bTrc-bTrH0-bTrH1) , MIN(MIN((BEAN ROOT DEPTH-ThiknessH0H1)/ThicknessH2 , 1)*WATER H2/dt *sqrt(MIN(1,MAX(0,(WATER H2/SAWmaxH2))*Units sqrt correction mm/(SAWmaxH2*ASWD))), bTrc-bTrH0-bTrH1)) , 0)
97	$mm.d^{-1}$	**Actual Evaporation (Ea)** = MAX(0, MIN(WATER H0+Rain XLS-cTrH0Calc-bTrH0Calc , EaCalc))
98	$mm.d^{-1}$	**Actual Evaporation calc (EaCalc)** =IF THEN ELSE(WATER H0>0 , IF THEN ELSE(WATER H0>SAWmaxH0 , MIN(SAWmaxH0, Ec) , MIN(WATER H0 , Ec)) , 0)
99	$mm.d^{-1}$	**Actual Water infiltration from H0 to H1 (Infiltration H0 H1)**= MAX(0, MIN(WATER H0+Rain XLS-cTrH0Calc-bTrH0Calc-EaCalc,InfiltrationCalc H0 H1))
100	$mm.d^{-1}$	**Actual Water infiltration from H0 to H1 calc (InfiltrationCalc H0 H1)** = MAX(0,WATER H0-SAWmaxH0)
101	$mm.d^{-1}$	**Actual Water infiltration from H1 to H2 (Infiltration H0 H1)**= MAX(0, MIN(WATER H1+Infiltration H0 H1-cTrH1Calc-bTrH1Calc , InfiltrationCalc H1 H2))
102	$mm.d^{-1}$	**Actual Water infiltration from H1 to H2 calc (InfiltrationCalc H0 H1)** = MAX(0,WATER H1-SAWmaxH1)
103	mm	**Max. soil available water (SAWmax)** = (FC-WP)*DensAp*Thickness*Units g mm by cm3 to mm; parameters specific for each layer
104	$mm.d^{-1}$	**Potential Drainage (DrainageCalc)** = MAX(0,WATER H2-SAWmaxH2)
105	$mm.d^{-1}$	**Actual Drainage (Drainage)** = MAX(0, MIN(WATER H2+Infiltration H1 H2-cTrH2Calc-bTrH2Calc , DrainageCalc))
106	$Kg.ha^{-1}.day^{-1}$	**Addition of fresh organic matter nitrogen (NAGBiomass)**

		*=bSenes*bNbiomass+cSenes*cNBiomass* StrawResidue +Manure N*
107	*Kg.ha^{-1}*	***Nitrogen in Fresh Organic Matter in the soil (NFRESH OM)=*** *INTEG(NAGBiomass-HumificationK1, FRESH OMinit); FRESH OMinit= StrawResidue*cNBiomass*Initial Fresh OM*
108	*Kg.ha^{-1}.day^{-1}*	***HumificationK1 rate =*** *0.021*NFRESH OM/dt*
109	*Kg.ha^{-1}.day^{-1}*	***Mineralization rate =*** *0.004*NHUMUS/dt*
110	*Kg.ha^{-1}*	***Nitrogen in Humus (NHUMUS)*** *= INTEG (HumificationK1+Immobilization-Mineralization, NHumusi)*
111	*Kg.ha^{-1}*	***Amount of ammonia in the soil ("NH4+N")*** *= INTEG (Mineralization+NH4supply+Nfix-NH4uptkb-NH4uptkc-Nitrification-Volatilization , "NH4+i")*
112	*Kg.ha^{-1}.day^{-1}*	***NH4 supply =*** *(NH4cF1 ferti +NH4cF2 ferti+NH4bF1 ferti)*Increase of N supply factor);* ***NH4cF1 ferti*** *=IF THEN ELSE(0<cF1 length pulse, cF1 pNH4* MIN(cF1 product, MAX(0 , SMALLHOLD CASH FLOW/(ecF1pprice*cAREA ha))),0);* ***NH4cF2 ferti*** *=IF THEN ELSE(0<cF2 length pulse , cF2 pNH4* MIN (cF2 product ,MAX(0 , SMALLHOLD CASH FLOW / (ecF2 pprice*cAREA ha))), 0);* ***NH4bF1 ferti*** *=IF THEN ELSE(0<bF1length pulse, bF1 pNH4* MIN (bF1 product , MAX(0 , SMALLHOLD CASH FLOW/ (ebF1 pprice*bAREA ha))),0)*
113	*Kg.ha^{-1}.day^{-1}*	***Potential nitrification rate (Nitrifp)=****IF THEN ELSE (ZIDZ("NO3-N", "NH4+N") <5, 0.04*"NH4+N" /dt, 0.02*"NH4+N"/dt)*
114	*Kg.ha^{-1}.day^{-1}*	***Nitrification rate=*** *IF THEN ELSE (ZIDZ("NO3-N", "NH4+N") <5, 0.04*"NH4+N" /dt, 0.02*"NH4+N"/dt)*
115	*Kg ha^{-1}*	***Amount of nitrite in the soil ("NO3-N")*** *= INTEG (Nitrification+NO3supply-Denitrification-Leaching-NO3uptkb-NO3uptkc-Immobilization , "NO3-i")*
116	*Kg ha^{-1} day^{-1}*	***NO3 supply =*** *IF THEN ELSE(0<cF1 start, cF1 pNO3*cF1 product , IF THEN ELSE(0<bF1start, bF1 pNO3*bF1 product , 0))*
117	*Kg ha^{-1} day^{-1}*	***Potential Immobilization rate=****MAX (0 , 0.008*"NO3-N"/dt)*
118	*Kg ha^{-1} day^{-1}*	***Actual Immobilization rate=*** *MAX (0 , MIN(Nitrification rate+NO3supply+"NO3-N"/dt-Leaching rate , Inmovp))*
119	*Kg ha^{-1} day^{-1}*	***Potential Denitrification rate*** *(**Denitrifp)=**MAX (0 , MIN (NO3supply+Nitrification rate-Immobilization rate-Leaching rate-NO3uptkc-NO3uptkb , Denitrifp))*
120	*Kg ha^{-1} day^{-1}*	***Actual Denitrification rate*** *=IF THEN ELSE(WATER H0>0.75*FCH0*Unit mm :OR: WATER H1>0.75*FCH1*Unit mm :OR: WATER H2>0.75*FCH2*Unit mm, "NO3-N"/dt*0.01 , "NO3-N"/dt*0.001)*
121	*Kg ha^{-1} day^{-1}*	***Volatilization rate****= MAX (0 , MIN (NH4supply+Mineralization rate+"NH4+N"/dt-Nitrification rate, Volatp)); Volatp=(phvol/100)*"NH4+N"/dt*
122	*Kg ha^{-1} day^{-1}*	***Volatility of Nitrogen as a function of Soil ph (phvol) =*** *WITH LOOKUP (Soil ph , ([(0,0)-(10,10)],(1,0),(2,0),(3,0),(4,0),(5,0.004), (6,0.04),(7,0.4),(8,4),(9,40),(10,90)))*
123	*Kg ha^{-1} day^{-1}*	***Potential NH4 uptaken rate by maize calc (NH4uptkcp) =****plant NH4 resist*"NH4+N"*(cTra)/(SAW)*

124	Kg ha^{-1} day^{-1}	***Actual NH4 uptaken rate by maize (NH4uptkc) =*** *IF THEN ELSE((NH4uptkcp+NH4uptkbp) <= ("NH4+N"/dt +Mineralization rate+NH4supply-Nitrification rate-Volatilization rate), MAX (0 ,NH4uptkcp) , MAX (0 , ("NH4+N"/dt +Mineralization rate+NH4supply-Nitrification rate-Volatilization rate)/2))*
125	Kg ha^{-1} day^{-1}	***Potential NH4 uptaken rate by bean (NH4uptkbp) =*** *plant NH4 resist*"NH4+N"*(bTra)/(SAW)*
126	Kg ha^{-1} day^{-1}	***Actual NH4 uptaken rate by bean (NH4uptkb) =*** *IF THEN ELSE((NH4uptkcp+NH4uptkbp) <= ("NH4+N"/dt +Mineralization rate+NH4supply-Nitrification rate-Volatilization rate), MAX (0 , NH4uptkbp) , MAX (0 , ("NH4+N" /dt+Mineralization rate+NH4supply-Nitrification rate-Volatilization rate)/2))*
127	Kg ha^{-1} day^{-1}	***Potential NO3 uptaken rate by maize (NO3uptkcp) =*** *"NO3-N"*cTra/SAW*
128	Kg ha^{-1} day^{-1}	***Actual NO3 uptaken rate by maize (NO3uptkc)=*** *IF THEN ELSE((NO3uptkcp+NO3uptkbp) <= ("NO3-N"/dt +Nitrification rate+NO3supply-Immobilization rate-Leaching rate), MAX (0 , NO3uptkcp) , MAX (0 , ("NO3-N"/dt +Nitrification rate+NO3supply-Immobilization rate-Leaching rate)/2))*
129	Kg ha^{-1} day^{-1}	***Actual NO3 uptaken rate by bean(NO3uptkb)=*** *IF THEN ELSE((NO3uptkcp+NO3uptkbp) <= ("NO3-N"/dt +Nitrification rate+NO3supply-Immobilization rate-Leaching rate), MAX (0 , NO3uptkbp) , MAX (0 , ("NO3-N"/dt +Nitrification rate+NO3supply-Immobilization rate-Leaching rate)/2))*
130	Kg ha^{-1} day^{-1}	***Potential NO3 uptaken rate by bean (NO3uptkbp) =*** *"NO3-N"*bTra/SAW*
131	Kg ha^{-1} day^{-1}	***Leaching rate =*** *IF THEN ELSE(Drainage=0, 0 , MAX (0 , MIN ((Nitrification rate+NO3supply+"NO3-N"/dt) , Drainage *MIN("NO3-N"/SAW , SolubN))))*
FOOD		
132	Kcal fam^{-1} day^{-1}	***Total energy expenditure (fTEEfam) =*** *fBMRfam*fPAL*INPUT Fsize*
133	none	***Potential Physical Activity Level of the family (fPALfam) =****Fsize(fPALbw+fPALtm+fPALam+fPALaw+fPALem+fPALchm+fPALchw)/sum people*
134	none	***Actual Physical Activity Level of the family (fPAL) =*** *IF THEN ELSE(LABOUR AVAILABILITY POOL/dt<Journal h, fPALfam , 1.7)*
135	Kg day^{-1}	***Actual daily family maize intake (Fc consum rate) =*** *MIN(MAIZE STOCK/dt, fMaize intake)*
136	Kg day^{-1}	***Actual daily family bean intake (Fb consum rate) =*** *MIN(BEAN STOCK/dt , fBean intake)*
137	Kcal fam^{-1} day^{-1}	***Daily family maize potential intake (fMaize pot intake) =*** *fTEEfam*Percentage kcal from Corn/fMaize Nutrient Database*
138	Kcal fam^{-1} day^{-1}	***Daily family bean potential intake (fBean pot intake) =*** *fTEEfam*Percentage kcal from Bean/fBean Nutrient Database kcal*
139	Kcal fam^{-1} day^{-1}	***Daily family maize intake with scarcity (fMaize intake) =*** *IF THEN ELSE(MAIZE STOCK<cPurchase quantity2, (MAIZE STOCK*(fTEEfam-fBMRfam*INPUT Fsize)*Percentage kcal from Corn/fMaize Nutrient Database/cPurchase quantity2) +fBMRfam*INPUT Fsize*Percentage kcal from*

		Corn/fMaize Nutrient Database, fMaize pot intake)
140	Kcal fam^{-1} day^{-1}	**Daily family bean intake with scarcity (fBeanintake) =** IF THEN ELSE(BEAN STOCK<bPurchase quantity, (BEAN STOCK*(fTEEfam-fBMRfam*INPUT Fsize)*Percentage kcal from Bean/fBean Nutrient Database kcal/bPurchase quantity)+fBMRfam*INPUT Fsize*Percentage kcal from Bean/fBean Nutrient Database kcal, fBEAN pot intake)
141	none	**Total Work Efficiency as a consequence food requirements satisfaction (fwEffTOT) =** [MAX (0.48 , ZIDZ(Fb consum rate, fBEAN pot intake))+ MAX (0.48 , ZIDZ(Fc consum rate, fMaize pot intake))] /2)*lTech factor
142	Kg	**MAIZE STOCK =** INTEG(Fc Stock in-Fc consum rate-Fc loss-Fc sale, 200)
143	Kg	**BEAN STOCK =** INTEG(Fb stock in-Fb consum rate-Fb loss-Fb sale, 150)
144	Kg ha^{-1}	**Maize production (Production whumidity)** = (AREA ha*Yield + (AREA ha*Yield)*Crop humidity); parameters specific for each crop
145	Kg day^{-1}	**Maize sales (F sale) =** IF THEN ELSE(CROP STOCK/dt>Crop storage, MAX(0 , CROP STOCK/dt-crop storage-F consum rate), 0) parameters specific for each crop
146	Kg day^{-1}	**Maize purchase (cPurchase) =** IF THEN ELSE(MAIZE STOCK<30 :AND: SMALLHOLD CASH FLOW>(cPurchase quantity1*2*eCorn buyprice), cPurchase quantity1 , IF THEN ELSE (MAIZE STOCK<30 :AND: SMALLHOLD CASH FLOW>(cPurchase quantity2*2*eCorn buyprice) , cPurchase quantity2 , 0))
147	Kg day^{-1}	**Bean purchase (bPurchase) =** IF THEN ELSE(BEAN STOCK<3 :AND: SMALLHOLD CASH FLOW-cPurchase*eCorn buyprice> (bPurchase quantity*eBean buyprice) :AND: MAIZE STOCK>35, bPurchase quantity , IF THEN ELSE(BEAN STOCK<3 :AND: SMALLHOLD CASH FLOW-cPurchase*eCorn buyprice>(bPurchase quantity*eBean buyprice) :AND: MAIZE STOCK>91, bPurchase quantity*2 , 0))
148	Kg day^{-1}	**Losses during storage (F loss)** = IF THEN ELSE ((CROP STOCK-F consum rate-F sale)>0 :AND: Production whumidity>100 ,Production whumidity* percent loss , 0); parameters specific for each crop
149	Kg day^{-1}	**Maize shortfall =** fcrop intake-F consum rate; parameters specific for each crop
CASH FLOW		
150	€	**Actual Smallhold Capital for Food purchase and Agricultural Inputs (ASHC FOOD AND AG INPUTS) =** INTEG (((ecommun incomes+ eIncome corn sale+eIncome bean sale+Other incomes)*eS for FAMILY CAPITAL + (ecoffe incomes *eScoffe for FAMILY CAPITAL))- (eCorn Food Expenditure+eBean Food Expenditure+ eF Expenditure + eWC Expenditure+Other expenditures),0)
Expenditures		
151	€.day^{-1}	**Agricultural input and food expenditures (eExpenditures) =** eCorn Food Expenditure+eBean Food Expenditure+ eF Expenditure + eWC Expenditure+Other expenditures
152	€.	**Fertilizer expenditure (eF Expenditure) =** ecF1 Expenses+ebF1 Expenses+ecF2 Expenses

	day^{-1}	
153	*€ day^{-1}*	***Fertilizer expenditure on Fertilization 1 maize (ecF1 Expenses) =*** *IF THEN ELSE(cF1 length pulse>0 ,cF1 Actual product*ecF1pprice*cAREA ha/dt, 0)*
154	*€ day^{-1}*	***Fertilizer expenditure on Fertilization 2 maize (ecF2 Expenses) =*** *IF THEN ELSE(cF2 length pulse>0 , cF2 Actual product*ecF2 pprice*cAREA ha/dt , 0)*
155	*€ day^{-1}*	***Fertilizer expenditure on Fertilization bean (ebF1 Expenses) =*** *IF THEN ELSE(bF1length pulse>0 , bF1 Actual product*ebF1 pprice*bAREA ha/dt , 0)*
156	*€ day^{-1}*	***Herbicide expenditure on Weed Control (eWC Expenditure) =*** *ecWC1 Expenses+ecWC2 Expenses*
157	*€ day^{-1}*	***Herbicide expenditure on Weed Control 1 maize (ecWC1 Expenses)*** *= IF THEN ELSE(cWC1 length pulse>0 , ecWCp dose*ecWCp price*cAREA ha, 0)*
158	*€ day^{-1}*	***Herbicide expenditure on Weed Control 2 maize (ecWC2 Expenses)*** *= IF THEN ELSE(cWC2 length pulse>0 , ecWCp dose*ecWCp price*cAREA ha, 0)*
159	*€ day^{-1}*	***Expenditure on maize purchase (eCorn Food Expenditure) =*** *cPurchase/dt*eCorn buyprice*
160	*€ day^{-1}*	***Expenditure on bean purchase (eBean Food Expenditure) =*** *bPurchase/dt* eBean buyprice*
161	*€ kg^{-1}*	***Purchase price of maize at the community transport included (eCorn buyprice) =*** *WITH LOOKUP (doy, ([(1,0)-(365,1)],(1,0.29),(152,0.33),(244,0.34), (274,0.35),(305,0.29),(365,0.29)))*
162	*€ kg^{-1}*	***Purchase price of bean at the community (eBean buyprice) =*** *WITH LOOKUP (doy, ([(1,0)-(365,1)],(1,0.74),(152,0.844),(244,0.8), (274,0.949),(305,0.949), (335,0.68),(365,0.68)))*
	Income	
163	*€ day^{-1}*	***Income from maize sale (eIncome corn sale) =*** *Fc sale*eCorn sellprice*
164	*€ day^{-1}*	***Income from bean sale (eIncome bean sale) =*** *Fb sale*eBean sellprice*
165	*€ kg^{-1}*	***Sale price of maize at the community (eCorn sellprice) =*** *WITH LOOKUP (doy, ([(1,0)-(365,1)],(1,0.243),(152,0.279),(244,0.288), (274,0.297), (305,0.243), (365,0.243)))*
166	*€ kg^{-1}*	***Sale price of bean at the community (eBean sellprice) =*** *WITH LOOKUP (doy, ([(1,0)-(365,1)],(1,0.674),(152,0.866),(244,0.732), (274,0.77), (335,0.616), (365,0.616)))*
167	*€ day^{-1}*	***Incomes from out-farm labour in coffee plantations (ecoffe incomes) =*** *wCoffe length pulse*eDaily wage coffe*fNfarmers coffee*
168	*€ day^{-1}*	***Incomes from out-farm labour at the community (ecommun incomes) =*** *wCommunity length pulse *eDaily wage community* fNfarmers*

ª Eq. 17: Labour length is the generic equation for duration of soil preparation (cTSP), maize and bean sowing (cTSow, bTsow), maize weed control 1 (cTWC1) and 2 (cTWC2), maize and bean fertilization 1 (cTF1, bTF1) and maize fertilization 2 (cTF2) and maize bent (cTBent), labour speed varies depending on each activity.TSW: Thousand seed weight; SLM: Ratio of leaf mass to leaf area; $Lwr_{ant:}$ Minimum ratio leaf mass to absolute crop mass to anthesis; $Lwr_{mat:}$ Minimum ratio leaf mass to absolute crop mass to maturity; SWC: Soil Water Content in the root area; and Whci:

Available water holding capacity multiplied by maximum Root Depth; tav XLS: Daily average temperatures; ctxs: temperature above which maize development no longer responds to increasing temperature; ctt1: thermal units (C d) from sowing to anthesis; ctb1: base temperature from emergence to anthesis; ctt2: thermal units (C d) from anthesis to maturity; ctb2: base temperature from anthesis to maturity;

Supplementary Materials Table 5. Output values of the model.

Variable Name	Variable description	Units	min	max	mean	SD	Ref. Value or range	References
WEATHER								
ETP	Potential Evapotranspiration	mm day^{-1}	0.1	9.2	4.9	2.48	5-6.67	5-6.67 (Medina et al., 2008)
MAIZE								
MAIZE BIO initial	Initial seed biomass	*kg* ha^{-1}	18.75	18.75	18.75	0.00	25	25 (Tsubo et al., 2005)
cPlDens	Sowing density	Plants ha^{-2}			20833		22000-67000	**22000-67000** (Tsubo et al., 2005)**;** **35000** Bolaños et al. (1993))**;** **53000** (Fuentes López, 2002); **20000-25000 (Carrasco et al., 2009)**
cTGW max	Maximum daily growth	*kg* ha^{-1} day^{-1}	62	320	247	49	100-439	100 (Bolaños, 1995); 160 (Connor et al., 2011); 439 (Soplín et al., 1993)
cLai max	Maximum Lai	m^2 m^{-2}	0.6	5.9	3.0	1.0	3.26-5.59	3.26 CERES-Maize (Lizaso et al., 2011); 3.26-4.85 (*Sonohat et al 1994);* 3.66-4.59 (Amanullah et al., 2007); 5 (Díaz-ambrona et al., 2013); 5.59 (Soplin, 1993)
MAIZE BIO	Total biomass	*kg* ha^{-1}	1153	7403	4976	1493	2000-9000	2000-9000 (Tsubo et al., 2005)
cYield	Yield SASHACA1.0.0	*kg* ha^{-1}	565	2392	1560	560	261-3000	261-1201 (MAGA, 2012); 500-3900 (Sobvio Barrientos, 2008); 1308 (Fuentes-López et al., 2005); 1369-1623 (MAGA, 2013); 1400-1500 (Fieldwork, 2013); 1632 (INE, 2003); 1900-2400 (COSUDE-SICTA-IICA, 2012) 2500-3000 (CEPAL-FAO-IICA, 2014)
cHInd	Harvest Index	*Dimensionless*	0.26	0.37	0.31	0.03	0.3-0.55	0.3-0.37 in Central America (Bolaños, 1995); 0.36 in Peru (Soplín et al., 1993); 0.4-0.55 based on Unstressed Harvest index in Cropsyst (Stockle and Nelson, 2001(Stöckle et al., 2001)
cGrnfill	Length grain filling	*day*	42	46	44	32-60	32-60	(Vargas et al., 2007) 56-60 (Bolaños, 1995)
MAIZE PhSTAGE	Sowing to maturity	*day*	80	87	83	118	118	(Bolaños, 1995)
cSenes	Senescence	*kg* ha^{-1} d^{-1}	1	37	18	50	0-50	(Connor et al., 2011)

BEAN								
bPlDens	Sowing density	*Plants ha^{-2}*			41666		21000-67000	21000-67000 (Tsubo et al., 2005)
BEAN BIO initial value	Initial seed biomass (3seeds/hole)	*kg ha^{-1}*			61.3		45.4-72	45.4 (DICTA, 2012) 50 (Tsubo et al., 2005); 72 (Saenz de Tejada and Ramírez, 2013)
bTGW max	Maximum daily growth	*kg ha^{-1}* day^{-1}	42	169			235-375	235 - 375 (Connor et al., 2011)
bLai max	Maximum Lai	*m^2 m^{-2}*	0.6	3.16			5	5 (Díaz-ambrona et al., 2013)
BEAN BIO	Total biomass	*kg ha^{-1}*	246	1889	1069	416	1000-5000	1000-5000 (Tsubo et al., 2005);
bYield	Yield SASHACA1.0.0	*kg ha^{-1}*	211	1255	636	278	199-900	199.22 - 264.92 (MAGA, 2012); 250-910 Guatemala Frijol criollo (IICA, 2008); 331 Guatemala (INE, 2003); 592.86 in Guatemala, in Oriente Guatemala 800 Chiquimula (FAO-PMA, 2010); 900 Guatemala (COSUDE-SICTA-IICA, 2012)
bHInd	Harvest Index	*Dimensionless*	0.37	0.55			0.45-0.55	0.5 Unstress (Díaz-ambrona et al., 2013); 0.45-0.55 based on Unstressed Harvest index in Cropsyst (Stockle and Nelson, 2001)(Stöckle et al., 2001)
bGrnfill	Length grain filling	*day*	21	42	37		29	29 (Vargas et al., 2007)
BEAN PhSTAGE	Sowing to harvest	*day*	35	70	63		66-80	66-72 (Tapia 1987); 70-75 (Fieldwork, 2013); 70-105 (Wallace and Enriquez, 1980); 72-92 (Yoldas and Esiyok, 2009); 75-90 (Schoonhoven and Voysest, 1991; Voysest, 2000); 80 (Ghamari and Ahmadvand, 2013);
LABOUR								
cSoilp length pulse	Manual soil preparation labour rate	*h.day^{-1}person^{-1} ha^{-1}*	272	367	277	27	270	(Fieldwork, 2013) CALIBRATION SET
Csow length pulse	Maize sowing labour rate	*h.day^{-1}person^{-1} ha^{-1}*	90	115	93	7	89	(Fieldwork, 2013)
bsow length pulse	Bean sowing labour rate	*h.day^{-1}person^{-1} ha^{-1}*	208	378	219	38	195	(Fieldwork, 2013)
cWC1 length pulse	Manual weed control labour rate	*h.day^{-1}person^{-1} ha^{-1}*	284	592	309	87	284	(Fieldwork, 2013)
cF1 length pulse	Fertilization 1 of maize labour rate	*h.day^{-1}person^{-1} ha^{-1}*	86	117	91	10	87	(Fieldwork, 2013)

cF2 length pulse	Fertilization 2 of maize labour rate	*h.day^{-1}person^{-1} ha^{-1}*	63	132	88	30	63	(Fieldwork, 2013)
bF1 length pulse	Fertilization 1 of maize labour rate	*h.day^{-1}person^{-1} ha^{-1}*	60	81	61	6	63	(Fieldwork, 2013)
cBent length pulse	Maize bending labour rate	*h.day^{-1}person^{-1} ha^{-1}*	100	208	140	47	100	(Fieldwork, 2013)
cHarvest length pulse	Maize harvest and post-harvest labour rate	*kg DM h^{-1} person^{-1}*	3.6	7.6	7.1	1.08	7.6	(Fieldwork, 2013)
bHarvest length pulse	Bean harvest, post-harvest and transport labour rate	*kg DM hr^{-1} person^{-1}*	2.6	5.4	5	0.77	5.4	(Fieldwork, 2013)
wCoffee length pulse	Annual working days out-farm coffee	days year^{-1}	31	46	43		46	(Fieldwork, 2013)
WCommunity length pulse	Annual working days out-farm community	days year^{-1}	45	56	51		59	(Fieldwork, 2013)
SOIL WATER								
cTra	Max. Maize transpiration	mm	2.3	7.6	5.4	1.3	1.1-3.3	1.18-3.25 daily average (from 350 kg_{H2O} $kg_{dry\ matter}^{-1}$; Hay and Walker, 1989)
bTra	Max. Bean transpiration	mm	0.4	6.0	2.9	1.6	0.3-1.6	0.31-1.58 daily average (Wakrim et al., 2005)
Ea	Evaporation	mm	0	6.56	0.64	1.38	4.5	4.5 (Insivumeh, 2013)
SOIL NITROGEN								
NFRESH OM	N in Fresh Organic Matter form	Kg ha^{-1}	0.6	191	40	36	29	Panel consensus
NHUMUS	Nitrogen in humus	Kg ha^{-1}	129	422	270	67	46	Panel consensus
$NH4^{+}N$	N in Ammonia in soil	Kg ha^{-1}	11	112	28	11	8	Panel consensus
$NO3^{-}N$	N in Nitrate in soil	Kg ha^{-1}	3	80	34	20	18	Panel consensus
NUPTAKEc	Nitrogen uptake maize	kg ha^{-1}year^{-1}	22	130	85	35	16-54	(N Uptake 2.1% of grain weight) (Bellido, 1991)

NUPTAKEb	Nitrogen uptake bean	kg ha^{-1}year^{-1}	6	76	29	18	54-95	(Westermann et al., 2011)
FOOD								
fTEEfam	Total energy expenditure	kcal day^{-1} person^{-1}	1815	2194	1991	189	1808-2440	1808-2098 (FAO, 2014) 2440 (FAO, 2008),
ANN MAIZE NEED	Maize consumption	kg fam^{-1} year^{-1}	885	1145	1068	79	861-1722	1452 Eastern Guatemala (MAGA, 2012); 1648 (Serrano and Goñi, 2004); 861-1722 (ICTA, 2002)
ANN BEAN NEED	Bean consumption	kg fam^{-1} year^{-1}	179	203	194	7	164-318	164 (IICA, 2008); 318 Eastern Guatemala (MAGA, 2012)
cPurchase	Maize purchase over maize consumption	%	12	56	33	12	25-85	45% (Fieldwork, 2013);In rural Guatemala, 25- 85% of white maize consumption (WFP-PMA, 2008)
bPurchase	Bean purchase over bean consumption	%	0	32	10	9	40-90	64% (Fieldwork, 2013); In rural Guatemala, 40-90% of black bean consumption (WFP-PMA, 2008)
Maize storage	Duration of own maize production	month	2	7.9	6.5	2	8.3	(Fieldwork, 2013)
Bean storage	Duration of own bean production	month	2.4	5.5	5.5	0.9	5.4-7.6	5.4 (Fieldwork, 2013); 7.6 in Camotán (Saenz de Tejada and Ramírez, 2013)
Maize and bean shortfall	Lean months	month		April-October			Jun-September	Jun to September (Bacon et al., 2014)
CASH FLOW								
ANN FOOD Expenditure	Annual expenditure on food	€ year^{-1}	-175	353	82	84	196	(Fieldwork, 2013)
eF Expenditure	Annual expenditure on fertilizer	€ year^{-1}	718	916	787	179	704	(Fieldwork, 2013)
ecoffe incomes	Average annual incomes from work at coffee farms	€ year^{-1}	228	341	326	41	345	(Fieldwork, 2013)
ecommun incomes	Average annual incomes from work at community farms	€ year^{-1}	123	153	133	32	278	(Fieldwork, 2013)
FOOD sale income	Incomes from food sales	€ year^{-1}	0	180	85	49	50	(Fieldwork, 2013)

ª(3seeds/hole)

APPENDIX 1- SURVEY MODEL.

[<u>Nota al encuestador:</u> Las entrevistas van dirigidas SÓLO a los jefes de hogar].

Encuesta de evaluación

A. Encuestador:________________ B. Número de encuesta_____________________
C. Comunidad:_________________ D. Municipio______________________________
E: Fecha entrevista______________ F. Beneficiario UPM______________________

ENCUESTA PARA TIPIFICACIÓN DE PRODUCTORES AGROFORESTALES.

Buen día. Estamos realizando una encuesta a fin de conocer algunos datos generales y de toma de decisión en las tareas agrarias de la población de la comunidad. Todos los datos que nos proporcione serán confidenciales. Siéntase libre de responder la encuesta. No existen respuestas buenas ni malas.

SECCIÓN A: INFORMACIÓN SOCIO-DEMOGRÁFICA.

1. Nombre de la persona entrevistada______________________________________

2. Sexo de la persona entrevistada (1) Masculino (2) Femenino

3. ¿Edad del jefe de hogar?____

4. ¿En los últimos meses, cuántas personas residen habitualmente en esta vivienda?

5. ¿Cuántos de ellos son menores de 15 años?________________________________

SECCIÓN B: CARACTERÍSTICAS AGRÍCOLAS.

1. ¿Cuánta extensión ocupan todas sus propiedades (en uso o no)?. Hacer un dibujo.

2.1 ¿Arrenda algún terreno para cultivar?____

2.2 ¿Cuánto paga en total?____

3.1 ¿La superficie o la distribución de los cultivos que siembra es cada año la misma?_____

3. 2 De que depende la variación entre un año y otro.
EXÓGENOS:

a) Rendimientos del año anterior o problemas en algún cultivo (enfermedad, plaga)
b) Precios de compra-venta
c) Clima de años-meses precedentes
d) Introducción de un cultivo más rentable
e) Precio de la tierra (alquiler, compra…)
f) Otros

ENDÓGENOS:

g) Tengo suficiente <u>pisto</u> (para manejar bien mi parcela, fertilización, alquiler…)
h) Tengo suficiente <u>tierra</u> disponible
i) Tengo suficiente <u>tiempo</u> para poder dedicarle a ese cultivo
j) Tengo suficiente <u>fuerza de trabajo</u> (sin pagar) como para poder dedicarle a ese cultivo

4.3 ¿Si no tuviera limitación de inputs (pisto, tierra, tiempo, fuerza de trabajo) cómo distribuiría la superficie dedicada a cada cultivo?____

5.1 ¿El cultivo de maíz y frijol se realiza en asocio?___________________________________
5.2 ¿Por qué prefiere esta opción?____

6. Característica generales del uso del suelo.

Cultivo	Área cultivada	Tenencia	Pendiente	Cuales	Manejo	Rendimiento	Distancia	Riego
Maíz				X				
Frijol 1ª				X				
Frijol 2ª				X				
Café								
Hortalizas		X	X		X	X	X	
Frutales		X	X		X	X	X	
Pastos			X	X	X	X	X	X
Monte grueso			X	X	X	X	X	X
Bosque			X			X		X

ª Pendiente: 1=Plano o casi plano (0-5%); 2=Moderadamente inclinado (5-15%); 3= Muy inclinado – inadecuado (>15%)

7. En el caso de cultivar granos básicos. ¿Qué variedades cultiva? (Criolla, certificada, mejorada)

Cód.	Cultivo	Variedad (**MESES** que dura el ciclo)
1	Maíz	
2	Fríjol primera	
3	Frijol segunda	
4	Café	

8. ¿Qué activos agrícolas posee su familia?

		2. ¿Cuántos tiene actualmente?	3. ¿Cuánto paga por ella al año?
Cód.	Nombre		
1.	Silo/granero		Cap(qq):
2.	Agua (pila/pozo/manantial)		
3.	Bomba de fumigación		
4.	Electricidad		

5.	Celular-cobertura		

9. ¿Qué animales posee su familia?

		ALIMENTACIÓN			INGRESOS		
Cód.	Nombre	Cantidad	Frec. alimentación	Frec. derivados	Venta (ud/año)	Precio (Q/ud)	Cuando venta (mes- época)
1	Gallina						
2	Patos						
3	Chumpes						
4	Coche						
5	Vaca						

10. ¿Qué alimentos come su familia?

		ALIMENTACIÓN		INGRESOS		
Cód.	Nombre	Frec. alimentación	Cantidad (lb/semana, mes) (con o sin pollos)	Venta (qq/año)	Precio (Q/qq)	Cuando venta (mes-época*)
1	Maíz					
2	Frijol					
3	Café					
4	Hortalizas					
5	Frutas					
6	Otros					

*Época: especificar causa de venta (x fertilizante, x enfermedad…)

11.1 Trabajo como asalariado

Cod	Concepto	Café fuera comunidad	Asalariado en comunidad u otro
1	Nº personas/ hogar		
2	Meses		
3	Nº días/mes		
4	Jornal (Q/día)*		

*Si dice Q/qq, indicar el nº de qq medio al día que cosecha y calcular.

11.2 ¿Qué actividad considera más importante o prioritaria, la agricultura propia o como asalariado?
____

12.1 ¿Recibe algún ingreso proveniente de alguna otra actividad (artesanías, remesas, arrendamiento de terrenos, venta de algún producto ?________________________________
12.2 ¿Cuánto al año?____

SECCIÓN C. PARTICIPACIÓN EN ORGANIZACIONES COMUNALES.

1. ¿Participa usted o algún miembro de su familia en algún programa de capacitación o asistencia técnica? (1) Si (0) No
2. ¿Cómo se seleccionan los participantes?
(1) Voluntarios (2) Votación democrática (3) Amistad-Familiares
3. ¿Cada cuanto tienen reuniones? ____

SECCIÓN D. ESTABLECIMIENTO DE LA TOMA DE DECISIÓN EN LOS PROCESOS PRODUCTIVOS DEL MAÍZ y FRIJOL

1. CUADRO DE TOMA DE DECISIÓN DE LOS PROCESOS PRODUCTIVOS DEL CULTIVO DE MAÍZ primera

a. ¿Cuál es el área dedicada al maíz? ____

Nº	1	2	3			4		5	6
b. CODIGO Pregunta	**L**	**S**	**D1**	**D2**	**D3**	**F1**	**F2**	**Doblado**	***C (Tapizca, destuse y acarreo)**
1. ¿Cuántas veces al año?									
2. Mes									
3. ¿Cómo? Manual (chuzo, machete, azada) o Nombre productos									
4. Cantidad input	qq/lb/L:	qq:	qq/lb/L:	qq/lb/L:	qq/lb/L:	qq:	qq:		qq:
5. Inicio									
6. ¿XQ en ese momento?									
7. Límite (si todo sale mal)									
8. Personas									
9. Tiempo (días/superficie)									
10. Otras actividades en el mismo tiempo de frijol y café									

L: Limpia y preparación del terreno, S: Siembra, D1: Desherbado 1, D2: Desherbado 2, D3: Desherbado 3, F1: Fertilización 1; Fertilización 2

c- ¿Qué hacen con el maíz después de la tapisca (post-cosecha)?_______________
d- ¿Cuándo, mes? ______________
e- ¿Quienes? ____________
f_ ¿Cuánto tardan?_______________

2. CUADRO DE TOMA DE DECISIÓN DE LOS PROCESOS PRODUCTIVOS DEL CULTIVO DE FRIJOL primera

2.1.¿Cuándo siembra?____

2.2. ¿Cuál es la fecha límite para el comienzo de la siembra?____

2.3. ¿Por qué motivo esa es la fecha límite y no sembraría más tarde?____

2.4. Insumos:

Nº	1			2	
Código	**D1**	**D2**	**D3**	**F1**	**F2**
1. Inicio					
2. Nombre del producto					
3. Cantidad (qq, L, lb/superficie)					
4. Precio (Q/(qq, L, lb)					

L: Limpia y preparación del terreno, S: Siembra, D1: Desherbado 1, D2: Desherbado 2, D3: Desherbado 3, F1: Fertilización 1; Fertilización 2

2.5. ¿Cuándo cosecha?____

2.6. ¿Fecha límite para el comienzo de la cosecha?____

2.7. ¿Por qué motivo esa es la fecha límite y no cosecharía más tarde?____

3. CUADRO DE TOMA DE DECISIÓN DE LOS PROCESOS PRODUCTIVOS DEL CULTIVO DE FRIJOL segunda

a.¿Cuál es el área dedicada al frijol de segunda? ____

Nº	**1**	**2**	**3**			**4**		**5**
b.CODIGO Pregunta	**L**	**S**	**D1**	**D2**	**D3**	**F1**	**F2**	**C (Arranque, aporreo y acarreo)**
1. ¿Cuántas veces al año?			X	X	X	X	X	X
2. Mes								
3. ¿Cómo? Manual o Nombre productos								
4. Cantidad input	qq/lb/L:	L b o qq:	qq/lb/L:	qq/lb/L:	qq/lb/L:	qq:	qq:	qq:
5. Inicio								
6. ¿XQ en ese momento?			X	X	X	X	X	
7. Límite (si todo sale mal)								
8. Personas								
9. Tiempo (días/superficie)								

L: Limpia y preparación del terreno, S: Siembra, D1: Desherbado 1, D2: Desherbado 2, D3: Desherbado 3, F1: Fertilización 1; Fertilización 2

c- ¿Qué hacen con el maíz después de la tapisca (post-cosecha)?_______________
d- ¿Cuándo, mes? ______________
e- ¿Quienes? ____________
f_ ¿Cuánto tardan?_______________

4. TOMA DE DECISIÓN DE LOS PROCESOS PRODUCTIVOS DEL CULTIVO DE CAFÉ

4.1 Su plantación de café mayormente es: a) De siembra (0-4 años) b) De producción (+ de 4 años)
4.2 ¿Cuántos desherbados realiza? ____
4.3 ¿Cuándo realiza cada uno? 1º) __________ 2º)_________ 3º)__________ 4º)__________
4.4 Tipo de desherbado (producto o mecánico): 1º) __________ 2º)_________ 3º)__________ 4º)__________
4.5 Cantidad de producto: 1º) __________ 2º)_________ 3º)__________ 4º)__________
4.6 Personas empleadas: 1º) __________ 2º)_________ 3º)__________ 4º)__________
4.7 Tiempo empleado: 1º) __________ 2º)_________ 3º)__________ 4º)__________

4.8 ¿Cuántas fertilizaciones realiza? ____
4.9 ¿Cuándo realiza cada una? 1º) __________ 2º)_________ 3º)__________ 4º)__________
4.10 Nombre del producto: 1º) __________ 2º)_________ 3º)__________ 4º)__________
4.11 Cantidad de producto: 1º) _________ 2º)_________ 3º)__________ 4º)__________
4.12 Personas empleadas: 1º) _________ 2º)_________ 3º)__________ 4º)__________
4.13Tiempo empleado: 1º) _________ 2º)_________ 3º)__________ 4º)__________

4.14 ¿Cuántas tratamientos contra plagas realiza? ____
4.15¿Cuándo realiza cada una? 1º) __________ 2º)_________ 3º)__________ 4º)__________
4.16 Nombre del producto: 1º) _________ 2º)_________ 3º)__________ 4º)__________
4.17 Cantidad de producto: 1º) __________ 2º)_________ 3º)__________ 4º)__________
4.18 Personas empleadas: 1º) _________ 2º)_________ 3º)__________ 4º)__________
4.19Tiempo empleado: 1º) _________ 2º)_________ 3º)__________ 4º)__________

4.20¿Cuándo cosecha? ________________________
4.21¿Cuántas pasadas realiza? _________________
4.22¿Cuánto tarda en realizar cada pasada (días)?

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