Rethinking agriculture in a shrinking world: operationalization of resilience with a System Dynamics perspective

Herrera, Hugo. Palermo University*
Kopainsky, Birgit. Bergen University

Abstract

It is needed to rethink the way we design and manage agriculture systems in order to face the unavoidable challenges that undeniable global climate change carries with it. This paper contributes to this process by proposing a framework to operationalize resilience into system dynamics models. Resilience is a broad concept that includes the creation of resilience, flexibility and adaptability of systems to unexpected disturbances. Rethinking agricultural systems from a resilience perspective is needed to ensure their ability to continue providing enough food. System dynamics simulations can support decision makers in this process by providing holistic representations of the interconnected systems (economic, social and environmental). However, there is no clear framework to operationalize and measure the concept of resilience into system dynamics models. The present paper contributes to fill-in this gap, by proposing a framework to evaluate resilience in that context. This proposed framework is used to compare different policies to improve the maize production of Jutiapa, Guatemala and to analyse the structural causes of their differences. The results, observed in the case, show the usefulness of our approach and constitute a step in the integration of resilience into system dynamics models.

Keywords: *resilience, agriculture, agricultural systems, food security, system dynamics.*

1. Introduction

Climate change is an unavoidable fact (Anderies & Jansen 2013) and it observed effects on social, economical and ecological systems are expected to increase in the upcoming years (Jones & Thornton, 2003; Parry et al. 2004). One of the most vulnerable systems to these changes is agriculture. Agricultural system is a specific type of food system that focuses on cultivating soil, producing crops and raising livestock (McConnell and Dillon, 1997). Since agricultural systems are highly vulnerable to climate change effects and stresses (Cutter et al., 2008; Milman and Short, 2008), they require management that enhances their possibilities to achieve sustainable food production in changing environments (Rockström, 2003). In particular, we focus on the resilience management as a way to enhance the resistance and adaptation capacity of agriculture systems to climate change effects.

Agriculture without risk would be unrealistic expectation (Maleksaeidi and Karami, 2013), hence managerial practices need to properly oversee potential: crises, external stresses and shocks; all of that without compromising the system's capability to produce food and human or ecosystem wellbeing (Cutter et al., 2008; Milman and Short, 2008). This need to cope with risk requires of a shift of paradigm, from a focus on efficiency to a more integral perspective. This new perspective needs policy makers to rethink the practices currently used and promoted in agriculture (Chapin et al., 2009). New paradigms and policies need to be able to enhance systems' robustness and capacity of adaptation as a mean to secure their outputs in a dynamic environment (Cutter et al., 2008; Milman and Short, 2008).

*Corresponding author:
H. Herrera
Hugo.Leon@student.uib.no
Department DEMS- University of Palermo
Via Ugo Antonio Amico 3
90100 Palermo (Italy)

Resilience is commonly defined as the capacity of a system to absorb disturbance and reorganize itself to still retain essentially the same function, structure, identity, and main feedbacks (Walker et al. 2004). In particular, when it is applied to socio-ecological systems, resilience is defined as "the process of using a set of resources abilities and adaptive capacities to absorb disturbance while conserving self-organization and enabling recovery" (where is this citation from?). In this context, we understand system's resilience as a necessary condition for sustainability since resilient system will respond better to external stresses, retaining the desirable state of the system and adjusting it structure to cope with the changes in the environment (Hansen, 1996,118).

System's resilience is based on the internal system's mechanisms that allow it to balance the stresses in the system and reorganize itself (Chaplin et al., 2009). However, agriculture systems are complex and involve not only environmental but also social and economic systems. System`s complexity and uncertainty makes it hard to operationalize, measure and evaluate system's resilience (Frankenberger et al., 2012). There is a need to "confront the difficulty of measuring resilience as interventions focused on building resilience at multiple scales" (FSIN, 2014). Therefore, in the present paper we contribute to close this gap by proposing a framework to operationalize and evaluate resilience in System Dynamics (SD) models.

The present paper builds over the work done by Stave and Kopainsky (2014) to conceptualize resilience using SD simulation models. System dynamics is a modelling simulation technique grounded in the assumption that the observed behaviour of a system is the result of the relations between its different components (dynamic complexity). By acknowledging the dynamic complexity of the system, SD can contribute to exploration of the mechanisms that contribute to: a) keeping the system in equilibrium and b) reacting to different disturbances. By using SD to evaluate resilience of agriculture systems, it is possible to support a shift on decision makers understanding of the systems and potential policy interventions. So far there were few research using SD to evaluate resilience in Social Ecological Systems (SES) (Stave and Kopainsky, 2014), and the policies that can enhance it.

In particular, this paper proposes a framework that allows to: a) evaluate and compare resilience in SD models and b) identify leverage points that could enhance resilience. The paper proceeds as follows; first, we briefly describe resilience in the context of agriculture systems sustainability and climate change adaptation. Then, we describe the proposed framework and present the results of applying it to the study case of maize production in Guatemala. Finally, we outline next steps and further research to follow this paper.

2. Resilience and sustainability of agriculture systems.

2.1 Food and agriculture systems

Food systems are usually conceived as a set of activities to supply food from production to consumption, including intermediate activities as packing, transport and retail (Ericksen et al., 2008; Heller and Keoleian, 2003). Food systems include: cageling, fishery and the ones of particular interest of this research, agricultural systems.

Agricultural systems have evolved as a combination of social and ecological systems (Norgaard, 1984). Agricultural systems include mutually dependent social and ecological components and their outcomes depend not only of natural factors but also directly and indirectly of human decisions (Berkes and Folke, 1998). In particular, societies needs and values determine which ecosystem services (ES) – benefits that society receives from ecosystems (Chapin et al. (2009) – are more important than others. These preferences influence the understanding of what is the role of a particular ecosystem in the society and the trade-offs between different ES. For instance, some societies may understand that crop production is the main ecosystem service they required from a specific area. The decision to devote land to agriculture itself represents a trade-off with other ES the land could provide, like housing, recreation or scenery. Moreover, seeking more productivity and efficiency, the society may decide to compromise other ES like biodiversity (in monoculture for example), carbon sequestration (replacing forest by plantations) or even its own safety (by introducing transgenic crops).

Ericksen et al. (2008) classify the activities in food systems into four groups: a) producing food, b) processing and packing, c) distributing and retailing food and d) consuming food. Nevertheless, this paper is focused only on the first group. Production of food includes all the activities related to the production of raw materials, in our case crops and vegetables. These activities include planting, caring for plantations and harvesting and require many different social and ecological resources like capital, land, water and labor.

Figure 1 shows the expected outcomes of food systems. These outcomes can be grouped in three main categories: a) food security, b) social welfare and c) environmental capital (Ericksen et al., 2008). These outcomes are used in the present research as the main performance indicators of agricultural systems. Table 1 provides a summarized definition of these outcomes. Even though all the contributions are important and are closely related, in this paper we decided to focus only on the outcomes contributing to food security and specifically only in the elements: production, affordability and nutritional value (see Figure 1).

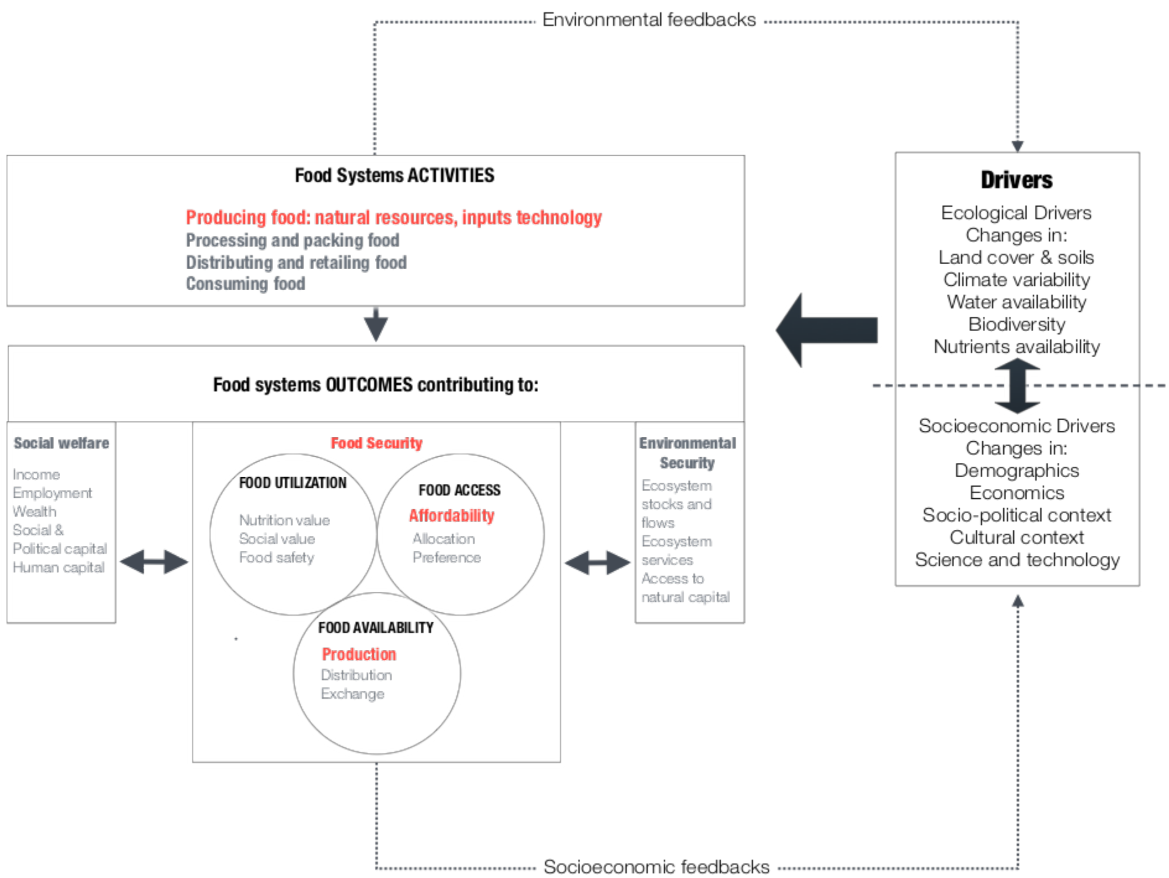

Figure 1. Components of food systems
Note: Adapted from Ericksen et al. (2008, p. 239 Figure b)

Table 1
Outcomes of food systems

Outcome	Definition
Food security	"When all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (p.234). Its three major components are: • *Food availability*: including the production, distribution and trade of food • *Food utilization*: including the food's nutritional and social value as well as food safety. • *Food access:* including affordability, allocation of food and the preferences of the consumers
Environmental capital	The creation and conservation of the natural capital (land, water and biological resources) needed to supply and sustain the ecosystem services associated with the food systems.
Social welfare	Side economic and social benefits provided by the food systems as income, employment, human capital and wealth.

Note: Adapted from Ericksen et al. (2008)

Agricultural systems performance and outcomes are highly vulnerable to climate change as was determinate by the FAO/IIASA Agro-ecological Zones (AEZ) model (http://www.fao.org/nr/gaez/programme/en/), when it was assessed within the socioeconomic scenarios defined by the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions (SRES) (Fischer et al., 2002). Vulnerability is understood as the "degree to which a system is likely to experience harm due to exposure to a specified hazard" (Chapin et al., 2009). Since agricultural systems convene many social and ecological components interconnected, they are vulnerable to social, economical and environmental disturbances and stresses. We focus in this paper on the environmental vulnerability of agricultural systems, in particular, their vulnerability to climate change effects.

Climate change is expected to have unpredictable effects on the outcomes of the food systems (Ericksen et al., 2008). In particular, in the case of agriculture systems, global warming, droughts, floods, increase of pest and disease infestations can be anticipated as potential disturbance (Fischer et al., 2002). Therefore, we need to rethink the way we manage agricultural systems to consider not only the optimization of their outcomes, but also ensure their sustainability over time and enhance their resilience to environmental changes.

2.2 Sustainability of agriculture systems

Sustainability is a broad concept that includes understanding, interactions and management not only of ecological systems but also of social systems and the relations between both. In that sense sustainability looks to the links between social and ecological process in order to manage them to "meet the needs of the present without compromising the ability of future generations to meet their own needs" (Chapin et al. 2009).

Particularly, in the context of agriculture systems, Ikerd (1996) defines sustainable agriculture as a system capable to maintain productivity and effectiveness to society in the long run. However, to this definition it should be added that the system must also be environmentally friendly and resource conserving, economically viable, socially supportive and commercially competitive (Rigby and Caceres, 2001).

In a more practical sense, this concept of sustainability is summarized by the performance of any agricultural system on three components (Hayati et al. 2011): ecological, economic and environment. The ecological component refers to the preservation and improvement of the natural environment, the economic component refers to maintenance of yields and productivity of crops, and the social component refers to self-reliance, equality and improved quality of life (Forouzani and Karami, 2010).

2.3 Resilience and sustainability

Resilience is a multidimensional and complex concept. In a broad sense, resilience is the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks (Walker et al. 2004). Sustainability, economics and social sciences have increased their interest in analysing and understanding resilient characteristics of systems, such as: robustness, vulnerability, and risk. There is a good reason for that, since these characteristics of social–ecological systems (SESs) will determine their ability to adapt to and benefit from change.

In particular, ecological agriculture literature identifies two paradigms for defining resilience, engineering resilience and ecological resilience (Maleksaeidi and Karami, 2013). The engineering resilience paradigm understands resilience as the rate of return to an equilibrium following a disturbance (Walker et al., 2006). On the other hand, the ecological resilience paradigm understands resilience as the amount of disturbance that a system can absorb before change its state (Adger, 2000). The present research is framed in the paradigm of ecological resilience and approaches it as a condition to adaptation.

While natural systems are inherently resilient, evolving and changing through adaptive repetitive cycles, social systems are learning systems, persisting through time mainly as a result of learning processes. To understand SESs analytically, we need to appreciate fundamental features of society such as cultural norms and human attitudes and behaviour (Adger, 2000). Therefore, some authors, like Folke (2006), Gibbs (2009) and Röckstrom (2003), refer to the resilience of food systems as social-ecological resilience. Social ecological resilience is the process of using a set of resources, abilities and adaptive capacities to absorb disturbance while conserving self-organization and enabling recovery.

This means, social-ecological resilience focuses not only on the natural variables and feedbacks but also on the ability of the individuals, groups, institutions and their production systems to cope with external shocks and disturbances (Adger, 2000). For example, when a drought occurs in a sustainable agriculture system, social-ecological resilience will include more than the resilience of ecological system to absorb the shock but also resilience in economic viability of farms and food security of communities depending on such systems.

Resilience, hence, is not a single characteristic of the system, but rather a group of features that increase the capacity of the system to outstand disturbances. Chapin et al. (2009, p.24) identify some elements resilience depends on, these elements are: a) adaptive capacity, b) diversity, c) social capacity to deal with uncertainty, d) a balance between "stabilizing feedback loops" and innovation, and e) capacity to adjust governance. When any of these elements is eroded, the system lost resilience and it is pushed to its limits. Under such conditions, a disturbance may "push the fragile system over a threshold into an alternative state with a new trajectory" Chapin et al. (2009, p.24). These changes in the system may alter its capability to provide the desired ES and therefore threaten the sustainability of the associated livelihoods as well as the social and ecological wellbeing.

Nevertheless, resilience may be negative and undesirable in certain systems (Carpenter et al., 2001). If the systems are in an undesirable state and they are highly resilient it could be hard to change the existent state to a more positive one. For instance, the eutrophication of lakes is an undesired state of the system that can be highly resilient and recover a lake can require long time and effort. Therefore, it is important to acknowledge that, unlike resilience, sustainability is a primary goal that includes assumptions about which states of the system are preferable.

Hence, any consideration of resilience in the context of sustainability requires a clear specification of "resilience of what to what" (Carpenter, 2001). In this line, Biggs et al. (2012, p.423) understand resilience as: "the capacity of the social-ecological system to sustain a desired set of ecosystem services in the face of disturbance". This concept implies that at least tacitly there is an agreement about the set of desired ES of the system and the possible meaningful disturbance to the system. Agreement about the desired ES is, however, not something that can be given for granted, especially if we consider that enhance resilience of some features of the system can result in trade-offs in terms of productivity or efficiency.

Therefore, policies that aim to enhance sustainability of agriculture need to provide the necessary conditions to prepare the system for shocks and changes in the environment and contribute to adjust it to the effect of such changes. In other words, to contribute to foster sustainability in agricultural systems, policies should increase the resilience of the components that allow them to provide their main ES.

However, there are many threats and potential disturbances that can affect the food production in agriculture systems. For example, economic crisis, earthquakes or floods can affect the needed resources of the agriculture systems pushing them to limits where they cannot fulfil their function anymore. The present paper focuses only on the resilience of agriculture systems to water availability and, in particular, to the effects of climate change on it, because agriculture systems are particularly vulnerable to water availability. However, the framework proposed in this paper is applicable to other conditions that could threat agriculture systems and their ES.

2.4 Climate change adaptations

No matter how aggressively CO_2 and greenhouse emissions will be reduced in the upcoming years, climate change is inevitable (Fischer, 2012). Climate variability and extreme events like floods and droughts are becoming more and more frequent, especially in some regions of the globe with effect on natural, social and economic systems (Easterling et al., 2000; McCarthy et al. 2001).

Climate change is understood as the global change in the weather conditions (average temperature, rainfalls, wind streams, etc.) mainly due to the increase of the concentration of greenhouse gases in the atmosphere. Climate change affects key ecosystem drivers and may modify the ecosystem services currently provided (Ericksen et al., 2008). In the particular case of food and agricultural systems, this represents a threat to the capability of the current systems to provide their main outcomes (food security, environmental capital and social welfare).

Two possible responses are identified to the risk of anthropogenic climate change: mitigation and adaptation (Füssel & Klein, 2006). Mitigation refers to limiting the global climate change caused by human activities. Adaptation, on the other hand, deals with the actions that should be taken to reduce the impact of climate change. Easterling (2007) stress that the last one (adaptation) is the key response that will reshape the way we conceive and manage food and agriculture production (Easterling, 2007). Adaptation policies include relatively simple changes in the system, like shifting planting dates or switch to other crop varieties, and more complicated ones, like the developments of new crop varieties or new technologies (Rosenzweig and Parry, 1994).

In particular the present research focuses on the management practices that enhance the systems' resilience as a mean to foster adaptive capacity of the system (Chapin et al., 2009). Resilience particularly contributes to adaption by enhancing the systems properties needed to outstand shocks, learn and evolve. This resilience approach implies that social and ecological systems should be considered as a whole rather than isolated by focusing on the feedbacks, and connectedness of the system components (Nelson et al., 2007).

3. Operationalizing resilience in SD models

This paper focuses in the challenges of effective use of SD models to support policies that enhance resilience. In order to do this, first, a definition of what characteristics that identify the resilience of a system are expected to be represented in a SD model. These characteristics should not only bring a clear idea of the overall resilience of the systems to a particular disturbance, but also should be measurable and quantifiable in a SD model. Once a framework to evaluate resilience has been defined, it is possible to use this framework to select policies based on their effects on systems resilience.

The next sections of this paper present first the framework to evaluate resilience in SD models and the technical and theoretical bases for such measurements. Then the results of applying this framework to a study case are briefly discussed in the context of how well it suited the desired purpose and the insights learned.

3.1 Evaluating resilience

Measure and quantify resilience is a problem not only in the context of SD simulations, but also in general, since resilience is a broad concept including many different characteristics of the systems, many of which are hard to quantify. However, it is possible to evaluate systems' resilience by observing and estimating the behaviour of variables that underline the capacity of the SES to provide ecosystem services (Carpenter et al., 2001). Hence, system's resilience can be linked to a function representing an outcome of the system *F(t)*. In the case of agriculture system this function could be, for instance, food production. To illustrate this concept, it is assumed that the system has achieved its desired level of food production and that this desired level is constant (see Figure 2).

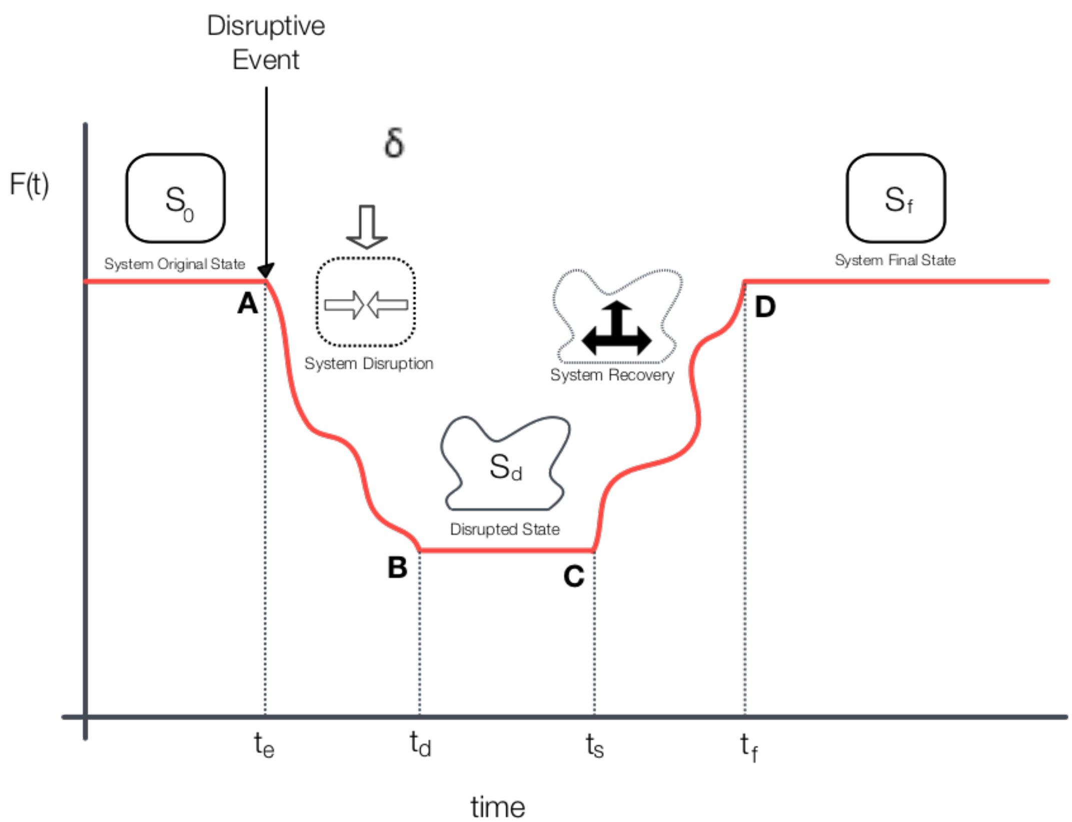

Figure 2. Simplified representation of system's F(t) function in response to a disturbance.
Note: Adapted from Henry & Ramirez-Marquez (2012, p. 117)

However, like it will be explored in further sections, in real life the assumption of a constant *F(t)* function is not always accurate. First, the system could be providing lower levels of the desired ecosystem service we define as its performance measurement. For instance, the system could be providing lower amount of food than needed or than expected. Moreover, the required amount or quality of the ecosystem services provided by the system could also change. For example, if population growth, it needs more food production in order to satisfy the needs of every person. These considerations represent additional challenges because there would be a need to deal with two, sometimes competitive, objectives, increase productivity and increase resilience.

Figure 2 shows that in the presence of a disruptive event (δ) in the time t_e the function *F(t)* can temporary change its behaviour to an undesirable state. In our case, this undesired state could represent lower values for food production. Three intermediate states are identified between the time the disruptive event takes place (t_e) and the time when the system reaches back an equilibrium state (t_f):

a) a system disruption state, during which the system is exposed to the disruptive event. It takes place since the start of the disruptive event (δ) in the time t_e until the time t_d when the δ disappears.
b) a system disruptive state, is a transitional state that happens between the end of the disruptive event in the time t_d and the start of the recovery in the time t_s. This is an instable state, and in some cases could last for so short time that I might be even imperceptible.
c) a system recovery state, is the system's path through reorganization or self balancing mechanisms to a new stable state. This stable state can or can not be the same than the original one.

Since SD models are interested in evaluate system performance over time rather than discrete events, an appropriate measure of the accumulated disturbance the system receives is needed. This measure should account not only for the magnitude of the disruptive event but also for the time the disruptive event lasts. In the present paper we label this measure as system disturbance *σ,* and is defined as:

$$\sigma = \delta \times (t_d - t_e) \qquad (1)$$

δ: magnitude of the disruptive event
t_d: time when the recovery cease
t_e: time when the disruptive event starts

Based on these observable properties of the systems' behaviour and on the assumption that the resilience of a system can be characterized through indirect measures of its performance (Carpenter et al., 2001), this paper proposes to focus on five indirect properties of the system as key performance indicators (KPIs) when evaluating resilience in SD models:

- ✓ Hardness σ_M
- ✓ Elasticity σ_L
- ✓ Recover Rapidity $\bar{R}$
- ✓ Robustness $\bar{\rho}$
- ✓ Resilience Index over time I_R

Therefore, in this framework the resilience of the system will be assessed as a profile of the system rather than a single measurement. The question of how resilient is the system, hence, will depend on the context and the objectives defined by the stakeholders and the relevance they attribute to the proposed properties. The Table 2 presents the definition of these properties in the context of the framework proposed by this paper.

Table 2
Definition of resilience properties of systems

KPIs		Description	Formula
Hardness	σ_M	The ability of the system to withstand a disturbance σ without change in its performance	$\sigma_M = \delta_M \times (t_d - t_e)$ (2)
Elasticity	σ_L	The ability of the system to withstand a disturbance σ without change to a different steady state	$\sigma_L = \delta_L \times (t_d - t_e)$ (3)
Recover Rapidity	$\bar{R}$	Average rapidity of the system to recover from a disturbance σ (Attoh-Okine et al. 2009)	$\bar{R} = \frac{D-C}{t_f - t_d}$ (4)
Robustness	$\bar{\rho}$	The ability of the system to withstand a big disturbances σ without significant loss in performance (Attoh-Okine et al. 2009)	$\bar{\rho} = \frac{\sigma}{A-B}$ (5)
Resilience Index over time	I_R	Indication of the ability of the system to withstand and recover from a disturbance σ overtime (Henry & Ramirez-Marquez, 2012)	$I_R = \frac{\int_{t_e}^{t_f} F(t)dt}{100(t_e - t_f)}$ (6)

4. Rethinking the maize production system in Guatemala

The framework proposed in this paper was used to analyse the resilience of different policies proposed to improve the maize production of the agriculture systems in Guatemala. This case is illustrative of how the framework previously described in this paper can be used to evaluate system's resilience and compare different policies. The case and its results are briefly presented next focusing on the main insights provided by a focus on managing resilience.

The Inter-American Development Bank has identified Guatemala among the top 10 countries most vulnerable to climate change. Guatemala has been seriously affected by climate change mainly experiencing a drastic change in the average rainfalls what have caused both droughts and floods of magnitudes that have not ever been seen before. Relying on agriculture as its main economic activity, 26% of it GDP, Guatemala's vulnerability to climate change is a high risk to its economic and social activities. Additionally, Guatemala is the fourth most susceptible nation to natural disasters and suffers the fifth highest rate of incidence of childhood malnutrition in the world, according to UNICEF. Guatemala's chronic malnutrition, an accepted measure of food insecurity, is the third worst in the world (World Bank 2003). Stunting is at 70% among the population of indigenous children (GOG 2004). This combination of factors places the country's food security in high vulnerability to the possibility of increases of the climate change effects in the upcoming years.

One of the most relevant systems to look at, in this context, is the Maize production system. Maize represents the main grain consumed among Guatemala population (71.2% of share in basic grains consumption), especially among those in the rural areas, around 52% of the total population (Jandry and Saudolet, 2010).

Beside the impact of the insights provided by this paper to the particular case of Guatemala, the learning lessons are easily transferable and applicable to a many similar cases since:

- Maize production systems are well spread and share common practices in L.A. and particularly in the region from Mexico to Panamá
- Clear relationship exists between maize production and food security in many countries in L.A.
- Increase in the variation of rainfall precipitation, as effect of climate change, is a well spread effect in the zones close to the Equator.
- Maize is a crop particularly susceptible to droughts due to it high water requirements.

4.1 A simplified explanatory model

A SD model was developed with collaboration of different stakeholders from the communities of Jutiapa, Guatemala and the support of local academics in agriculture science in order to explore possible alternatives to enhance the capacity of the current agriculture system to outstand the increasing effects of climate change in the area.

SD models allow evaluating not only short but also long term effects at the same time as providing a comprehensive understanding of the system's structure. The explanatory model was built, in cooperation with some key stakeholders, able to represent the main dynamics and to capture in a causal structure the different relationships between economic and natural components of the system. The Figure 3 presents lay off of the model including the main feedback loops identified in the process.

For practical purposes, the model includes some assumptions to simplify it without compromising its usefulness. These assumptions are: a) the system is isolated to external market effects, b) only nutrients in soil and water availability were consider among the natural resources supporting the system, c) potential effects of the improvement of seeds and maize varieties are not consider. The model was calibrated with historic data and validated with local experts in the area in order to reproduce the historic behaviour with enough accuracy and for the right reasons (see Figure 4).

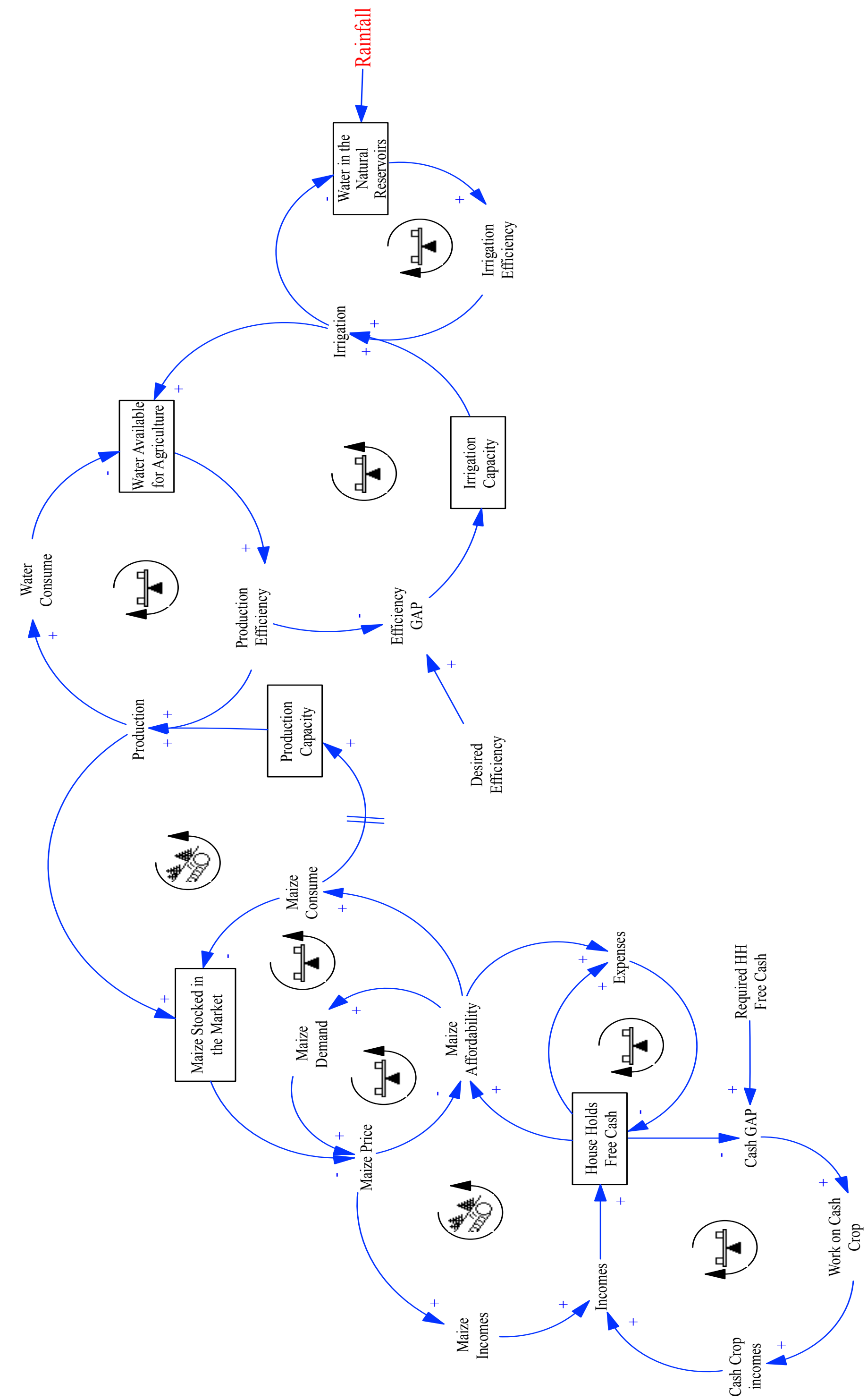

Figure 3. CLD of a simplified model of the maize production in Jutiapa, Guatemala

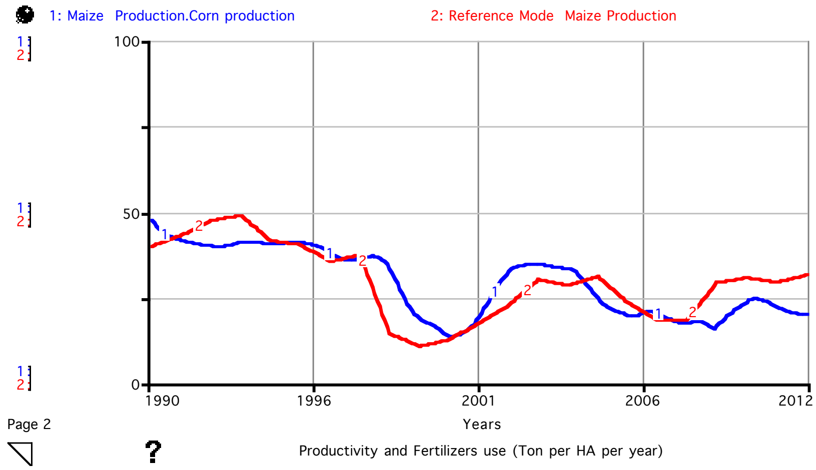

Figure 4. Real and simulated maize production in Jutiapa, Guatemala

During the process, important opportunities to improve the performance of the system where found in the loops:

- Long term adjustment of demand
- Short term adjustment of consumption
- Long term adjustment of supply
- Carrying capacity of the Natural System

The analysis of the model revealed that the main constraint of the system's growth was the "Carrying capacity of the Natural System". In the past years, small farmers have experienced a shift from traditional and more eco-friendly techniques to more industrialised ones. This shift in agriculture practices partially promoted by the central government policies and partially by aggressive strategies of agro industries have resulted in the depletion of the soil. By 2012 plantations were operating at 30% of their potential capacity and up to 25% less productivity than other farms in the country.

In addition, changes in the rainfall in the past years have disturbed the equilibrium of the water resources in the area. The storms Mitch and Stan in the past 20 years are examples of the visible effects of climate change in Guatemala. These and other storms of smaller magnitude have increased considerably the chances of floods in areas where this phenomena has never been seen before. However, the effects are observable not only in the increase of floods during the raining season but also in the increase in the intensity and severity of the dry periods. The two phenomena, excess and lack of rainfall have adverse effects for the maize production. The excess of rainfalls floods the plantations and removes soil nutrients, speeding up the degradation of the soil. The lack of rainfall, on the other hand, decreases the quantity and quality of the maize yields because maize plantations require relatively high quantities of water.

By identifying leverage points susceptible to intervention in those loops, stakeholders came up with three different potential policies to improve the outcome of the system (food production *F(t)*). Even, these policies were not completely new, since they have been used previously in similar systems, stakeholders recognised that by using a SD model they discover unintended consequences in the medium term and also implementation challenges in the short run. In particular, the model contributed to identify explicitly the existence of delays in the system and to uncover through simulations their effect on the outcomes of the proposed policies.

Based on the analysis of the system, three different policies were proposed to increase the resilience of the food production outcome to the climate change effect on rainfall. The description of the proposed policies is summarized in the Table 3. Since the intention of this paper is not to describe system's performance itself but to present the insights gained from the resilience evaluation, details of each policy and their impact on the food supply outcome are not presented.

Table 3.
Selected policies description

Policy	Description
Policy 1	Increase in the irrigation capacity by the investment in artificial storage capacity like tanks and damps to storage water to ensure supply during droughts.
Policy 2	Increase in irrigation efficiency by the introduction of technologies to improve the capture of water from rivers and natural reservoirs.
Policy 3	Decrease of water requirements by the promotion of drop irrigation systems where water is applied in an extremely targeted way to plants among the small agricultures.

To compare the resilience of the different policies, Monte Carlo simulations were used in the SD model to assess the impact of different disruptive magnitudes for different periods of time, the details can be found in the Table 4. Using Monte Carlo simulations, random disruptive events following specific probability distributions shock the system for a lapse of time that also takes a random value within a specific range. In this way, 500 different potential scenarios were evaluated for each policy, each of them with a different disruptive magnitude and elapse time. These results were exported to a spreadsheet where they were treated to measure each one of the five KPI`s described in the previous section. The final results are summarized in the Figures 5 and 6.

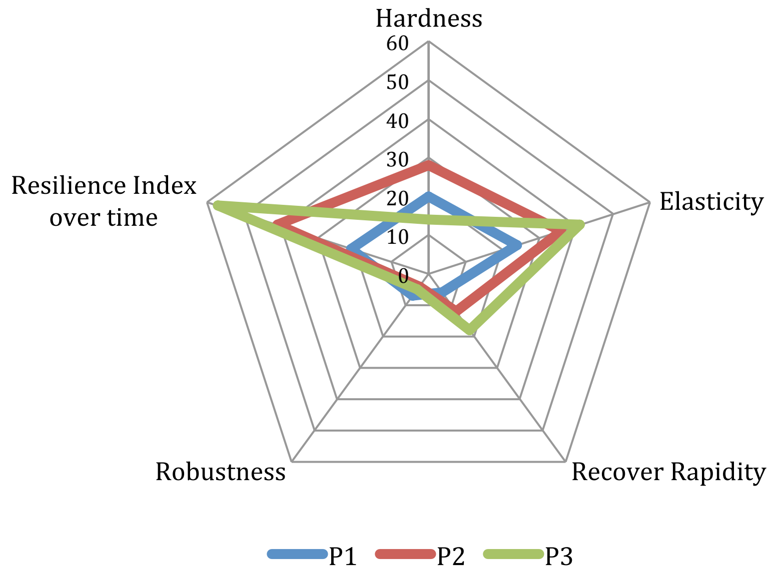

Figure 5. Resilience profiles of the system resulted from the proposed policies.

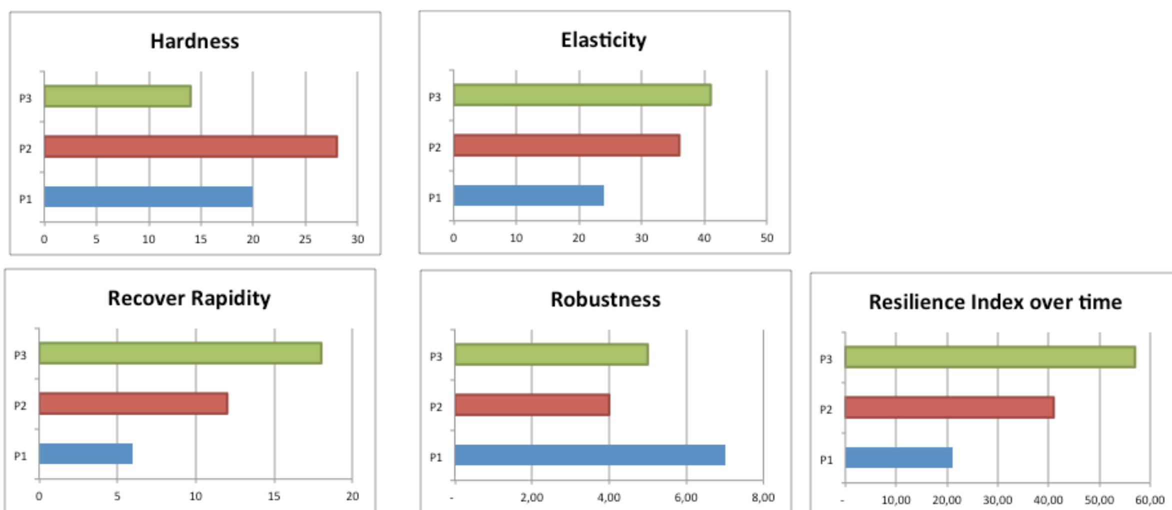

Figure 6. Resilience profiles of the system resulted from the proposed policies.

The figure 5 shows an integrated gird that represent the values of each one of the five KPI`s values for the policies proposed in a single chart. In theory, the broader the profile the better, and the policy that has the bigger area should be the preferable one. However, find a single policy that rank the highest for all the criteria is probably not often the case and individual assessment of each of the KPI`s (like the one show in the Figure 6) is needed to carefully evaluate what policy fulfil better the particular objectives and needs of each case.

4.2 Results analysis

The results show that policies have affect system's resilience in a different manner by introducing different pieces of structure in the system or altering the existent ones. For example as the Policy 2 is the one that enhances the most the system's hardness, it seems to have poor effects on the recover rapidity. Similar, the Policy 3 outstand to enhance recovery rapidity, but it effects on robustness are modest. These differences remark how case specific is the evaluation of resilience and the importance of gaining a broad perspective in each case so that policy makers and stakeholders can decide what the best criteria to be applied is.

For example, a farmers' community could find that by investing in infrastructure to artificially storage water for agriculture they can make the system harder and especially more robust, than by using the other policies. More robustness would mean that the system would provide a more constant output when facing disturbance than otherwise. Constant throughput is beneficial not only to keep the supply of food, but also to reduce the price fluctuations in the market what can bring stability to their small economies.

On the other hand, another community could find that a flexible system that can recover quickly is better. In this case, introducing new technologies for irrigation (policy 3) would be the best option. A flexible system would show a reduction in its throughput even whit small disturbance, however it would be able to came back to its normal values faster than other options. Moreover, policy 3 also provide high degree of elasticity, which means that system will tolerate higher disturbances and still be able to come back to its original performance, making it more reliable in circumstances where uncertainty is high and where higher variation could be expected.

In summary, the results remark the importance of evaluating resilience as a multidimensional concept, and involving policy makers and stakeholders in the definition of criteria and selection of options. The results also show the effectiveness of the approach proposed in this paper to support the evaluation process by providing objective measures of the systems resilience and the impact of different policies on it. Moreover, by conducting this evaluation in a SD model, it is possible to gain insight not only about the system's behaviours, but also about the structures driving them.

By analysing the system's structure of the different policies presented above and their effects in terms of system's resilience in a SD model, it was possible to gain some insights about what kind of structures can have effect on the system. The main insights gained from this analysis, in the particular case analysed in this paper, are presented next.

Stocks and robustness: It was possible to identify a relation between the level of the stocks and the systems robustness to eventual disturbances. For instance, the Policy 1 increase the stock of water available to use in agriculture by increasing the system's capacity to capture, storage and distribute water from the natural sources to the maize plantations. The role of the stocks as buffers in this policy is clearly an advantage, in terms of robustness, since the changes in the system are smoother and the throughput show small variations. This can be also understood, in a more general context, from the perspective of redundancy, since the construction of more strategic resources and a higher variety of them would be expected to enhance systems' robustness.

Delay times and recovery rapidity: However, relaying only on development of stocks seems to diminish recovery rapidity. If the resilience of the system relays only on the construction of one particular stock, like the Policy 1, it could result in longer time such system would need to go back to the equilibrium. In the same way that stocks seem to act as buffer between the desired and the undesired states when the system is affected by disturbance, they also act as a buffer that slows down the systems' recovery after the disturbance. Once the stocks have been depleted it requires time until they can reach their desired operational levels again. This is not a new concept for SD; since it is generally accepted that there is a relation between stocks and the presence of delays. Policies that focus on the decrease of the consumption rate (outflows), on the other hand, reduce the dependency of the stocks, like the Policy 3, seem to have better results in terms of recover rapidity.

These are however, just two insights from the specific case of the analysis and we acknowledge that more cases should be analysed in order to draw conclusions about the relations between system's structure and resilience. In any case, what these insights can confirm is that SD models are valuable tools to gain understanding about the system's resilience and the ways policy makers can influence them. In addition, it also remarks the importance of systematising the way we measure and analyse resilience in SD model by using and continue improving the framework proposed in this paper. Applying a common framework to many diverse study cases will allow us to draw general conclusions about structures that enhance resilience, how they do it, and improve our capabilities to design systems and policies that can cope with different kind of disturbances.

5. Conclusions and future research

To summarize and conclude, resilience is a complex concept and measuring it is not a simple task. The present paper contributes to this task by providing a framework to operationalize resilience in SD models with the intention to help policy makers to evaluate and compare the impacts of different policies on systems' resilience. By applying this framework to a specific study case, we show its capability to provide important insights to policy makers and to contribute to gain understanding about the structures that enhance resilience and the way they do it.

The framework proposed show the resilience profile of a system as it is or as result of a policy measuring five different dimensions. The analysis of the study case to which this framework was applied highlight the importance to analysing the system with different measurements since the evaluation of the best policy will be case specific, because for different cases, policy makers and stakeholders may have different criteria to assess what is the best policy to implement.

Moreover, using the current framework it is possible to uncover the general structures behind resilience and draw conclusions that can be applied to different systems and different contexts. By applying a standard framework to evaluate resilience in different cases would make it possible to learn more about what is behind resilience in operational terms and to replicate successful structures as policies that can contribute to enhance system's resilience.

Finally, it is important to remark that this paper is just the first step in the process to operationalize the concept of agriculture system's resilience into SD models. More study-cases applying the presented framework, validating it and documenting the insights gained from it are needed in order to have a robust and effective framework to study resilience with SD models. In addition, other important dimensions, like knowledge sharing, development of networks and participatory governance are needed to be included in a framework that aims to comprehensively use SD in the resilience management of agriculture and food systems. Forthcoming papers will extend the application of the present framework to its use in a community based SD modelling and the detailed design and implementation of policies that could enhance resilience using SD modelling.

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