MAIN ARTICLE

Do you bend or break? System dynamics in resilience planning for food security

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Abstract

This paper discusses our experience in using system dynamics to facilitate resilience planning for food security in rural communities that are exposed to ever-increasing climatic pressures in Guatemala. The social–ecological systems literature is rich in examples where policies to enhance resilience are deduced from factors generally accepted to be present in resilient systems (e.g. redundancy, connectivity and polycentrism). This deductive approach risks being overly simplistic. As an alternative, this paper explores how insights from analysing the structure–behaviour relationship of complex dynamic systems can be used to generate tailored policies. The results show that stability in food systems is mainly driven by key strategic resources that moderate the effects of environmental changes on food availability and affordability. Moreover, our experience highlights the importance of analysing mechanisms that determine a system's behaviour while and after the system is affected by a disturbance to formulate effective resilience policies.

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Introduction

Food systems are a particular type of social–ecological system (SES) managed with the primary purpose of producing food and, more specifically, of providing food security to their stakeholders (Ericksen, 2008a). FAO (2002, p. 50) defines food security as follows: "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".

Social, economic and technical developments have evolved during the last century, improving food systems' productivity, reliability and quality. The productivity of food systems has increased to such an extent that food production has not only kept pace with population growth but has also improved food security in many regions (Vermeulen *et al.*, 2012). For example, the International Food Policy Research Institute (2016) reported a dramatic drop in malnutrition among children between 1990 and 2014. On a global scale, there has been considerable progress in reducing undernutrition. These gains, however, have not been equal across the globe, and in

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many countries food insecurity and undernutrition conditions are still alarming.

Despite these overall improvements, progress made towards eliminating hunger is now at risk. Climate change and other factors are threatening progress towards increased food security (Richardson *et al*., 2018; Campbell *et al*., 2016; Ericksen, 2008b; Schmidhuber and Tubiello, 2007; Vermeulen *et al*., 2012; Wheeler and von Braun, 2013). This threat is higher among those already food-insecure countries with high dependency on local production and rudimentary production systems (Schmidhuber and Tubiello, 2007; Schipanski *et al*., 2016). In their 2018 report, the Food and Agriculture Organization of the United Nations (FAO, 2018, p. 1) reported, for example, that "70–80 percent of severely food insecure people worldwide rely on agriculture-based livelihoods". All these households are on the verge of disaster as climate becomes unpredictable and extreme events such as floods and droughts are more common.

This study focuses on the effects of climate change on food security, particularly among subsistence farmers in Guatemala. An increase in temperatures and changes in climate patterns have been consistently observed since the 1950s (Pielke *et al*., 2007; Wheeler and von Braun, 2013). Climate change, primarily attributed to anthropogenic causes, has significant, long-lasting and complex effects on local ecosystems (Pielke *et al*., 2007). Guatemala, like other developing countries, faces food security challenges that will only increase as climate change affects small-scale farmers' capabilities to produce food. Guatemala's chronic malnutrition, an accepted measure of food insecurity, is the fourth worst in the world (WFP, 2016), reaching 55% in rural areas (Guardiola *et al*., 2006). Climate change effects such as severe droughts and increase in average temperatures already compromise food production in Guatemala today, especially among small-scale farmers (Bouroncle *et al*., 2015).

Resilience, at a basic level, can be understood as the ability of a system to cope with, and adapt to, changes (Holling, 1996; Folke, 2006; Marshall and Marshall, 2007). Resilience is used in both theoretical and practical settings as a means to characterise systems but also as a framework to improve its adaptive capacity (Folke *et al*., 2004; Walker *et al*., 2006). In this paper we focus on the latter, and particularly on the way resilience is applied as a framework to study how systems can withstand bigger and/or more frequent changes. We look at resilience as an outcome of the planning and risk management processes (Berkes and Folke, 1998; Chapin *et al*., 2009) and emphasise those attributes that can help a system to live with, learn from and adapt to change (Berkes and Jolly, 2001; Adger *et al*., 2005; Davoudi *et al*., 2013; Brown, 2014; Crowe *et al*., 2016).

In the past, case study research has been used to identify system attributes and characteristics that contribute to resilience. By studying systems that have been identified as resilient, researchers have proposed that attributes such as redundancy, connectivity or polycentrism contribute to enhance

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systems' resilience. For instance, McConney *et al.* (2015) found that social networks, self-organisation and adaptive capacity were fundamental to fostering resilience of fisheries in the Caribbean. Their results highlight the importance of strengthening cooperation among fisheries in order to enhance collective responses to unexpected events.

However, transferring these attributes and operationalising them into specific policies to enhance resilience is not straightforward, and approaches using resilience are often criticised for their crude approach to complex systems (Pizzo, 2015). Operationalising resilience in complex systems is particularly challenging because their behaviour is dynamic and shifts as their configuration adapts and responds to exogenous disturbances. Complex systems often behave in counterintuitive ways when impacted by change. This complex behaviour makes it difficult to assess the effects of policies aimed at enhancing resilience (Chu *et al.*, 2003).

In this paper we take a different approach to resilience planning and utilise system dynamics (SD) for exploring the complex mechanisms that influence resilience in complex systems. There are many examples showing that, at the right level of abstraction, a careful analysis of complex systems' structures yields valuable insights about the systems' behaviour. For instance, SD has been successfully applied to water management problems (Wei *et al.*, 2012), challenges of reducing CO_2 emissions (Sterman *et al.*, 2012) and stakeholder involvement in environmental decisions (Stave, 2002; Videira *et al.*, 2017). This focus on how stocks, flows and feedback structures drive behaviour makes SD a great candidate for exploring how systems react and adapt to change (Hawes and Reed, 2006).

By using SD in our work with rural communities in Guatemala, we managed to identify particular adaptive mechanisms that improve food security resilience in the area. For example, the lessons learned from our experience highlight the importance of food reserves and diversity of food sources and revenues as key factors for food security resilience. While broadly fitting within the general resilience attributes described in the literature, our study also shows that recommendations for improving resilience are context specific and that the effectiveness of policies varies from case to case.

Operationalising resilience

While there is no agreement about how to measure resilience (Davoudi *et al.*, 2012; Duit, 2015; Pizzo, 2015; Tendall *et al.*, 2015), it is often assessed through the behaviour of system outcomes (e.g. food security, energy supply or quality of drinking water) during and after the system has been shocked by a change in the environment (Biggs *et al.*, 2012). In mathematical terms these outcomes can be conceptualised using an outcome function $F(x)$ (Henry and Ramirez-Marquez, 2012; Barker *et al.*, 2013).

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Resilience studies about how a disturbance affects $F(x)$ focus on the magnitude of a disturbance that could be tolerated by the system before seeing changes in its outcomes (Carpenter *et al.*, 2001). Walker *et al.* (2004, p. 5) describe three general changes that *F(x)* might exhibit after the system has been affected by a disturbance:

Stability (no change)

The system does not exhibit changes in its behaviour. Note that stability in this context is not a synonym of a constant or a linear behaviour (see Figure 1). Stability is $F(x)$ showing the same behaviour that it would show otherwise, despite the system being affected by a disturbance. For instance, the amount of available crops might remain stable despite the presence of moderate droughts if sufficient crops are maintained in storage facilities.

Adaptation

The behaviour of the system "bends" when affected by a disturbance and eventually bounces back while retaining its current nature. Walker *et al.* (2004) emphasise that this return to normal behaviour is not given but driven by factors (e.g. resources, decisions, actions) within the system. For instance, food systems might adapt to changing weather conditions if farmers introduce different seed varieties or different crops that require less water.

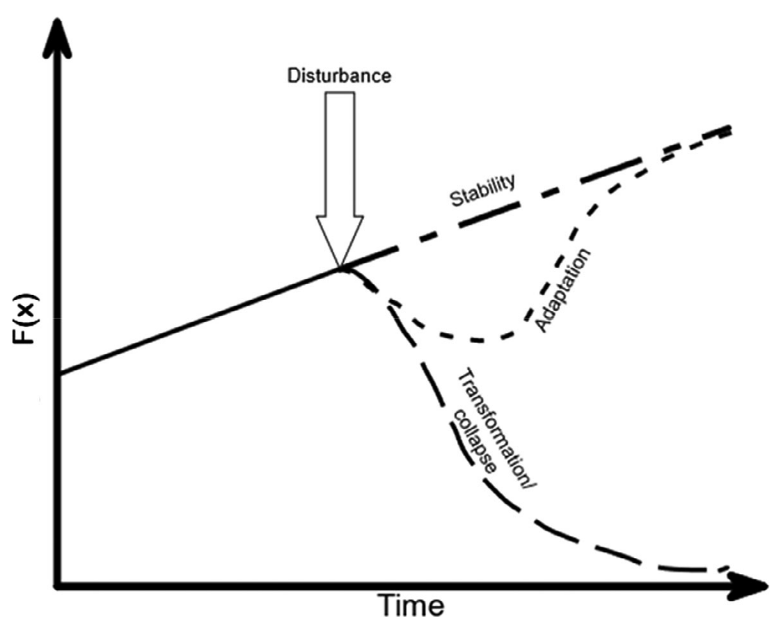

Fig. 1. Generic system responses to a disturbance affecting one of its outcomes

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Transformation

The system as it currently exists "breaks" and changes into a new system with a fundamentally new structure, relationships and identity (Ludwig *et al*., 1997; Walker *et al*., 2004). The new system might or might not produce the same outcomes or just might not produce them at the same rate. While certain transformations might be positive, risk management is concerned with those transformations that are not positive and the cases in which the system might collapse (see Figure 1). For example, food systems might become economically unfeasible if they are not able to recover from severe weather disasters.

The changes described by Walker *et al*. (2004) can be observed and quantified by simulating $F(x)$ when the system is exposed to change. Herrera (2017) proposes several measures for assessing resilience (see Table 1). The proposed approach starts by defining σ (see Eq. 4) in terms of magnitude of the disturbance (M) over a given period (d = duration):

$$\sigma = M^* d \quad (1)$$

In this paper, σ is the drought (a disturbance), M is the magnitude of the drought as a percent reduction below average rainfall expected for that period and d is duration of the drought in months.

It is then required to estimate the probability $P(\sigma)$ that a discrete disturbance will happen. Additionally, the magnitude and duration of the disturbance can also be set as stochastic parameters to test the effect of different disturbances on the system outcomes. Such effects can be simulated running Monte Carlo simulations in an SD model (see, for example, Herrera, 2017; Walrave, 2016; Moxnes, 2005).

The characteristics presented in Table 1 can be used to identify the thresholds between the three behaviours described by Walker *et al*. (2004) as illustrated in Figure 2. "Hardness" indicates the threshold between stability and adaptation, i.e. the degree of disturbance needed to perturb the outcome's stability (see Figure 2). Similarly, the measure "elasticity" indicates the threshold between adaptation and transformation, and the "index of resilience" indicates the probability of reaching this threshold (see Figure 2).

Resilience planning for food security in subsistence food systems in Guatemala

The experiences presented in this paper are part of an independent study aiming at exploring the policies for enhancing resilience of food systems in Guatemala. The results are based on model-based discussions held with

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Table 1. Measures for assessing resilience (adapted from Herrera, 2017)

Measure	Description	Calculation
Hardness (σ_H)	The ability of the system to withstand a disturbance without presenting a change in the performance of the outcome function $F(x)$. The higher the hardness, the higher is the system resilience	Hardness is calculated as the smallest disturbance σ that produces a *different outcome* function $F(x)$. This disturbance is denoted by σ_H and can be calculated as $\sigma_H = M_H \times d_H$#(2)
Elasticity (σ_E)	The ability of the system to withstand a disturbance without changing to a different steady state (Holling, 1996; Holling and Gunderson, 2002). The higher the elasticity, the higher is the system resilience	Elasticity is calculated as the smallest disturbance σ that moves $F(x)$ to a *different state*. This disturbance is denoted by σ_E and can be calculated as $\sigma_E = M_E \times d_E$#(3)
Index of resilience (I_R)	The probability of keeping the current steady state or regime (Holling, 1996; Holling and Gunderson, 2002; Martin *et al.*, 2011). The higher the index of resilience, the higher is the system resilience	The index of resilience is calculated as the probability of experiencing σ_E and can be calculated from the area underneath the probability distribution function of the simulated outcome: $(I_R) = P(\sigma \leq \sigma_E)$#(4)

stakeholders in the districts of Huehuetenango and Jutiapa, Guatemala. The model was developed using group model building (GMB), as summarised in Figure 3. In short, for each case we engaged with farmers and representatives from the central and local governments to develop causal loop diagrams explaining the main relationships in the respective food systems and the variables affecting the resilience of food security to climate change. This understanding was then translated into quantitative SD models used to facilitate a discussion about potential policies. For more details on the GMB process, see Herrera (2018).

The two original models jointly produced with the stakeholders of each community were combined into a general model. The purpose of the model was to develop realistic assessments of the behaviour and underlying processes of maize-dominated subsistence agriculture systems. This purpose fits within the definition of Costanza *et al.* (1993, p. 547) of "high-realism impact-analysis models". Within this definition, some degree of numerical precision is sacrificed to increase model applicability to different contexts. The models can be used to assess specific case studies by adjusting initial conditions and other parameters in the model (as we did in the two districts). Within this definition, the purpose of the modelling exercise is to learn about general principles that could be applied to different contexts rather than predict future outcomes.

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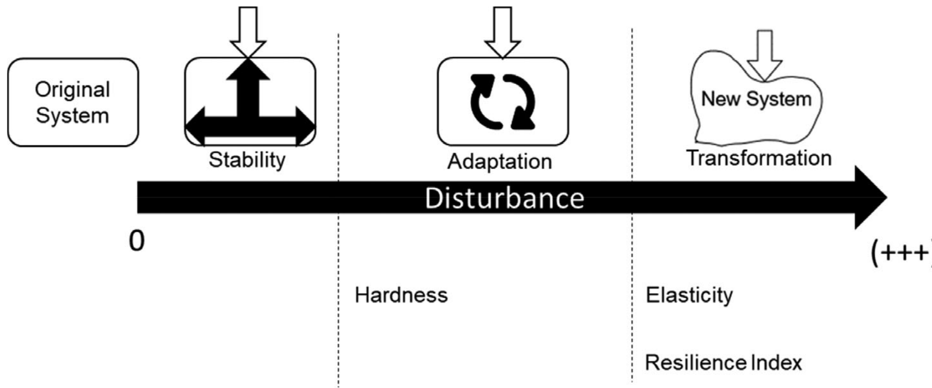
Fig. 2. Thresholds between system responses. “Hardness” marks the threshold between stability and adaptation; “Elasticity” and “Resilience Index” mark the threshold between adaptation and transformation



During the formulation of the model, we continuously engaged with stakeholder representatives to validate the variables and the relations represented in the model (see Figure 3). A careful process was followed ensuring that proper documentation was created in parallel with the modelling activities. Most of the data needed for the model was found in publicly available statistics or provided by the central government from their database. When information was not available, we made assumptions about values or relationships represented by each variable. These assumptions were registered in the model documentation and discussed with stakeholders in one-to-one interviews.

Model description

Figure 4 summarises the key feedback loops driving the resilience of food security to climate change. A detailed description and documentation of the model is available in the supplementary material as supporting information. Next, we explain the main feedback loops that impact the system in its current state.

Commercial agriculture

Revenues from maize increase households’ cash, increasing households’ ability to spend on farming (see Figure 5). Higher expenditures on fertilisers and irrigation systems result in better soils and higher water uptakes. Water and nitrogen availability are directly related to maize yields and consequently to a further increase in the households’ available cash.

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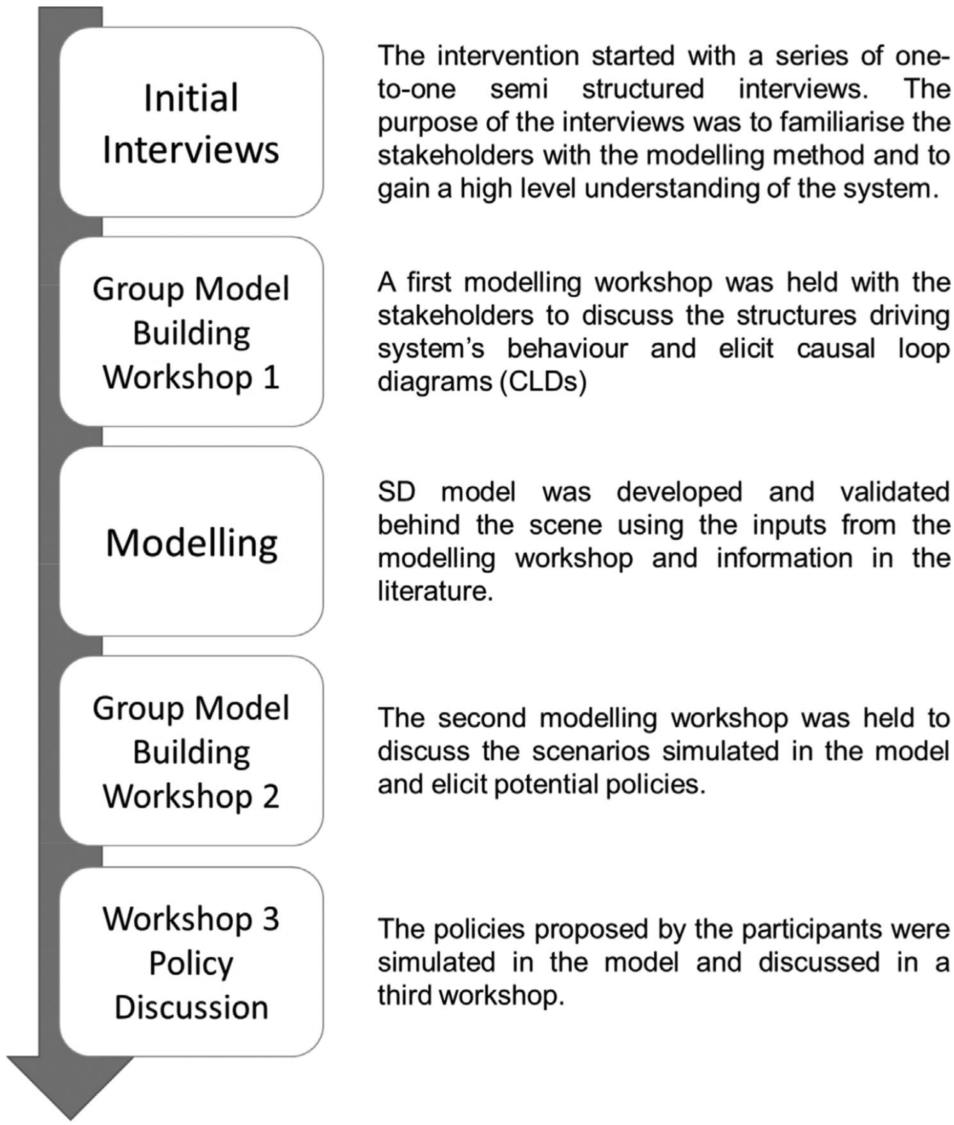

Fig. 3. Summary of the modelling process. Adapted from Herrera (2018)

Poverty trap

A fraction of the maize production is allocated to self-consumption. The higher the proportion of the maize production dedicated to self-consumption, the less maize is available for the market. Figure 6 shows how lower sales than otherwise will likely lead to lower revenues, less cash available

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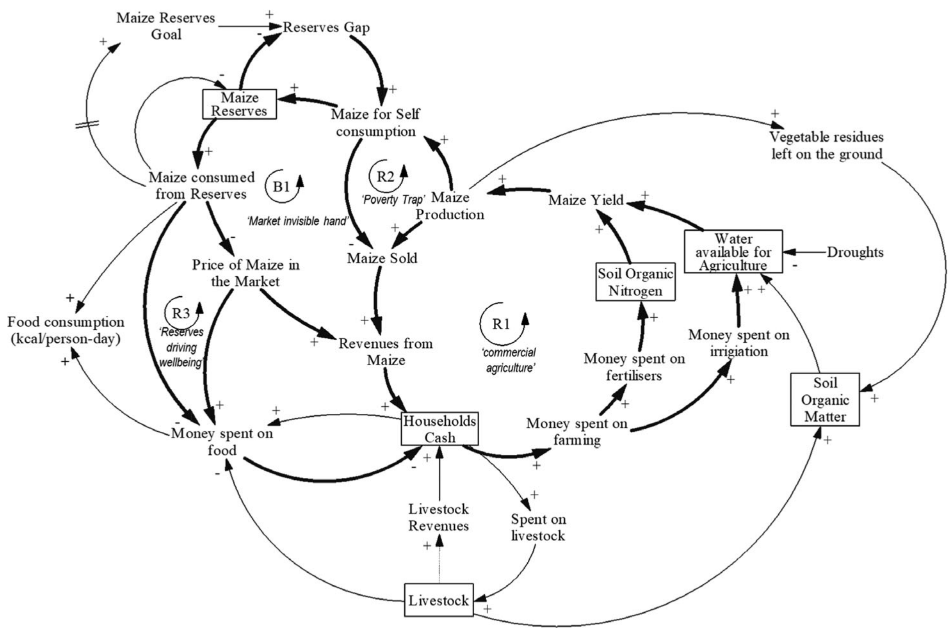

Fig. 4. Causal loop diagram summarising resilience of food security to climate change

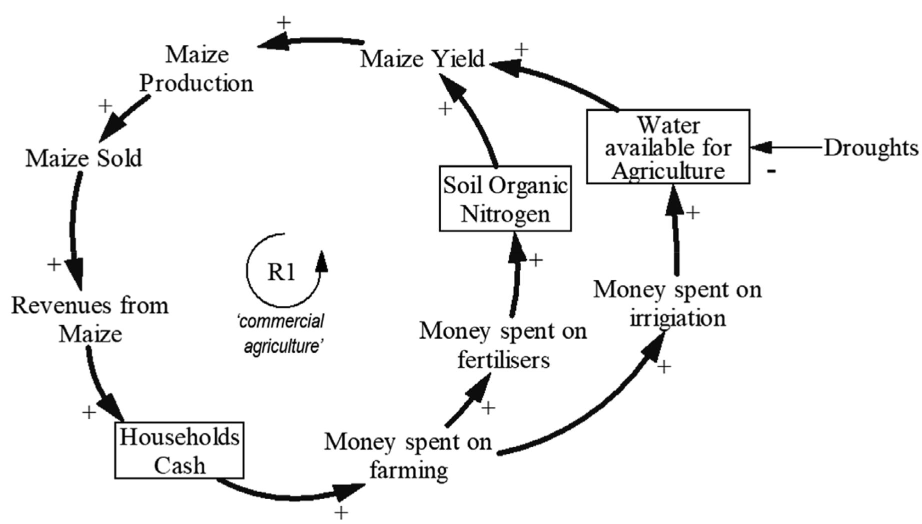

Fig. 5. Reinforcing loop 1 (R1): commercial agriculture

and, subsequently, less investment in farming. Low investment in farming leads to low yields, reducing further the amount of maize that can be sold.

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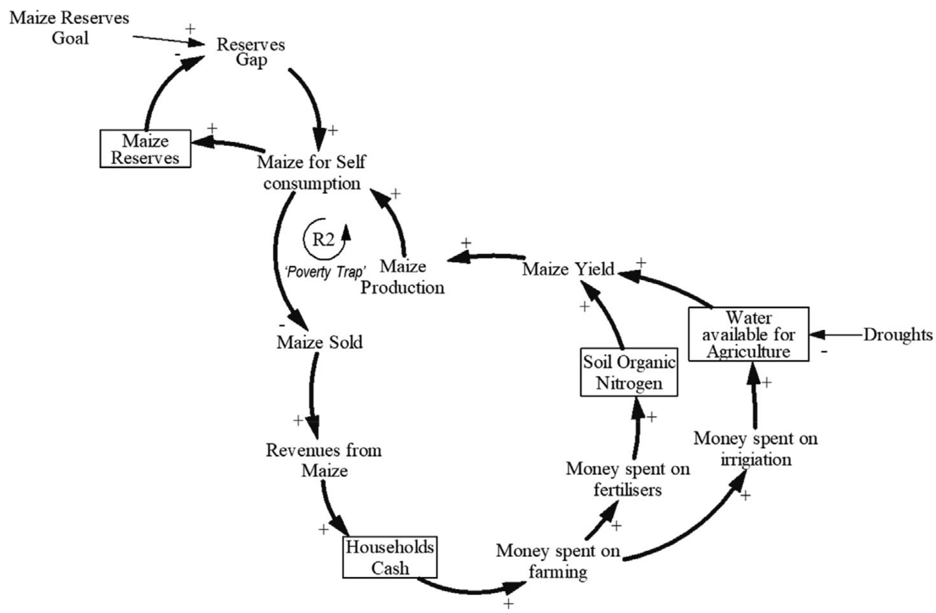
Fig. 6. Reinforcing loop 2 (R2): poverty trap



Reserves driving wellbeing

Higher production rates mean more maize is available for self-consumption and less money is used for purchasing food. If households spend less on food they have more cash available for farming. Higher expenditures on farming lead to higher yields and production rates (see Figure 7).

Market's invisible hand

Figure 8 illustrates the role of local markets in the system. Higher production rates mean more maize might be used for self-consumption, reducing the local demand for maize. Low demand and high supply eventually result in lower prices and hence lower revenues. Conversely, if production is low, reserves are likely to decrease and local prices are likely to increase.

Historical behaviour

We used the model to represent and understand the behaviour exhibited by the system in the recent past (between years 2000 and 2014). While the conditions in each district are different, the underlying structures of the system are similar. The similarities between the two cases enabled us to qualitatively reproduce, with some degree of accuracy, the behaviour of the two districts using the same model (see Figure 9). The difference in the simulated

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Fig. 7. Reinforcing loop 3 (R3): reserves driving wellbeing

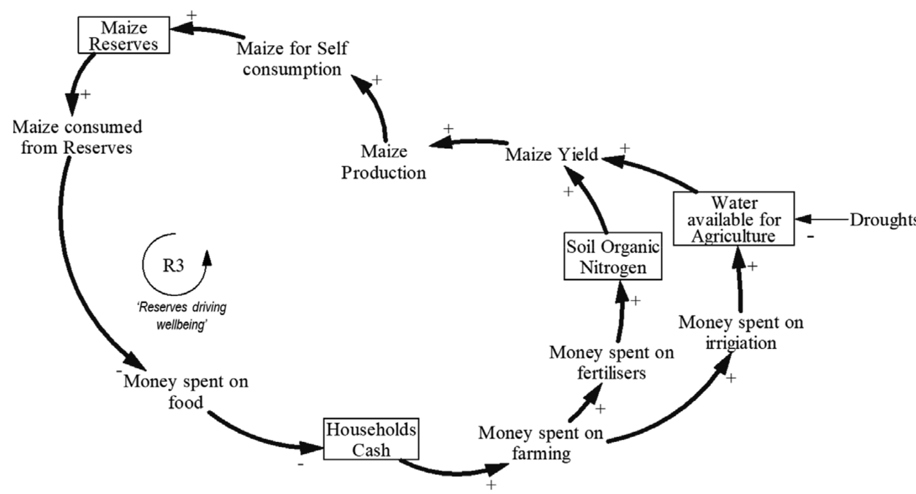
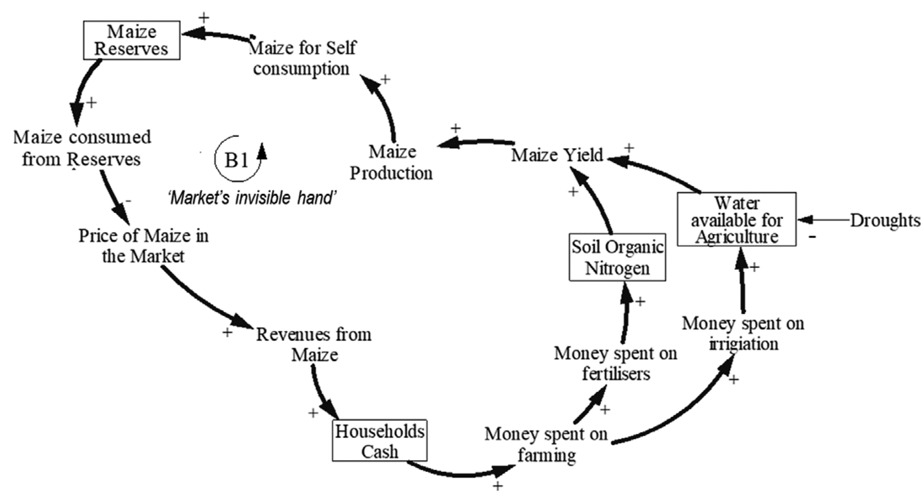


Fig. 8. Balancing loop 1 (B1): market's invisible hand



behaviour is only a result of the parameters used to initialise the simulation. This fact has two implications: (i) the two cases can be represented as the same system but operating under different conditions; and (ii) while the model can yield case-specific insights, it also illustrates generic principles that are transferable to other small-scale food systems.

Resilience to what?

As previously discussed, the main focus of our analysis was to understand the magnitude of disturbance that changes the behaviour of food consumption in

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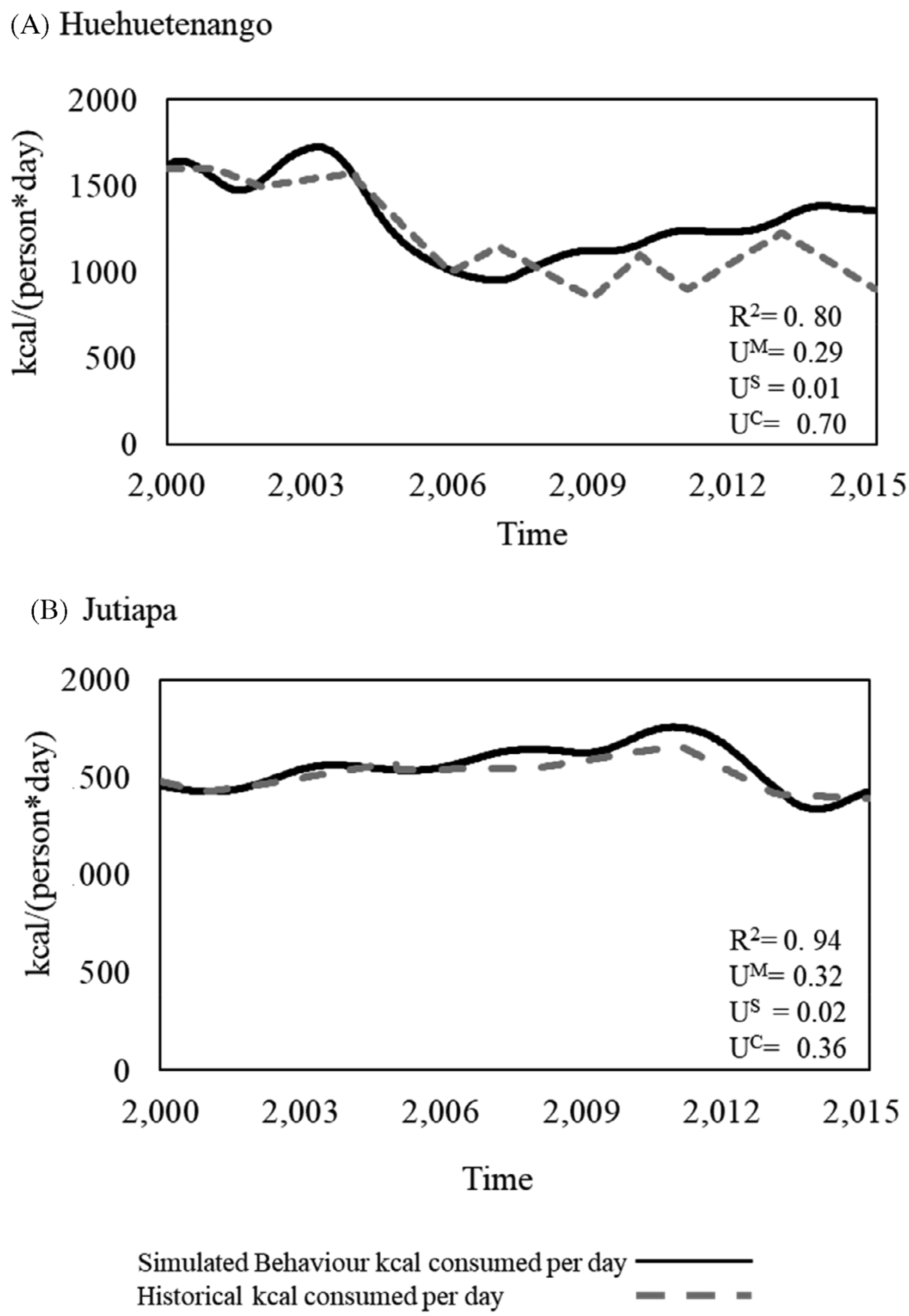

Fig. 9. Reference behaviour modes for (a) Huehuetenango and (b) Jutiapa. R^2 = coefficient of determination; U^M = bias; U^S = unequal variation; U^C = unequal covariation

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each district. Resilience is assessed specifically for a particular disturbance. In these two districts, we focused on the resilience of food consumption to the intensification of droughts (σ). We characterised droughts in terms of the percentage of rainfall reduction (magnitude) over a given period (duration) (see Eq. (1)).

We assumed that the probability of having a drought at any given year follows a Poisson distribution with a frequency λ:

$$P(k) = e^{-\lambda}\frac{\lambda^k}{k!} \tag{5}$$

where k is the number of droughts per year and λ is average number of droughts per year.

To account for uncertainty about how weather will develop in the upcoming years we explored how the system reacted to a range of conditions and used triangular distributions in a Monte Carlo simulation to estimate its effect on the calories consumed per capita per day. The intervals used for the parameters characterising the droughts affecting the district are presented in Table 2.

Analysis

The simulated behaviour for representative droughts (minimum, maximum and expected) is presented in Figure 10. In both cases it was observed that under minimum and expected conditions the system is only likely to show minor variations from the otherwise expected behaviour. However, major increases in the droughts (close to the maximum conditions considered) are likely to change the system behaviour considerably. For example, in the case of Huehuetenango severe droughts might reduce calorie consumption to ~1000 kcal per day per capita for long periods of time (see Figure 10a).

Table 2. Parameters used to characterise the disturbance affecting the system

Parameters of the droughts affecting the district	Average in previous years	Range considered for upcoming years
M (% of normal rainfall)	10%	Minimum: 10% Expected: 20% Maximum: 50%
d (months)	3	Minimum: 3 months Expected: 3 months Maximum: 3 months
λ (droughts per year)	0.25	Minimum: 0.25 Expected: 0.33 Maximum: 0.5

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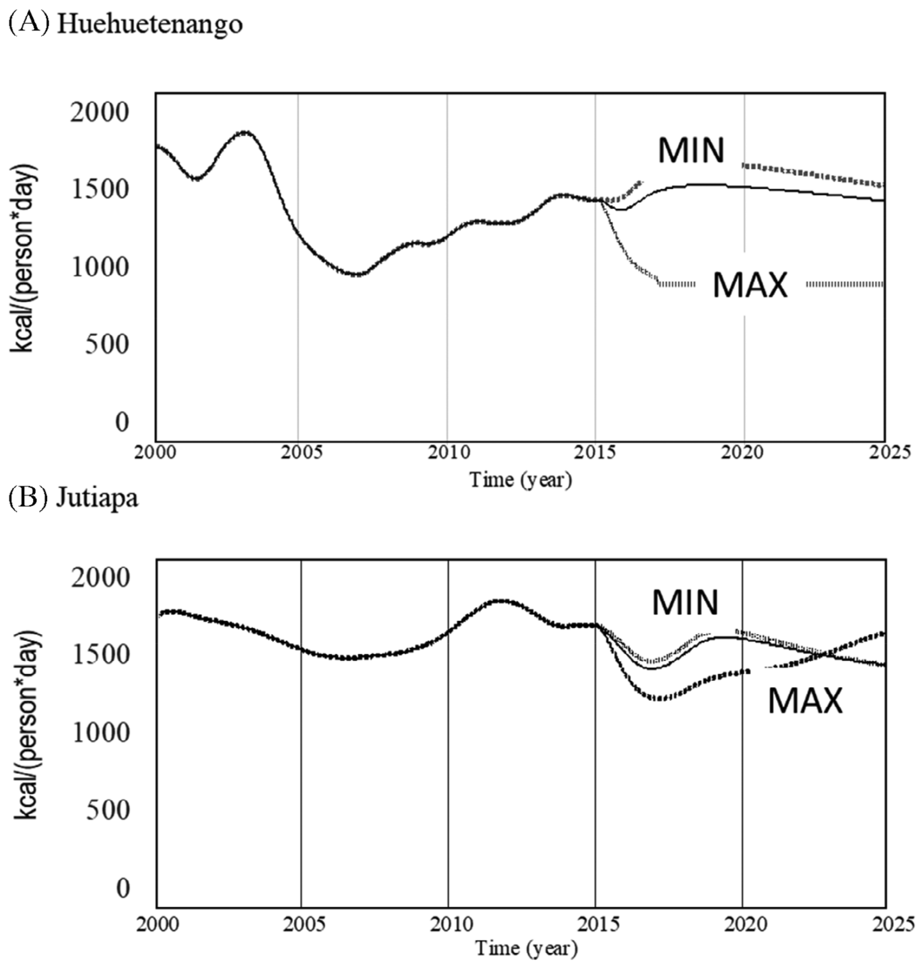
Fig. 10. Simulated behaviour for the variable "average calorie consumption per capita" in (a) Huehuetenango and (b) Jutiapa for a range of potential weather conditions, where MIN is the minimum droughts anticipated and MAX is the maximum



Severe droughts might provide opportunities for some farmers, as shown in Figure 10b. Severe droughts increase prices of maize, reduce farmers' maize reserves and reduce farmers' revenues, making food less affordable. However, if farmers have alternative sources of revenue (e.g. livestock) or sufficient cash reserves, they can keep farming and take advantage of higher prices in the market. Once the disturbance is removed farmers not only bounce back but do better than otherwise.

As described before, we used the measures proposed by Herrera (2017) (i) to identify the changes in the systems' responses and the thresholds between them and (ii) to link systems' responses to the feedback loop mechanisms driving them. The quantitative assessment of each case is presented in Figure 11.

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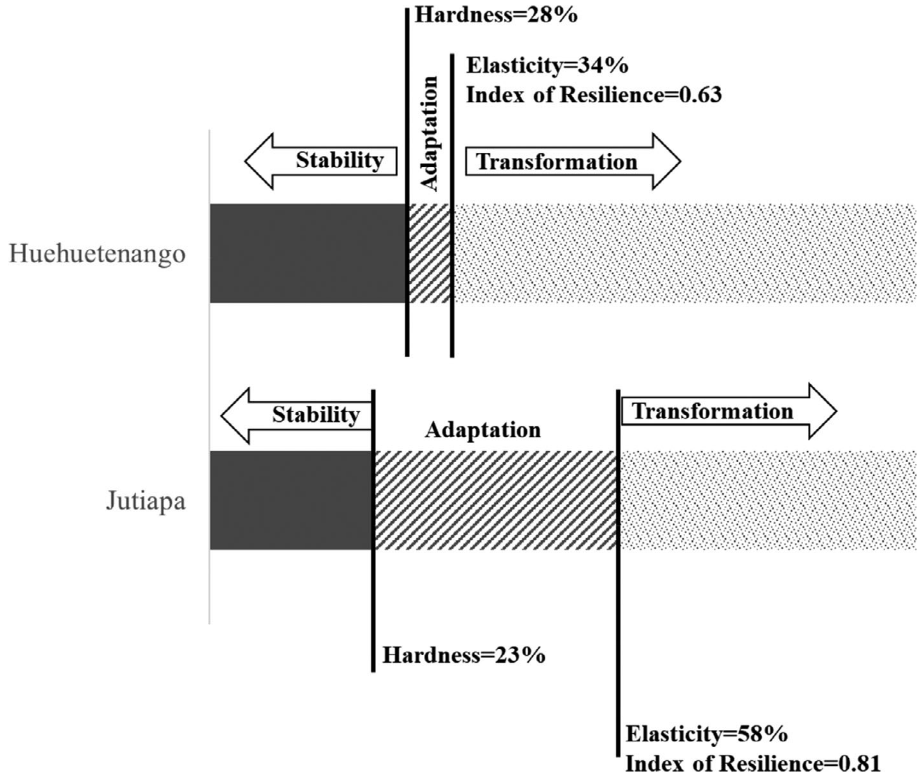
Fig. 11. Illustrative assessment of resilience using resilience measures



As shown in Figure 11, the magnitude of a drought that produces visible changes in the number of calories consumed in Huehuetenango (28%) is higher than the magnitude needed to produce similar changes in Jutiapa (23%). Hence food security is more likely to remain stable in Huehuetenango than in Jutiapa when affected by moderate droughts.

The elasticity index indicates the other important threshold of the system. This threshold marks the change between adaptation and transformation. As seen in Figure 11, the magnitude needed to transform the system towards a new state is lower for Huehuetenango (34%) than for Jutiapa (58%). Similarly, the index of resilience indicates how likely the system is to remain within the current configuration. In this case, the food system in Jutiapa is more likely to remain within its current configuration (index of resilience = 0.81) and the one in Huehuetenango is more likely to transform (index of resilience = 0.63). In practice, this indicates that Jutiapa is better at adapting to reductions in rainfall than Huehuetenango.

The differences between the two systems' behaviours is driven by a core part of the systems' structure, illustrated in Figure 3. Since the system is dominated by subsistence farms, the primary goal of farmers is to produce

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maize for their own families. The more maize they produce for their own consumption, the less they depend on the markets and the less they need to spend on food, leaving more money available for farming (see R3 in Figure 7).

In normal conditions, once the amount needed for subsistence has been met, the remaining maize can be sold at the market price. The more maize is sold, the more revenue farmers have. Famers can, and often do, use these resources to buy seeds, fertilisers and irrigation systems that improve their productivity (see R1 *commercial agriculture* in Figure 5).

However, when droughts unexpectedly reduce maize production, farmers need to allocate higher percentages of their production to self-subsistence (illustrated by R2 *poverty trap* in Figure 6). This adjustment in the allocation of maize production results in less maize available for the market and lower revenues for the farmers. Lower revenues result in lower production than otherwise, increasing once more the percentage of production that needs to be used for subsistence. This is a vicious circle, exacerbated by market dynamics and scarcity of local production driving local prices up.

The stability of food security depends on the two stocks “maize reserves” and “households’ cash”. If the magnitude and frequency of the disturbance are not too great, these two stocks act as buffers, diminishing the effects of production shortages on food consumption without affecting food consumption. Farmers could temporarily reduce their reserves to maintain their consumption while only making slow adjustments to the percentage of the production allocated for self-consumption. In a similar way, if there is sufficient cash in the stock, households might cut other expenses for a short period of time to continue the investment in agriculture at normal levels and to maintain production rates.

However, if the droughts are too intense or too frequent, stocks are not sufficient to maintain the normal behaviour, and the *property trap* loop (R2 in Figure 6) is triggered. The amount of maize sold declines quickly, reducing farmers’ revenues and their ability to invest in agriculture. As a consequence, maize production declines even more, putting even more stress on maize reserves and reducing the amount of maize available for sale even further.

The opportunities for adaptation depend on the strength at which the “vicious” feedback loops act and the time farmers must adapt to the new conditions. In our cases the strength of such loops was determined (i) by farmers’ dependency on agriculture as revenue source and (ii) on the dependency of maize production on the money spent on farming.

In Jutiapa, farmers combine subsistence maize production with poultry farming, which offers an alternative source of revenue and food during drought periods. Farmers in Huehuetenango, on the other hand, mainly depend on revenues coming from agriculture. Since the farmers in Huehuetenango consider poultry farming a “feminine” activity, alternative

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revenues come from working seasonally on large commercial farms. However, droughts affecting small-scale production affect large commercial farms at the same time. During severe droughts the farmers in Huehuetenango see both sources of revenue diminish, and the cash in their stock reduces rapidly.

The resilience literature has highlighted the importance of redundancy to enhance resilience. In this case, redundant sources of revenues, like revenues coming from poultry, can reduce the strength of the *poverty trap* loop (R2 in Figure 6) by reducing the depletion rate (outflow minus inflow) of the "households' cash" stock.

Another factor strengthening the vicious circle is the condition of the soil used for agriculture. Huehuetenango is characterised by poor soils that require special seeds and investment in fertilisers to reach minimum production levels. When farmers cut their expenditure on farming the yields decline significantly. The areas studied in Jutiapa, on the other hand, have better soils and even with minimum investment farmers can realise acceptable returns.

The additional sources of revenue, together with a soil that is less sensitive to annual expenditure on fertilisers, are factors that give the farmers in Jutiapa the time and flexibility needed to cope with more severe and frequent droughts.

Planning for food security resilience

Using the model and its results, we facilitated a discussion about potential policies to enhance the resilience of food security to droughts. The insights described in the previous section were presented to local and government stakeholders as part of the group model-building exercise that led to the formulation of four potential policies (see Table 3).

The policies were tested in the model and we quantitatively assessed their benefits using the same metrics that we used before to characterise the historic behaviour (hardness, flexibility and index of resilience). The results are graphically presented in Figure 12. The results show that Policy 2 (increasing poultry farming) is the most effective policy to increase system elasticity. Since the farmers in Jutiapa are already involved in poultry farming, the benefits of this policy are likely to be higher in Huehuetenango than in Jutiapa.

The benefits of Policies 1 and 3 on food security resilience were more modest (see Figure 12). Further model analysis revealed that this is because subsidies were not high enough to offset the loss of purchasing power resulting from the droughts. However, government representatives considered higher subsidies to be unaffordable. While policies 1 and 3 might be attractive in theory, in practice they turned out to be too costly.

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Table 3. Potential policies for enhancing resilience of food systems to climate change

Policy name	Policy description	Dynamic principle
Policy 1: Increasing subsidies to fertilisers	The central government currently subsidises fertilisers by 15%. The policy proposes to increase this subsidy to 35% among vulnerable farmers after a crisis	Reduces the strength of R2 by reducing the sensitivity of yield to households' cash
Policy 2: Increasing poultry farming	The policy proposes to offer subsidies, credits and training to farmers to help them to increase their livestock. Considering the households' size, the policy focuses only on increasing poultry	Reduces the strength of R2 by reducing the sensitivity of households' cash to maize production
Policy 3: Subsidies for irrigation systems	The policy proposes to offer subsidies to build irrigation systems including pumps, wheels, reservoirs and irrigation lines. The policy will offer constant support to farmers under the poverty threshold for up to 5 years	Reduces the strength of R2 by reducing the sensitivity of yields to households' cash
Policy 4: Emergency food bank	The policy proposes to create a food bank where farmers could store their food. For each kilogram deposited by farmers, the government will contribute with 10% on top in kilograms of maize.	Increases the system stability by virtually increasing the maize reserves stock

Finally, Policy 4 offers a promising alternative for increasing stability of the system (see Figure 12), particularly in Jutiapa, where farmers had lower maize reserves than the farmers in Huehuetenango. Increasing maize reserves by having an emergency food bank also reduced the strength of the "poverty trap", increasing the elasticity in both cases.

Conclusions

Climate change poses a severe threat to families relying on subsistence agriculture around the world. In this challenging context, it is urgent to identify how food systems can be more resilient and to formulate policies that help farmers to adapt to the challenging conditions.

Analysis of empirically based SD models revealed that stability in food systems is mainly driven by key strategic resources that moderate the effects

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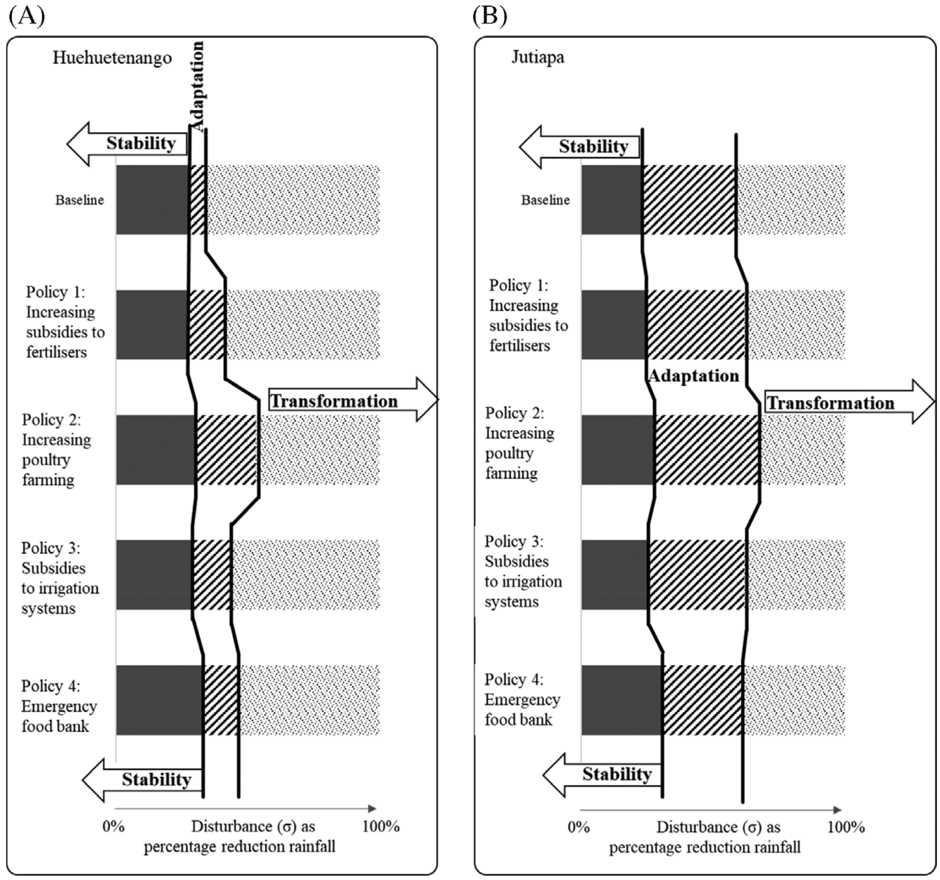

Fig. 12. Graphic representation of the impact of proposed policies on food security resilience

of environmental changes on food production and prices. We also discussed how adaptive capacity is shaped by the strength of feedback mechanisms within the system structure. If we can identify the feedback loops that move the system to a new state, it is possible to design policies that reduce their strengths and give farmers time and opportunity to adapt. For instance, in our case studies, redundancy of revenues and mixing crop farming with poultry farming could help farmers deal with more severe and frequent droughts.

While the above recommendations might be applicable to other cases, our experience also shows that resilience is context specific and it is unlikely to result in a "one size fits all" policy. Hence it is important to consider the entire dynamic complexity of the systems under study. As shown in this paper, the insights gained from identifying the key stocks and feedback loops dominating system behaviour help in understanding how policy recommendations might differ from case to case.

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Conflict of interest

The authors declare that they have no conflict of interest.

Biographies

Hugo Jose Herrera de Leon is Erasmus Master in System Dynamics alumnus and has a PhD in model-based public planning, policy design and management from the University of Palermo, Italy. He is currently working as researcher at the Department of Geography, University of Bergen. His goal is to help create sustainable and resilient systems by supporting the decision process using stakeholders' involvement, computer simulation models and a wide range of analytical tools. He has spent the last years working on a broad scope of projects, from public policies to business strategies. As diverse as these projects have been, in all of them the goal has been the same: to incorporate dynamic and systemic thinking in the decision making process.

Birgit Kopainsky has a PhD in agricultural economics from ETH Zurich, Switzerland, with a diploma degree in geography and environmental studies from the University of Zurich, Switzerland. She is currently working as Professor in System Dynamics at the Department of Geography, University of Bergen, Norway. In her research she explores the role that system dynamics analysis and modelling techniques play in facilitating transformation processes in social–ecological systems, such as the transition towards sustainable agri-food systems on local, national and international levels. Her goal is to provide guidelines for learning about complex dynamic systems and for making information about climate change, agriculture and food security both accessible and relevant for action. She works both in Europe and in several sub-Saharan African countries. She is particularly passionate about engaging with a wide range of stakeholders by creatively adapting proven tools and techniques, from systems thinking and system dynamics modelling to advance decision-making in social–ecological systems and to achieve breakthrough moments of understanding for those stakeholders to become champions of change towards resilience and sustainability.

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Supporting information

Additional supporting information may be found in the online version of this article at the publisher's website.

Appendix S1: Supporting information

Appendix S2: Supporting information

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