

# Shocks in coupled socio-ecological systems: what are they and how can we model them?

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**Abstract:** Coupled socio-ecological systems (SES) are complex systems characterized by self-organization, non-linearities, interactions among heterogeneous elements within each subsystem, and feedbacks across scales and among subsystems. When such a system experiences a shock or a crisis, the consequences are difficult to predict. In this paper we first define what a shock or a crisis means for SES. Depending on where the system boundary is drawn, shocks can be seen as exogenous or endogenous. For example, human intervention in environmental systems could be seen as exogenous, but endogenous in a socio-environmental system. This difference in the origin and nature of shocks has certain consequences for coupled SES and for policies to ameliorate negative consequences of shocks. Having defined shocks, the paper then focuses on modelling challenges when studying shocks in coupled SES. If we are to explore, study and predict the responses of coupled SES to shocks, the models used need to be able to accommodate (exogenous) or produce (endogenous) a shock event. Various modelling choices need to be made. Specifically, the ‘sudden’ aspect of a shock suggests the time period over which an event claimed to be a shock occurred might be ‘quick’. What does that mean for a discrete event model? Turning to magnitude, what degree of change (in a variable or set of variables) is required for the event to be considered a shock? The ‘surprising’ nature of a shock means that none of the agents in the model should expect the shock to happen, but may need rules enabling them to generate behaviour in exceptional circumstances. This requires a certain design of the agents’ decision-making algorithms, their perception of a shock, memory of past events and formation of expectations, and the information available to them during the time the shock occurred.

**Keywords:** *complex system, modelling, structural change, non-marginal-change, regime shift.*

## 1. SHOCKS AS DRIVERS AND SHOCKS AS CONSEQUENCES

Financial crises, outbreaks of virulent diseases or invasive species, hurricanes, volcanic eruptions, earthquake and tsunamis all can be considered as shocks that disturb economic, ecological, or coupled socio-ecological systems (SES) and interrupt their normal way of functioning. Although at first glance it may seem that the concept of a shock is straightforward, there in fact exists a dichotomy in the definition and nature of shocks. A distinction can be drawn between a systemic shock and a shocking event (disturbance) as a driver of system dynamics. In this paper by *disturbance* we mean an exogenous forcing either in the form of a hazard event or in the form of an extreme change in an input variable. After a disturbance, the system may either recover back to the same state (Figure 1, I) or may shift to a

new state<sup>1</sup> (Figure 1, III). A *systemic shock* stands for such a sudden structural non-marginal change in the system, i.e. regime shift. Systemic shocks are not only triggered by an exogenous disturbance (Figure 1, III), but can also occur through endogenous gradual changes in the system's components (Figure 1, IV), which prior to the critical point at which the shock occurred had not caused the system state to change (Figure 1, II). Below we discuss each type of shock in detail.

	<i>Current system state is maintained</i>	<i>Systemic shock (shift to a new system state)</i>
<i>Shock as a driver (disturbance)</i>	I. Recovery back to the same state	III. New state driven by exogenous shock
<i>Gradual change</i>	II. Remain in the same system state	IV. New state driven by endogenous gradual change

**Figure 1:** Concepts of a shock (system states and drivers of change). Shocks occur in boxes I, III and IV; a potential shock is building in box II.

This paper aims to highlight specific modelling challenges to consider when exploring coupled SES experiencing shocks. First, we provide a discussion on the difference between shocks as a disturbance and a systemic shock. Then, the modelling challenges are outlined. An example of an agent-based model studying systemic shocks follows, and we conclude with a discussion on challenges for future modelling work and the design of policies to mitigate or adapt to systemic shocks.

### 1.1 Disturbance: shock as a driver of a possible system change

External shocks (disturbances) may take either (i) a form of an extreme hazard event (tsunami, flood, earthquake) or (ii) an extreme change in an input variable (e.g. water availability, temperature, interest rate) in the system analysis of SES. The former may lead to the physical destruction of the system. However, whether or not a structural change (i.e. systemic shock) is to occur highly depends on the magnitude of the hazard event and the spatial scale of the impact. For example, Hurricane Andrew hit south-east of the USA in August 1992 causing damage in several towns including Morgan City. While the town infrastructure was partially destroyed, it was eventually restored to its previous state, thus not causing structural changes in the city. In contrast, 2005 Hurricane Katrina destroyed almost the whole of the city of New Orleans. The external shock was so enormous that it affected the image of the city for years to come, shifted the major regional migration flows, labour markets in the neighbouring states, and the structure of the economy well beyond the city scale (Groen and Polivka 2010). This exogenous shock changed the structure, function, and properties of the system, and thus constituted a major systemic shock. Hence, while the city of New Orleans is hit by storms every 2.26 years<sup>2</sup> (with more than 40% classified as hurricanes), the external forcing needs to be of a high magnitude and with spatial consequences well beyond the occurrence area to trigger a truly structural non-marginal change in the system.

The second form of external disturbance is an extreme change in an input variable or system component: an intensive rainfall, decreased precipitation, volatility in raw materials prices, changes in interest rate, or temperature fluctuations. Dynamic behaviour is normal for SES where truly stable states rarely exist. Nevertheless, several attributes distinguish "normal" fluctuations constituting the envelope of system behaviour within its current regime from a real disturbance that may trigger a systemic shock: magnitude, rate of change, duration and frequency of the disturbance as well as the resilience of the system itself (Folke 2006). For example, a single mild drought event will not cause farmers to change their cropping pattern,

<sup>1</sup> A system *state* is not a steady-state or equilibrium, but rather a regime characterized by a certain system's structure, properties and functionalities (Folke, 2006).

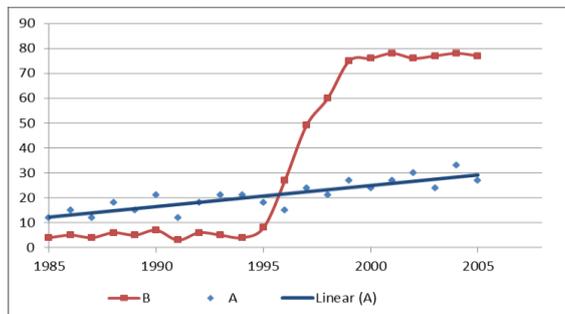
<sup>2</sup> Source: <http://www.hurricanecity.com/city/neworleans.htm>

let alone a structural change for the whole agricultural sector. However, if a drought is severe, lasts for a long time and repeats year after year, then a structural change in the agricultural sector is likely to occur.

In summary, disturbances such as natural hazard events or changes in the components and/or variables of a system do not always cause a non-marginal change on a system level. Whether they do so largely depends on system resilience and on the characteristics of the disturbance. Often concatenated shocks, i.e. disturbances that arise simultaneously, fuel each other and spread rapidly (Biggs et al, 2011), lead to the systemic crisis.

## 1.2 Systemic shock

From a complex adaptive systems perspective, SES are seen as constantly changing, co-adapting, and perpetually out of equilibrium (Arthur et al. 1997; Folke 2006). These dynamics can be in the form of *marginal change* when the system gradually moves along a certain trend (trend A in Figure 2). Such system dynamics are quite “convenient” for decision-makers (and modellers), as prediction of future states can with certain confidence rely on the historic trends and historic data. In other words, we know with a reasonable degree of certainty that with a unit change in explanatory variable(s) the dependent variable is likely to change in a predictable direction with a predictable extent.



**Figure 2:** Trends with marginal changes (A) and with a systemic shock (B)

structure, feedbacks, and underlying behaviour of components or agents (trend B in Figure 2). The number and diversity of regime shifts encouraged scholars to start collecting them into a ‘Regime shift database’<sup>3</sup>. It has been suggested that such regime shifts are preceded by generic early-warning signals that are universal in Earth science, medicine, and economics (Scheffer et al. 2009) (such as slowing down of the recovery rate after small perturbations, increased autocorrelation and variance in the pattern of fluctuations, asymmetry of fluctuations, flickering, and emergence of particular spatial patterns).

In complex ecological and economic systems, and hence in coupled SES, systemic shocks might be driven either (i) by an exogenous event, or (ii) by an endogenous gradual change in system components (economic, ecological, biophysical) and agents’ behaviour. As discussed above, the former often comes in the form of a shock such as an extreme hazard event or extreme change in an (independent) input variable. The latter has become especially apparent recently – in a time of collapse of ecosystems, financial crises, housing bubbles, and climate change. In all these cases it is difficult to identify a single shocking disturbance that caused a systemic shock. Instead, it was gradual overfishing that led to the near-extinction of species and destruction of coral reefs (deYoung et al. 2008), slow accumulation of CO<sub>2</sub> and other green-house gases that caused climate change and its adverse consequences (IPCC 2007; Stern 2008), economic agents one-by-one adopting seemingly rational rules that caused structural changes in financial markets and economy (Anand, et al. 2011), or the gradual spread of expectations among individuals of receiving a dividend from housing asset investments as housing prices grow annually driven by an increasing demand that was itself caused by those expectations (Arce and Lopez-Salido 2011). These ideas are taken up in the

At the same time, the growing body of literature suggests that it is common for complex SES to experience abrupt sudden shifts from one system state to another (Kinzig et al. 2006; Stern 2008; Scheffer et al. 2009; Anand et al. 2011; Vespignani 2012). A system experiencing a *non-marginal structural change (systemic shock)* transforms into a system with new properties,

<sup>3</sup> www.regimeshifts.org

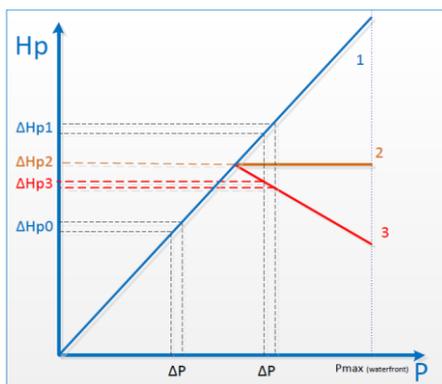
concept of self-organised criticality (Bak 1996), where in even quite simple systems, such as piles of sand, relatively large-scale changes (such as an avalanche) can arise from relatively small events (such as the addition of a single grain of sand). Interestingly, certain kinds of system tend towards the state of least stability (when the system is unstable with respect to small perturbations) (Bak et al. 1988), and have power law distributions in the size of critical events. Thus, due to interactions among system elements, feedbacks between scales, existence of thresholds, and path dependence in complex systems, the gradual accumulation of small changes at the micro-level can cause non-marginal significant change in macro-level dynamics.

Systemic shocks can arise not only from gradual changes in a single variable, but from the interactions among processes operating at different spatial and temporal scales. As Carpenter and Turner (2000) point out, the time periods of changes in ecosystems span several orders of magnitude. Moreover, the emergence of a systemic shock from the bottom up in complex socio-ecological systems is exacerbated by the fact that they are embedded in heterogeneous spatial landscapes. Both the initial spatial correlation of site conditions and the domino effect responses across neighbouring cells strongly affect the consequent evolving patterns of a dynamic adaptive system (Scheffer 2009). Indeed, criticality can arise solely from the connectivity of elements in a spatially embedded system, as attested by percolation theory, which explores the finding that there exists a critical threshold in the probability of connection among neighbouring elements in an underlying lattice topology, above which the probability of a path connecting one end of the lattice to the other tends to 1. For example, in a square lattice, the critical probability is  $\frac{1}{2}$  (Kesten 1980). Thus, if a shock is caused by connectivity across a lattice, then percolation theory tells us that the gradual accrual of connections among elements in that lattice makes a shock more likely.

A further complication to understanding the possible origin of shocks lies in the concept of the 'perfect storm', which suggests that shocks can arise through the a particular combination of a number of variables' values, each of which individually might not be thought extraordinary (at least, not to the extent that they would be seen as a shock), but collectively form a highly unusual set of circumstances. In systems with large numbers of variables, such shocks are more sinister, in that anticipating their occurrence requires a whole-system view that may be difficult for one person to gain.

## 2. MODELLING ASPECTS

In this paper, we are primarily interested in *systemic shocks* in SES and possible ways to model them. For example, as econometric studies show housing price ( $H_p$ ) rises with proximity ( $P$ ) to environmental amenity, e.g. beach or river front. As is often the case, such environmental amenity is spatially correlated with flood risk (Bin et al. 2008). Assuming that people's preferences remain the same, one may



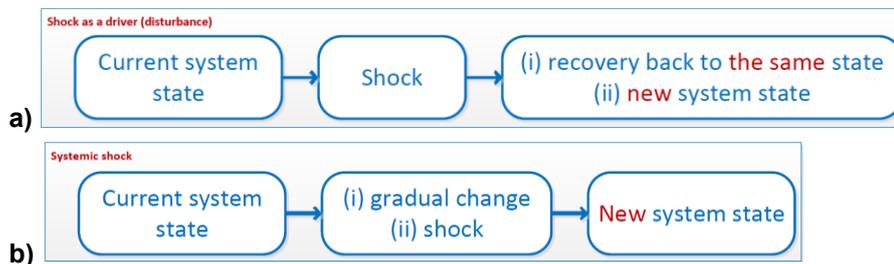
**Figure 3:** Marginal vs. non-marginal change

extrapolate the curve based on past choices. This implicitly means that a marginal change in the explanatory variable (proximity) will cause a marginal change in housing prices (see blue line #1 in Figure 3, where  $\Delta H_p0 > 0$  is proportional to  $\Delta H_p1 > 0$ ). Climate change exacerbates probabilities of river discharges and coastal storms leading to erosion, making these locations more risky for housing. As probabilities of natural hazards increase (exogenous driver of a structural change in the system) and risk perceptions among buyers grow (endogenous driver), the choices in this housing market will change.

At a critical point, the effects of higher amenities and growing risks may cancel each other out as proximity to the water front increases (orange line #2, Figure 3). As this structural change in demand

occurs, the marginal change in the explanatory variable (proximity) does not give the same gradual change in housing prices ( $\Delta Hp_2 = 0$  and is no longer proportional to  $\Delta Hp_0$ , Figure 3). When safety becomes a priority over high amenity level (because of growing hazard probabilities or increasing risk perceptions or both) the closer to the water front the house is, the further its price will fall (red line #3, Figure 3). Thus, the effect of proximity on housing price actually reverses ( $\Delta Hp_3$  is proportional to  $-\Delta Hp_0$  and  $\Delta Hp_3 < 0$ , Figure 3). In the case of such non-marginal structural changes affecting individual demand and consequently the whole housing market, statistical models tuned on historic data and relationships among system components based on its prior structure will not work. In other words, it is difficult to predict how much and in which direction the dependent variable will change with change in the explanatory variable(s) in one unit after the bifurcation point.

The dual notion of shocks for SES (sections 1.1 and 1.2) manifests itself in quite different visions of what the modelling of a system experiencing a shock should capture. If one focuses on modelling shocks as a disturbance there is often no perceived need to consider an alternative new state: the goal is to understand how the SES can maintain or recover back to the current state after a shocking event (Figure 4.a). This is especially true for economic models, in which the current equilibrium state is considered the most optimal one. In the case of a shock (e.g. major flood event) the concern is to return back to the “optimal” state, not to consider other possible states. However, in reality, the dynamics of SES affected by an external shock event may either bounce back to the old regime or slide into a new qualitatively and/or structurally different state (Figure 4.a). When simulating such a transition a modeller then has to consider various versions of alternative states, triggers for each of them (to identify a likelihood), as well as a set of criteria (possibly defined by different stakeholders) to identify the “optimal” one (in case management strategies are to be tested).



**Figure 4:** conceptual scheme for modelling various shocks

If however, we look at shocks as structural changes in the SES rather than just a disturbance (which may or may not change system state), the modelling logic is again different. There is a current regime and a possible new state of the SES (Figure 4.b). A transition between them can be either driven exogenously (for example by a shocking event) or endogenously (driven by internal dynamics of a system and positive feedbacks). Below we highlight what kind of modelling challenges one may face when simulating such systemic shocks.

## 2.1 Representation of systemic shocks

One dimension of shocks that applies to models rather than to reality is the question of whether the shock is endogenously generated or exogenously caused. As Scheffer et al. (2001) point out, a regime shift can be driven by external stochastic events, or by internal dynamics that drive the state of the system across a threshold. An exogenous shock (disturbance) to a simulation model would appear in the time-series data input to the model (but unaffected by its dynamics): e.g. climate change scenarios, scenarios of crop prices or population growth/decline. An endogenous shock is an emergent property of a system of interacting adaptive agents, processes and feedbacks across scales. Thus, a model should be able to accommodate the disturbance or be able to “grow” a systemic shock from the bottom up.

A matter specific to coupled SES and other multi-disciplinary modelling exercises as opposed to uni-disciplinary studies is that structural changes may be triggered by the feedbacks between the socio-economic and ecological systems, not necessarily by the micro-macro feedbacks within one domain (Kinzig, Ryan et al. 2006). This highlights the importance of explicit representation of two-way feedbacks in a simulation model (a fully-linked model in the terminology of Parker et al. (2008)). Systemic shocks may also be driven by a combination of anthropogenic and natural factors, when crossing a threshold in one domain causes cascading regime shifts across other domains.

Representation of endogenously generated shocks therefore requires the representation of the variable or variables in which the shock is to be observed, and the processes and feedbacks that drive it. Kinzig et al. (2006) observe that, as a rule of thumb, critical changes in socio-ecological systems are determined by a small set of three to five key variables. Representing endogenous shocks may thus not necessarily impose burdensome requirements in terms of number of variables.

The more challenging issue is not to omit important interactions among components and/or heterogeneous agents. While pursuing simplification (something any model has to do), we may aggregate and average certain empirically observed historic data. This aggregation and averaging could drop micro-level dynamics from which a systemic shock would have emerged. Thus, the appropriate balance between model details and complexity, and computational time and transparency of the results – a trade-off each modeller faces – becomes even more crucial when modelling systemic shocks.

## **2.2 Representation of system states**

One challenge when modelling a systemic shock is that the new system state has to be represented in the model. This entails the ability both to represent the entities and their relationships in the new system state, and to represent the system reorganisation that led to the new system being created. There are two senses to reorganisation: in one sense, the system restructures such that it consists of the same types of element, interacting in the same kinds of way, but the instances are different, and the connectivity of the elements may be different. A more radical sense of reorganisation, and a significantly greater challenge to model, is one where there are different elements and interaction types. An analogy for the difference is that, in the case of restructuring, for example, a feudal system is replaced by another feudal system, but with a different king and different lords pursuing different policy. The more radical sense of reorganisation would be the replacement of a feudal system with a democratic republic.

The capability to represent the restructured system in either case entails the representation of processes that create and destroy agents and links among them, and allow decision-making processes to adapt. Thus agent heterogeneity and learning are both potentially important aspects.

Moreover, there could be a variety of alternative states, and ideally each of them should be representable in the model studying systemic shocks. If there is a variety of alternative states, then the question is which of them is most likely to occur and under what circumstances (i.e. current system's state, endogenous or exogenous trigger of systemic shock, etc.).

## **2.3 Shock detection, persistence and thresholds**

For an exogenous disturbance, the modeller has advance knowledge of what the shock to the system is, and is presumably largely interested in how the system responds. In the particular case that a model is designed to explore the conditions under which a known shock emerges endogenously, the problem should also be relatively trivial. However, detecting that a systemic shock has occurred in the general case could pose more of a challenge. It requires knowledge of the 'normal' bounds of behaviour of the system in at least two regimes: those the model is in prior to and after the shock has occurred. It is possible that knowledge of more regimes would be required if there are multiple possible regimes the model could shift to as a result of the emergent shock. Moreover, a decision should be made on what degree of change in macro-measures of interest, which presumably

characterize the structure and underlying behaviour of the elements of the system, constitutes a shock.

There are, however, a number of heuristics that could be used to suggest that an endogenous shock has occurred, not least of which is unusual values for variables, and particularly those pertaining to evidence of system restructuring, such as changes in connectivity of relationships among agents. One clear case is when the model shifts to states that would not occur in the real world (assuming this has not arisen from a bug). All models have a defined system boundary determined by the phenomena that are, and are not represented in the model, and in what way (endogenously or exogenously). An endogenous shock could push a model into a state that does not occur in the real world, because the phenomena that would prevent the occurrence have not been represented.

After any shock, there should be a period of time, however short, when the state of the model is not within the normal operating values of the regime it was in prior to the occurrence of the shock. In other words, the new state is irreversible or at least slowly-reversible. As mentioned earlier, in the case of a disturbance, the system may eventually restore itself to the regime it was in prior to the disturbance; this is a notion at the heart of resilience theory. We can measure the persistence of a shock as the length of time it takes to restore the regime prior to the shock's occurrence. In the case of a systemic shock, we expect the persistence to be longer than the short term. In some cases it may be impossible to restore the prior regime after the shock has occurred (an example could be the extinction of a keystone species in an ecosystem), and in these cases, the change caused by the shock is irreversible.

The persistence of a new system structure and properties is a vital element in the detection of systemic shocks. While the detection of regime shift in relatively simple systems (e.g. dominance of algae in coral reefs) is straightforward, it is a challenge in itself for large-scale complex systems such as world oceans (deYoung, Barange et al. 2008). Regime shifts in oceans are not sudden and are asynchronous across ecosystem components; observing them requires comprehensive statistical techniques to analyse data gathered over decades to make sure the new regime persists. Although, one does not need to wait decades to get simulated time series data from a model, the issue of which period of time to consider "persistent" is still vital. Obviously, it is relative to the duration of the previous regime and the suddenness of the transition.

Kinzig et al. (2006) also discuss thresholds – a point at which one regime gives way to another. If these are known, then the crossing of thresholds can be detected and used as a surrogate for other measurements of the model's behaviour that indicate a shock. However, after a system crossed the threshold there might be a time lag in the reflection thereof in the domain-specific macro-measures of interest that serve as indicators of systemic shock. Empirical research on marine ecosystems shows that while the atmospheric changes and the resulting physical oceanographic responses detect a regime shift quickly (in a year), the dynamics of various marine species in responses to these changes can have different spatial and temporal patterns (deYoung, Barange et al. 2008). There are a number of additional issues when modelling thresholds. Thresholds can shift as a result of changes in slow variables, and crossing a threshold may be a necessary, but not sufficient condition to indicate a regime shift (Kinzig, Ryan et al. 2006). That is to say, all times the regime shift occurs, the threshold is crossed, but not vice versa. The same logic can be applied more generally: perhaps regime shifts do not only occur because of anything that would be called a shock – they might arise from an evolutionary process without any unusually dramatic event occurring at all.

#### **2.4 Temporal scale (suddenness)**

A potentially important element to a shock is its 'suddenness'. A shock is typically an event which takes place over a relatively short period of time in comparison with other processes. Even in the case of a systemic shock arising from gradual endogenous changes within the system, it is the restructuring of the system – an event that occurs over a relatively short timespan – that constitutes the shock. For a disturbance, the same magnitude of change in the variable to which the disturbance is applied could, if applied over a longer time period, not cause a regime shift at all.

From a modelling perspective, particularly in the case of discrete event models, the possibility arises that when simulating a shock, there may need to be an adjustment to the schedule. Agents may need to make decisions over relatively short time scales than those they normally do. There may also be an issue with shock detection: the shock may not be detected by looking from one time step to the next, but by comparing more temporally distant time steps.

## **2.5 Spatial scale and system boundaries**

A systemic shock at one scale may not be pronounced or noticed on another scale. This is valid for scaling up in geographical spatial scales as well as in the number of agents in the system (when effects of heterogeneity and local interactions that are crucial for smaller-scale systems dissolve and disappear as number of agents grow in several orders of magnitude). The implication for modelling systemic shocks then is to test whether exogenous or endogenous shock still holds when one scales up. The opposite may also be relevant: large-scale, often highly-aggregated models may omit the occurrence of shock at lower scales, which are often more important for policy-makers as the implementation of policies is delegated to the local level. Naturally, it is also important where one puts the boundary of a system, especially for SES. Environmental economists consider the natural system embedded in the large economic system and include it in the models as a source of resource and a receiver of waste. Ecological economists and natural scientists view planet Earth as a large system that embeds the socio-economic system as a subsystem. The choice of boundary is subjective, but it can largely affect the occurrence and detection of systemic shock.

Coupled SES are characterized by multi-scale multi-domain feedbacks: the dynamics in various scales of organizational economic system affect the dynamics of natural system at various spatial scales (Kinzig, Ryan et al. 2006). The positions of critical thresholds and chances of crossing them in one domain and scale dynamically react on the changes in other domains and scales. This phenomenon of a moving threshold is another issue to consider when designing a model that is able to capture systemic shocks.

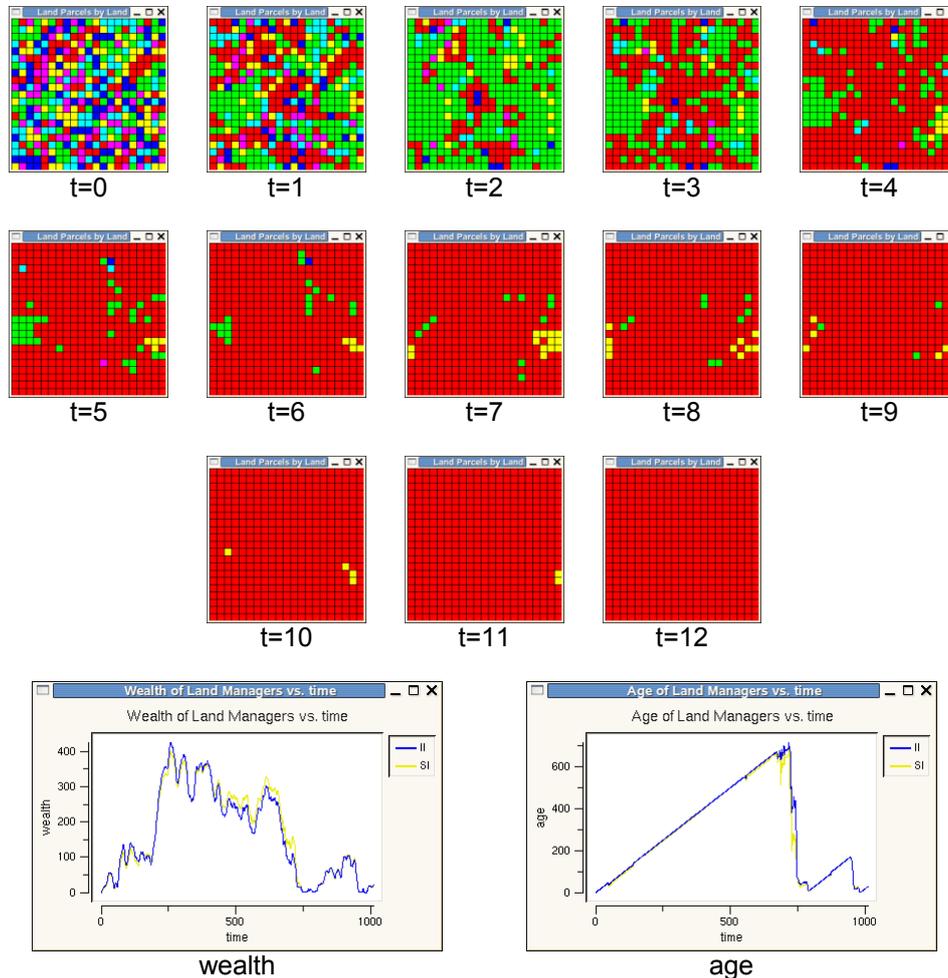
## **2.6 Subjectivity**

These challenges to modelling shocks derive at least in part from the subjectivity inherent in the concept of a shock. The system boundary, scale, timing (persistence and suddenness), spatial extent, degree of restructuring and magnitude of the shock are all matters of perception. Whether or not a shock is unexpected depends on prior knowledge and experience. Indeed, what constitutes a 'regime' may be a matter of opinion. As such, the concept of a shock may suffer many of the same problems as that of emergence does in the complex systems literature: emergence too, has been argued to contain an element of 'surprise' (Ronald et al. 1999). It thus behoves authors using the concept to explain what they mean by it, in the context of their own model. (It could be that 'shock' should be added to the list of 'Design concepts' in a future revision of Grimm et al.'s (2010) ODD protocol for describing agent-based models, especially where a model is intended to study a particular shock.)

## **3. MODEL EXAMPLE: SHOCKS IN FEARLUS**

The FEARLUS (Framework for the Evaluation and Assessment of Regional Land Use Scenarios, (Polhill et al. 2001; Gotts et al. 2003; Gotts and Polhill 2009; Gotts and Polhill 2010; Polhill et al. 2010)) model is an agent-based model of agricultural land use change, classified by (Boero and Squazzoni 2005) as a 'typification': a theoretical construct "intended to investigate some properties that apply to a wide range of empirical phenomena that share some common features." It simulates agents representing farmers, who must choose each year (the time step of the model), the land uses they will apply to their land parcels. These land uses are then harvested, and the land managers accrue wealth from selling the goods, from which is subtracted operating costs. Both the yield and the market for land uses are determined by exogenous time series (the climate in the former case, and the economy in the latter), the yield additionally by spatially varying biophysical

characteristics of land parcels. After accruing wealth each time step, farmer agents with negative wealth sell their land, which may then be bought by their neighbours or by in-migrant land managers. The agents are better conceived as farm businesses, as their lifespan is not limited by anything other than the period for which they can maintain non-negative wealth.



**Figure 5** (top) Time series of land uses in one run of FEARLUS showing lock-in in twelve steps; (bottom) Time series plots of mean wealth (left) and mean age of business (right), showing the initial regime lasting around 750 time steps before all agents become bankrupt (indicated by a sudden drop to zero in mean age), followed by another lasting roughly 200 time steps. The mass bankruptcy events are precipitated by a relatively prolonged decline in mean wealth. Plots are shown separately for two subpopulations of managers (labelled 'II' and 'SI') using different purely imitative algorithms to choose land use.

Much of the work in FEARLUS has been in the exploration of the relative success of various heuristic decision-making algorithms, and imitation in particular (Gotts and Polhill 2009). In experiments involving what we term 'purely' imitative strategies – those that only choose land uses appearing in the neighbourhood of the agent – all agents can 'lock-in' to a single land use in a finite period of time (Figure 5) (Gotts and Polhill 2010). Once lock-in occurs, no agent can choose anything other than the locked-in land use, and any difference in the performance of the imitative algorithms will, from that point on, have no effect. When the exogenous climate or economy time series entail changes that mean the locked-in land use is no longer profitable, the agents start to lose money, and if the land use remains unprofitable for long enough, they go bankrupt. In-migrant land managers are also 'pure' imitators in these experiments, with the consequence that when the locked-in land use is unprofitable, the in-migrant managers go bankrupt immediately. In such simulation runs, there can be several time steps in which all agents are bankrupt in each time step. A situation in which any abnormally large proportion of farmers

were going out of business each year would be regarded in the real-world as a shock; but if all of them go bankrupt, that is taking the situation to an extreme, one that in the real world would be unlikely to occur (not least because real farmers are not pure imitators). In the run in Figure 5, the mass-bankruptcy shock occurs a considerable time after lock-in. This time period is a function of the fact that, after lock-in, each agent's wealth is a random walk driven by the way changes in the economy are modelled, with 0 as an absorbing state. The decline in wealth is exacerbated by agents buying parcels off their bankrupt neighbours, which increases their exposure to losses if the unprofitability of the locked-in land use persists.

This is an example of a shock that is driven in the model by two forms of gradual change, one endogenous, the other exogenous: (i) the effective extinction of possible land use choices as the purely imitative land managers cease using them in favour of more profitable options given the current state of the climate and economy; (ii) the gradual change in profitability of the locked-in land use. It also shows how an endogenous shock can be recognised by the model entering an invalid state. FEARLUS has no contingency for handling the case where the bankruptcy rate is too high; this was simply not part of its design. Land abandonment due to lack of profitability in farming has been a concern for a number of years (MacDonald et al. 2000). Were we to simulate such a systemic shock in full, showing the system restructuring after land abandonment by farmers, we would need to include in the model processes such as urbanisation, gentrification, afforestation or the return of the land to nature. Thus, whilst it is quite possible to improve FEARLUS so that could handle such a shock, the effect has been to move FEARLUS outside its original system boundary.

As time progresses in the model, the locked-in land use can again become profitable, and the land manager agents do not keep going bankrupt. One way to look at the restructuring of the system is in the new land ownership pattern.

#### **4. CONCLUSIONS**

Either because a new alternative state is less desirable or because an abrupt change triggers significant losses in the short-term, policy-makers in various levels and domains are eager to understand the nature and drivers of these non-marginal changes and manage them where possible. This paper discusses the dichotomy in the definition of shocks (shock as a driver vs. systemic shock) and highlights the challenges that one may face when designing a model to capture exogenous or endogenous systemic shock. We have demonstrated an example of modelling both types of systemic shock with an agent-based model FEARLUS. In addition, we asked the participants of the session "Modelling responses to shocks in coupled socio-ecological systems" to reflect on the following questions when presenting their models of shocks in SES:

- Is the shock endogenous or exogenous?
- Does it originate in the human or the environmental system?
- Are the consequences of it experienced in the human or environmental system, or in both? (If both, which first? and is it still a shock by the time it propagates to the other?)
- Comment on the suddenness of the shock, the (set of) variable(s) in which it is observed, and the magnitude of change in those variables
- In what way is the shock 'surprising' to the agents? (If at all -- indeed, do you see this as a necessary condition?)
- What modelling method to study shocks did you choose, and why?
- What challenges specific to representing and responding to shocks in the model did you find, and how did you deal with them?

We are used to thinking of shocks as negative events and to try to minimise the chances of their occurrence. Ecologists talk about catastrophic regime shifts, economists – about a loss of equilibrium. Naturally, a highly eutrophic lake or a city destroyed by an earthquake is certainly tragic. But do shocks always bring the systems into a less desirable state? Aren't they sometimes a part of evolution and progress? A transition to a democratic society (probably through a revolution) or a

shift in consumer preferences to ecologically-friendly goods or low-carbon energy sources (likely through the bankruptcy of conventional individual producers or even the whole sector) widen our perspective on shocks. What is universal for shocks with positive and negative consequences, however, is that models with which we study these processes should be able to accommodate this structural change and out-of-equilibrium dynamics. This paper highlights specific modelling challenges to consider when exploring coupled SES experiencing shocks.

An overall aim when studying shocks in coupled SES is to understand their nature and, thus, to find effective ways of managing circumstances in which shocks occur (mitigation), or reducing negative consequences of shocks that cannot be avoided (adaptation). This is, however, an enormous challenge as designed policies run a risk of omitting vital positive feedbacks in SES. Consider for example catastrophic floods that have low probability of occurrence but enormous consequences. It is unreasonable to abandon the area as disaster does not hit often. Thus, it may seem rational to group most valuable properties and businesses in well-protected clusters. However, this policy stimulates positive feedbacks as demand for protected areas rises, considerably increasing the potential damage while still leaving a chance of a disaster. Thus, a policy meant to manage exogenous shocks in SES may in contrast shrink system resilience as diversity of patterns of resources and people allocation reduces. Indeed, as research in various domains shows, promoting diversity is the best way of governing shocks (Scheffer 2009). Models that are able to capture systemic shocks that are either triggered by exogenous disturbance or endogenous dynamics in system components will help to predict structural changes in the system, foresee their consequences and design effective policies to prevent or manage the transition. However, models of SES that comprehensively capture the adaptive nature of such systems and that are able to capture systemic shocks are still to come. We hope that the discussions during the session in addition to the issues outlined in this paper will help to move this forward.

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