Agricultural Systems 164 (2018) 152–164

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Building and evaluation of a dynamic model for assessing impact of smallholder endowments on food security in agricultural systems in highland areas of central America (SASHACA)

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ARTICLE INFO

Keywords:
Bean
Intercropping
Maize
Modelling, nutrition
Sustainable development

ABSTRACT

Smallholder agricultural systems have an important role in world food production. 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 incomes to supplement their own production from market sources. Modelling offers an approach for testing and improving knowledge about complex systems. The aim of this paper is to describe and assess a biophysical and socio-economic model of the smallholder agricultural systems based on maize-bean intercropping in highland areas of Central America. A Vensim® DSS system dynamics model was developed for assessing the impact of Smallholder endowments on food security and to identify critical points to achieve sustainable food security and poverty alleviation in Agricultural Systems in Highland Areas of Central America (SASHACA). 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 respectively. The model proved to be adequate for assessing food security under scenarios in low data availability areas. The SASHACA model could be adapted to simulate a wide range of smallholder agricultural systems in highland areas of Central America, and potentially in other locations.

1. Introduction

Agriculture is strategically important for the post-2015 development agenda (Ki-Moon, 2014). It is an important employer (UNCTAD, 2013) and driver of economic growth in low income countries. The International Assessment of Agricultural Knowledge, Science and Technology for Development places smallholder farmers at the heart of sustainable food, nutrition security and poverty reduction (IAASTD, 2009; FAO, 2012). Half of the world's population live in rural areas and two in five people derive their livelihoods directly from smallholder agricultural production systems (FAO, 2008a). Smallholders often live in remote and environmentally fragile locations and are frequently a 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 (795 million people; FAO etal., 2015) are smallholder farmers living in developing countries with agriculture and food production as their core business (Dioula etal., 2013). This paradox is explained by the number of challenges faced by the smallholder farmers, including production constraints, land policy, lack of investment, and social and environmental constraints (Dioula etal., 2013; Jansen etal., 2006).

The process-based modelling techniques of system dynamics (SD) are a powerful tool to assess the complex interactions between smallholder decision-making and the dynamics of the environmental system upon which their livelihoods depend (Stephens etal., 2012; Verburg

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https://doi.org/10.1016/j.agsy.2018.02.005
Received 25 March 2016; Received in revised form 22 February 2018; Accepted 28 February 2018
0308-521X/

etal., 2004). SD models are able to represent the evolution and adaptation of the system under different scenarios (climate, policies, shocks, and other changes) and test hypotheses without the need to physically repeat experiments at different locations or over time. Thus, models allow exploration of possible future scenarios, and can save money and time (Lee etal., 2008; Matthews and Stephens, 2002). SD models may provide greater flexibility to represent dynamic interactions and feedback effects compared to conventional econometric or mathematical programming models (Stephens etal., 2012). Humans are an integral part of such systems, both influencing and being influenced by them (Matthews, 2007). To assess the functioning of livelihood strategies in smallholder agricultural systems one should focus on the critical issues related with smallholder agriculture: 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 policies, and food prices (Rodríguez etal., 2008.

The real impact of socio-economic and environmental factors on smallholder agricultural systems depends on 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 etal., 2004). The integration of crop and soil (Tittonell etal., 2007, 2008), labour (Van Wijk etal., 2009), human nutrition, economic, and social models (Connor etal., 2008; Pfister etal., 2005) has already entered the literature. Nevertheless, further development will improve confidence in their ability to represent the diversity of agricultural systems (Le Gal etal., 2011; Parsons etal., 2011a).

One of the biggest constraints that farmers in mountainous areas face is that the land they cultivate is often more suitable for permanent forestry than for agriculture. Hillsides are defined as areas with slopes of more than 12% (Jansen etal., 2006). Tropical hillsides in Latin America, Africa, and Asia cover 13.4% (13 million km^2) of the landmass (CGIAR, 1999) with about 525 million people living and farming on these lands. In Central America, roughly 79% of total land area is classified as hillside (Fuentes López etal., 2005; GCARD, 2010). About 60% of land used for agriculture and livestock in Central America is located in hillside areas (IICA etal., 1997). In these areas the main smallholder economic activities are production of grains, coffee, and livestock. Agricultural potential in hillside areas is constrained by factors such as altitude, weather, soil characteristics, level of mechanization, access to market, and farm size. Food security is the main objective of most smallholders living in hillside areas (Jansen etal., 2006). According to FAO (2016) “Small-scale producers and rural communities in the Dry Corridor of Central America, remain the most vulnerable to drought, which is an important socio-economic phenomenon given its effects on the loss of livelihoods, decapitalization of household economies, impoverishment and migration to over-populated urban centres”. The significant reduction in agricultural production due to droughts causes a risk of the depletion of food stocks, decreasing dietary diversity and energy intake.

Smallholder agricultural systems in hillside areas of Central America were chosen as the target region on which to base model development, and we used a study case in Guatemala to calibrate and evaluate the model. The agricultural sector in Guatemala represents the 13.6% of the domestic economy (INE, 2014). Of the national land, 80% is considered hillside, and 30% of arable land is hillside. In this region 55% of maize (*Zea mais* L.) is produced in smallholder farms smaller than 3.45 ha (Fuentes López etal., 2005). Although smallholder farming systems are diverse, we aimed to represent the main common elements of their livelihood strategies. Staple and off-farm employment are the dominant livelihood activities in highland Guatemala.

The issue is that the subsistence smallholders are joint producer-consumers, with insufficient food or income to supplement their own production from market sources. The objective of this paper was to build a model with the aim of better understanding the complex relationships between biophysical (weather variability and environmental conditions) and economic endowments and welfare for smallholder farmers in hillside areas. We developed and applied a model to identify drivers and critical points in relation to food security and poverty of the households. Drivers and critical points steer sustainability of the agricultural system and it is important to identify the ones acting as bottlenecks to step out of the poverty cycle and achieve sustained food security. Also, since sustainability is by definition dynamic, it is interesting to assess evolution of the system over time (Barreteau etal., 2004). The model is meant to be used as a tool for decision makers to explore different scenarios (weather, policies, technologies, demographic trends etc.).

The key contribution of our work to the modelling literature is the integration of an agronomic model (crop growth, soil and weather) with labour, nutrition, economic, social, and farmer decision-making patterns, allowing assessment of drivers, critical points and evolution of agricultural systems in hillside areas of Central America. The inclusion of aspects such as crops dynamics and weather in the model allows simulation of climatic change scenarios.

We evaluate the model through a broad set of indicators to rigorously assess model performance. This paper is divided into two parts. The first part defines the study area and data collection process, and explains the development of the model and the assumptions made. It also describes the tests undertaken for assessing the performance of the model, and the calibration and independent evaluation procedures. The second part presents the results and discussion of model behaviour and limitations for its application. A subsequent paper will describe performance of the model and the implications of the results when applied to a case study in Guatemala.

2. Methods

2.1. Study area and data collection

The study was located in the Dry Corridor, in the south-easternGuatemalan region of Chiquimula, municipality of Camotán. Annual precipitation varies from 1200 to 1700 mm/year. The annual average temperature varies from 16 °C to 34 °C (INSIVUMEH, 2013). About 95% of Camotán land has forestry as the recommended land-use (SINAFIP, 2004), in an area of mountains and hillsides, with altitudes ranging from 334 to 1760 m.a.s.l. Just 5% is considered suitable for farming (MAGA, 2001; SINAFIP, 2004). The rest is occupied by natural pastures, highly eroded and degraded areas abandoned for their recovery after use for rain-fed agriculture, and beaches (SINAFIP, 2004). The population density is around 144 inhabitants km^{-2}(FAO-PESA, 2011, FAO-PESA 2013). Camotán has a poverty level of 54% (SINAFIP, 2004) and an undernourished population three times the average for Guatemala(FAO-PESA, 2011). Agriculture is the main livelihood for 91% of the economically active population (89% SINAFIP, 2004; 91% SEGEPLAN, 2010). The average population growth rate is 3.97% which means that in an 18-year period the population will double. The typical family size in the region is about 6.5 people per family (MAGA, 2012). The main productive activities 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). Maize and bean are the base of the Guatemalan diet. Their consumption in rural areas are approximately 2.8 and 6.6 times greater than the national average, respectively (50%–85% of total caloric intake in Alarcón and Adrino, 1991; FAO,