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Misperceptions of feedbacks and the resilience of common-pool resource systems: a discussion for irrigation systems based on loop dominance analysis

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Abstract: The paper proposes that irrigation schemes may be less resilient to environmental shocks than generally believed in the common-pool governance literature, because they are subject to positive feedback effects which may be not perceived timely by users. It builds on system dynamics literature to form a procedure in order to assess if the system is about to be locked into downward trajectories of loss of resilience. It concludes by suggesting that the basic ideas presented might be useful to build operational early warning signals for critical transitions not only in irrigation systems but in a wider range of systems where tipping points are suspected to exist.

Keywords: Irrigation systems, loop dominance analysis, resilience, sustainability, system dynamics

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1. Introduction

Common-pool resource management literature has recently made it clear the importance of incorporating ecological context to better interpret users institutional responses to environmental shocks in different settings (Anderies et al. 2011). Still, thus far, only limited attention has been paid to features of resources that affect their sustainable governance. One of the few papers to address this issue focus on two physical characteristics of resources – stationarity and storage – concluding that these factors have an impact on management because they affect information costs (Schlager et al. 1994). Specifically, greater mobility and difficulties of resource storage would make its management harder because it is more difficult to assess the quality and quantity of fugitive flow unities like fish, compared to stationary and/or stored flows. By the same token, the ability of store flows in irrigation systems, for instance, could smooth the pulses of water flows deferring surpluses for later use. The authors conclude that, due to these facts, users may be able to understand better the relationship of current appropriation activities to water stocks and thus interrupt cycles of depletion before systems pass critical thresholds and move toward extinction.

The above conclusion, however, might not always be true, once the acquisition of information about stocks and flows in complex systems can be very costly. A wide body of system dynamics literature has emphasized the experimental result that people do poorly on perceiving feedbacks driving their systems (Moxnes 2000; Sweeney and Sterman 2000). One significant reason for this is that most systems involve sets of interrelated activities, whose links over space and time people mostly underestimate or do not take into account timely even when information about their existence, length, and content is available and salient (Sterman 1994). This probably happens in all dynamic systems, but complexity matters in the sense that, since structural and behavioral correlations accumulate between components and across time in complex systems. The larger the set of interrelated components and hence the number of related stock variables in the system, that is the larger the order of the delays between initial in-flows and final out-flows, the smaller the initial response with a stepper and faster eventual rise to the final value (Sterman 2000, Chap. 11). It is easily proved as a general result that increasing the order and the time constant of delays, respectively, increases the maximum effect of a pulse function over the system and the time for the peak to occur. For instance, comparing the maximum effect caused by an exogenous shock and the time for that effect to occur in relationships separated by a second- and a third-order delay, the maximum effect and the time to this effect to occur increases, respectively, by about 10 and 33% (Meadows 1989, 219–224).

Adding stocks to the systems, in short, complicates its control and typically slows down reactions (Moxnes 2004, 150). Effective learning in those systems is difficult because there is no accurate and immediate feedback about the relation between the situational conditions and the appropriate response, which makes outcomes not easily attributable to a particular action (Tversky and Kahneman 2000, 222). A typical failure scenario in those settings is as follows. An environmental shock hits the system but the effect is not realized by users, which discourages the adoption of forceful control attempts before the system undergoes a sudden regime shift beyond which system's key outflows eventually start to decrease.

Learning about system dynamics, contrary to the conventional view presented at the beginning of the paper, may then be harder in "stock-type" resource systems such as irrigation schemes, in which resource is storable and time delays longer, than in “flow-type” resource systems like fisheries, in which resource is mobile but time delays are relatively shorter (Sweeney and Sterman 2000; Moxnes 2004, 150). Perhaps this is why, somewhat counter-intuitively, fishermen seem to be more aware of the bio-economics of their systems than irrigators, as tacitly recognized by Schlager et al.[1]

Irrigation schemes, thus, may be less resilient to environmental shocks than it is generally believed in common-pool resource governance literature. Intuitive analogies with houses, where the feasibility of storage indeed allows households smoothing variation in water flows, are misleading. In irrigation systems, the ability of store water for future use makes room for systems starting to be driven by positive feedback loops long before farmers can notice they have been locked into resource degradation trajectories. Increasing the efficiency of water deliveries or the drainage in order to control salinity, for instance, can make a whole irrigation scheme counter-intuitively more fragile, insofar that can lead people to increase irrigated land into drier and drier regions and, after a long delay, to lower water flows, inappropriate cropping and herding practices, and growing salinity levels through the system (Ford 1996a; Saysel and Barlas 2001; Férnandez and Selma 2004). The impacts of droughts become largely more severe as a result of these feedback loops, triggering local food shortages, forced liquidation of livestock at depressed prices and social conflicts, which implicate losses of social capital (Sivakumar 2005).

This probably helps to understand why farmers in many successful irrigation systems around the word have eventually allowed their systems approaching tipping points of sustainability. Again, that may happen because the misperception of long delayed feedback processes reduce learning effectiveness even in naturalistic contexts where subjects take decisions in familiar conditions.

Irrigation projects can be subject to long delayed feedback processes related to catchment degradation as well. Erosion, for example, leads to siltation of canals and of reservoirs, which makes poor operation and maintenance (O&M) the bigger problem for the sustainability of irrigation projects mainly in less developed countries, where many of those projects are managed for incompetent bureaucracies combined with weak irrigator associations (Jones 1995). However, causality between maintenance and catchment degradation can also manifest in reverse, leading to infrastructure degradation even if farmers are not particularly resistant in paying maintenance fees. Rather, they simply can be unable to do that if they are locked in feedback reinforcing loops of lack of maintenance. In

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[1] All fisheries studied by authors adopt simple and effective rules to preserve fish stock, such as prohibiting fish smaller than a specified size may be harvested in order to allow they have the opportunity to spawn at least once. Irrigators, on the contrary, prefer to limit out-flows by assigning rights to specific quantities of pumping, a flow allocation scheme which indicates they seem to rely on a far wrong heuristic that the water stock trajectory should have the same qualitative shape as the net rate (Sweeney and Sterman 2000, 278).

a classical study on the subject, Elinor Ostrom (1992, 89) states the problem as follows.

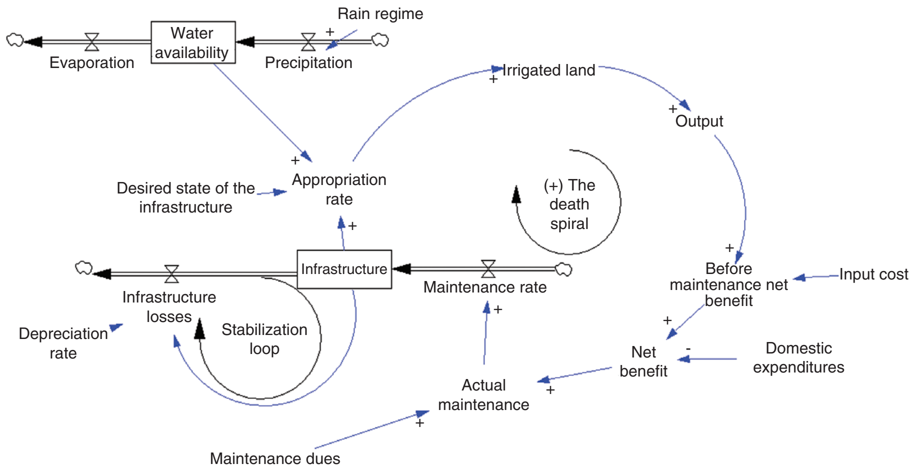
"Unless farmers pay the fees used to hire O&M staff or they perform these O&M activities themselves, many irrigation agencies will not be able to do anything more than operate systems in a minimal fashion. Little investment can be made in routine or emergency maintenance. The initial lack of maintenance triggers a vicious circle that has been characteristic of many large systems constructed in recent years. Without adequate maintenance, system reliability begins to deteriorate. As reliability diminishes, farmers are less willing to make investments in expensive seeds and fertilizers that are of little benefit without a reliable water supply. Without these input investments, the net return from irrigated agriculture declines. As returns fall, farmers become still more resistant to contributing to the system's sustainability."

This paper builds on system dynamics methodology of loop dominance analysis to show how irrigation systems may unexpectedly enter into downward paths of loss of resilience when hit by even tiny, and therefore hard to notice, environmental shocks, once they are operating near their sustainability tipping points. The remainder of the paper is organized as follows. The next section presents a hypothetical system dynamics model based on the work of Elinor Ostrom and colleagues, which underpins the above conclusion, and summarizes the essence of the loop dominance analysis approach. Section 3 presents an algorithm to study the sustainability of irrigation systems. Sections 4 and 5, respectively, present and discuss the main results, suggesting how to identify leverage intervention points and key actors for successful interventions in pre-collapsing irrigation systems. Section 6 concludes by suggesting that the basic ideas presented might be useful to build operational early warning signal of loss of resilience – that is the systems' ability to maintain their structure and function overtime under external stress – not only in irrigation systems but in a wider range of systems where tipping points are suspected to exist.

2. Model Description

Ostrom's ideas on the sustainability of irrigation systems outlined in the introductory section were later formalized in a system dynamics model by herself and colleagues at Indiana University (Sengupta et al. 2001). We propose below a VENSIM (Ventana Systems) simplified version of Ostrom and colleagues' model to assess the sustainability of irrigation systems (Figure 1). The fully documented original Stella version model, from which this simplified version was built, is presented in the referred paper and the present VENSIM version is available upon request.

System dynamics model approach is a method of analyzing problems in which time is an important factor, and which involve the study of how the system can be defended against, or made to benefit from, the shocks which fall upon it from the outside world (Coyle 1996, 9). A system dynamics model is designed as a hierarchical construct of a set of components that represent something quantifiable. The major components are as follows (Jopp et al. 2011).



Where Actual Maintenance = MIN (Maintenance Dues, Net Benefit)

Figure 1: Loop dominance in irrigation projects.
The state of the irrigation infrastructure depends on the irrigators perform properly its maintenance. The amount of water appropriated by irrigators – the appropriation rate – on the other hand, depends both on the water availability and on the state of the irrigation equipment (Infrastructure). The larger the amount of water that irrigators have access, the larger the portion of irrigated land and, given the land productivity, the output they produce (the arrows marked with a positive polarity sign mean that a direct relationship exists among the variables). Larger outputs mean larger profits and consequently better conditions to invest resources in the maintenance of the irrigation equipment, after the deduction of the domestic expenses. The amount spent by irrigators on equipment is given for Actual maintenance=MIN (Maintenance Dues, Net Benefit). That is, the smallest value among the net profit minus the domestic expenses and the value necessary to keep the equipment in operational conditions. That means simply that, under normal conditions of profitability, irrigators will pay their right portion of the equipment depreciation. However, irrigators may not be able to reinvest the total amount required to recover the depreciation of the equipment when profits fall and the system can enter a snowball downward trajectory of infrastructure losses – the death spiral. The amount invested in equipment maintenance in that case would be determined by the difference between the actual profit earned and the domestic expenses.

- Stocks or levels that store material, energy, or any kind of quantity in focus (e.g. the value of infrastructure).
- Connections or links that represent the flow of the quantities between the stocks. A + sign on the link means that when the variable at the tail of the arrow changes, the variable at the head always change in the same direction; a – sign has the opposite effect.
- Controls, drawn as valves, that are used to specify the extent of flows occurring between different stocks (e.g. maintenance and infrastructure losses).

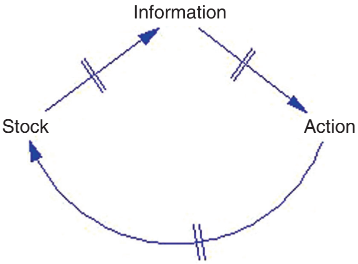


Figure 2: The system dynamics approach.

- Sources and sinks that indicate the systems borders and are represented by clouds. Sources are used for flows that don't originate from within the system (e.g. precipitation) and sinks, displayed with the same symbol as a source, that represent flows that originate from within the system but not end in a system stock (e.g. evaporation).
- Auxiliaries that represent expressions which occur more than once in the specification of different controls (e.g. the appropriation rate).
- Parameters that are constant variables used to specify controls (e.g. the depreciation rate).

System dynamics approach can be summarized as in Figure 2.

The state of the system, such as assessed by the state of an irrigation structure, derives from actions and choices made for users. The parallel marks on the links mean that there are usually significant delays among information, actions and the effect being felt in the state. The information about changes in the state of the system leads to new actions, such as attempts to improve the maintenance of the irrigation schemes. In that case, system is driven by a negative, goal seeking feedback loop. If the new information leads users to reduce further maintenance, for instance because they realize that the system is already locked in an irreversible collapse trajectory, it would be driven by a positive or self-reinforcing loop.

In the basic stock-flow structure of the simplified model presented in Figure 1, there are just two stocks and two loops. In the self-reinforcing loop labeled as "the death spiral", the degradation of the irrigation infrastructure due to inadequate maintenance leads to falling output, benefits and infrastructure maintenance, which further decreases the infrastructure reliability. In the stabilizer loop, decreases in the depreciation flow due to the reduction in the state variable balance the effect of the self-reinforcing-loop into the state of infrastructure.[2]

The degree of sustainability of the above system can be assessed as follows: what level of disturbance, droughts for instance, can the system withstand before

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[2] The model is fully documented in the Appendix.

the agents stop investing the total amount needed for the integral maintenance of the infra-structure?

It is easily seen that as far as irrigators are able to carry out their maintenance dues the infrastructure is maintained in appropriated use conditions. But if they are forced to spend less than that value, the maintenance rate will be lower than the infrastructure losses and the infrastructure will decrease in size. Hence, in the next period, the amount appropriated of water, output and profits will decrease and so will maintenance spending. Once the irrigators are forced to pay less than the right maintenance dues, the system can enter into a snow-ball trajectory we have labeled “the death spiral”, because the final outcome of the process is the complete degradation of the existing infrastructure.

The whole process can be summed up as follows:

1. An exogenous environmental shock such as a decrease in rains decreases Availability of Water, Irrigated Land, Output, Profits, and Actual Expenditures in Infrastructure Maintenance.
2. If Actual Expenditures in Infrastructure Maintenance equals the infrastructure losses, the infrastructure will be preserved at the present level.
3. If Actual Expenditures in Infrastructure Maintenance is lower than the infrastructure losses, the infra-structure will start to degrade and the system will enter into a collapse trajectory, dominated by the death spiral loop.

Figure 3 presents the above argument graphically.

Where k is the value of the infrastructure at time t and k1 its sustainability tipping point. Below that point the death spiral dominates (maintenance<infrastructure losses) and the system collapses to k0. Above it the equilibrium loop dominates the system’s dynamics and it eventually recovers its

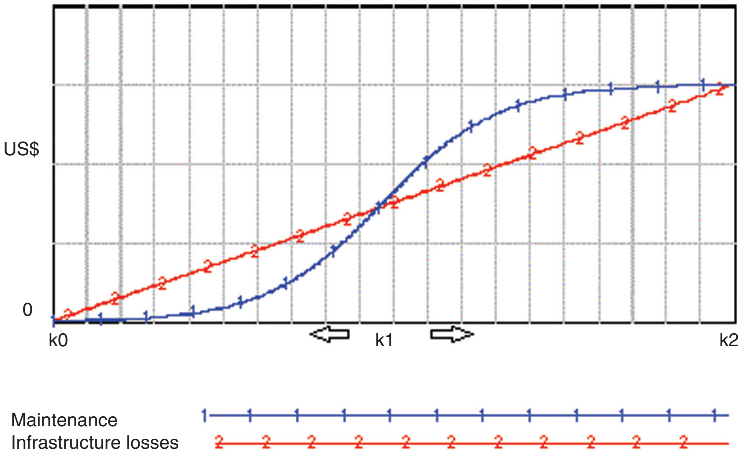

Figure 3: Irrigation systems’ sustainability tipping point.

former operation conditions (k2). In the following sections, we indicate how to calculate the sustainability tipping points of irrigation systems.

A more rigorous analysis on how important dynamic patterns arise in social ecological from feedback structures can be found in the classical Richardson (1995) paper on loop dominance, in which this paper is based on. Our conjecture is that the loss of sustainability in irrigation systems can be seen as a bifurcation point in their dynamics through time caused by shifts in loop dominance. More precisely, we shall argue that irrigation systems lose sustainability when their dynamics start to be driven by positive, self-reinforcing loops like the "death spiral" in Figure 1.

Several recent studies using the system dynamics approach have applied similar ideas to study tipping point properties of dynamic systems. Some examples are as follows. Rudolph and Repenning (2002) show that the accumulation of routine events can suddenly shift organizations from a resilient regime which off-sets the accumulation of interruptions in existing plans and procedures, to a self-escalating regime that amplifies them. Taylor et al. (2006) explain why the accumulation of tasks in the development phase of new projects in an organization can generate ripple effects during the completion of these projects leading them to collapse. Ford (1996b) suggests that electric companies may be trapped in a spiral of losses for expanding capacity ahead of demand beyond a certain critical level. Bueno (2012) shows how mathematically to compute tipping points in small socio-ecological systems. The basic idea of all these works is systems cross their resilience tipping points when they exceed certain thresholds in which shifts in dominance of feedback loops take place. Given the commonalities among the processes, it seems plausible that approach might also help to better understand regime shifts in economic processes as long wave cyclical movements in investments and output (Sterman 1985) and perhaps structural breakdowns in economic activity like the recent financial crisis.

3. Methodology

3.1. System dynamics methodology and system's behavior patterns

A central message of system dynamics methodology is that structure drives behavior; system dynamics methodology explains how exactly the former drives the behavior of variables of interest in a particular system (Forrester 1961). There are only three unique basic behavior patterns based on the net rate of change, or atomic linear behavior, of a variable of interest, say mature fish population in a fishery. The first is linear behavior, when the variable grows or declines steadly. The second atomic behavior is exponential growth or decay, when the variable moves away from its initial value faster over time. The last pattern is logarithmic growth or decay, when the variable moves away from its initial condition at a slower rate over time. Thus, atomic behavior can be described by the second time derivative of the values of the variable of interest: a second derivative equal to zero indicates a constant rate of change, and positive and negative second derivatives indicate, respectively, increasing and decreasing rates of change. The three atomic behaviors (or combinations among them) can describe most behavior presented by systems. For example, a positive second derivative of the level variable fish population indicates that the fishery is in a collapse trajectory, since its dinamics is driven by a positive feedback loop, in which smaller populations generate smaller regeneration rates of the system. This allow us to define loop dominance as follows (Ford 1999a,b, 8):

> "A fedback loop dominates the behavior of a variable during a time interval in a given structure and set of system conditions when the loop determines the atomic pattern (the second derivative) of that variable's behavior."

3.2. Procedure to test for loop dominance

For assessing the dominant loops and the possible leverage points of systems in each dynamical phase, we propose the algorithm for loop dominance analysis below, based on Ford (1999a,b). It reflects the intuitive idea that if one removes the element under consideration by switching off a feedback loop and the behavior disappears, we may say that the element causes the observed behavior.

1. Identify the variable of interest that will determine feedback loop dominance and simulate the behavior of that variable over time.
2. Identify as a time interval which the variable of interest display only one atomic behavior pattern, that is the time interval in which the trajectory overtime presents the same second derivative. This is the reference time interval.
3. Identify the candidate loops, that is the feedback loops that may influence the variable of interest.
4. Identify or create a control variable in each loop that is not a variable in other feedback loops and can vary the gain of the candidate loop. Use the variable to deactivate each loop.
5. Simulate the variable of interest over the reference time interval with each loop deactivated and identify the atomic behavior pattern of the variable of interest during the time interval.
6. If the atomic behavior pattern is different than the reference pattern identified in step 2, the loop tested dominates the behavior of the variable of interest under the conditions during that time interval.
7. If the atomic behavior pattern is the same, simultaneously deactivate other loops which may be influencing the behavior of the variable of interest. If the atomic behavior pattern of the variable of interest changes, those loops form shadow feedback structures with the original loop.[3] If the atomic

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[3] Shadow feedback structures occur when two or more loops jointly dominate the dynamics of a system.

behavior pattern does not change, the original loop does not dominate system dynamics in that time interval.

3.3. Procedure to validate the model

Though this is a system dynamics toy model, constructed with the sole purpose of helping better understand the general sustainability properties of irrigation systems, it is nevertheless necessary to check whether it is valid even for this limited purpose. As all models are necessarily wrong (Sterman 2000), the question is not whether a model is true but whether it is useful. That is, the critical issue is whether the model is able to generate insights that lead to improve the system at hand. The most important issue to assess this capability is a proper model documentation to ensure that these insights can be replicated by others (Sterman 2002). In the Appendix, we provide a detailed documentation of the model, which allows not only to re-build it but to implement a number of validation tests, such as the dimensional consistency test, in which one may check whether there are unit errors in the equations, and test the system behavior under extreme conditions, for example checking if the model responds plausibly when subjected to extreme shocks such as extremely severe droughts. For an appropriate documentation, we mean not only the printout of the model equations but a careful description of the assumptions and the structure of the model. Another important issue to validate the model is to check whether it endogenously generates the behavior that motivated the study. In order to test this feature, we perform reality checks on parameters and constraints, an automatic procedure available in VENSIM platform. We finally discuss the model boundaries underscoring model shortcomings and suggesting how to enlarge the range of safe applications of the methodology proposed.

4. Results

4.1. Loop dominance analysis

Figure 4a below shows that an (hypothetical) irrigation system can lose sustainability due to small variations in environmental conditions. A reduction of 0.1% in the annual precipitation from year 20 to year 24 (35.2% drought → 35.3% drought) is enough to set the system on the collapse mode if it is operating close to its tipping point. In that mode, farmers are unable to pay maintenance dues and therefore maintenance falls below depreciation and the variable of interest – infrastructure – enter into a downward endogenous trajectory (Figure 4c).

Note that between years 25–40 unsustainable systems present a slowing down pattern before abrupt change. This result – which indicates a tension among stabilizing (e.g. the stabilization loop) and amplifying (e.g. the death spiral) feedback loops working in tandem upon the system's dynamics near tipping points (see Figure 4a) – has been identified as a universal property of systems approaching that threshold, and hence may be seen as an early warning signal of sustainability loss (Dakos et al. 2008; Scheffer et al. 2009).

When the system is operating in collapse mode as in Figure 4e, the atomistic behavior of the variable of interest – the value of the infrastructure – shifts from negative to positive in year 49, which allows to compute its sustainability tipping

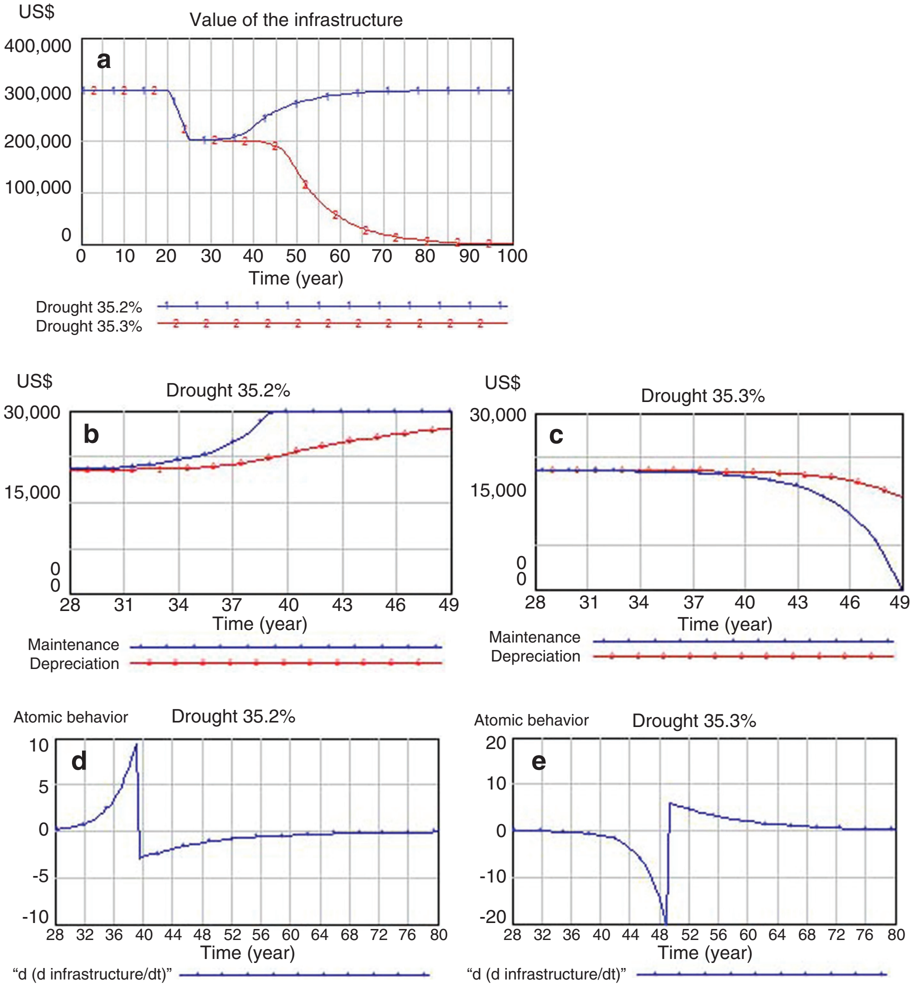

Figure 4: Sustainable and unsustainable irrigation systems.
(a) Shows that an irrigation system can lose sustainability due to small variations in environmental conditions. A small reduction in the annual precipitation from year 20 to year 24 is enough to put the system in its collapse mode if it is operating close to its tipping point. In that mode, farmers are unable to pay maintenance dues and therefore maintenance falls below depreciation and infrastructure enters a downward endogenous trajectory (c). If the system is operating in the collapse mode (e), the atomistic behavior of the value of the infrastructure shifts from negative to positive in year 49. This indicates that it has started to decrease at an increasing rate, progressively moving away from its equilibrium value. Finally, if the system is operating in the equilibrium mode (d), the atomistic behavior of infrastructure shifts from positive to negative, indicating that the system will tend toward equilibrium afterwards.

point as the point where atomistic behavior of variable of interest changes sign. This indicates it has started to decrease at an increasing rate, progressively moving away from its equilibrium value. When the system is operating in the equilibrium mode (Figure 4d), on the other hand, the atomistic behavior of the variable of interest shifts from positive to negative, indicating that the system will approach an equilibrium path afterwards.

As indicated in previous section, the explanation of why the system displays an explosive behavior is that it becomes dominated by amplifying loops, such as the death spiral in our basic model. To test this result, we use the algorithm 1–7 proposed in the Methodology section. Results are displayed in Figures 5a–5d. In Figures 4a and 4b, the death spiral and stabilization loops are deactivated for the period 25–49, whereas in Figures 5c and 5d each loop is deactivated for the period 50–80. The death spiral loop is deactivated by making maintenance costs equal to maintenance dues after the simulated drought. The stabilization loop is deactivated by assuming no depreciation of the infrastructure.

Recalling that the methodology prescribes that a loop dominates the dynamics of the system when its behavior changes in response to loop deactivation, Figure 4b indicates that the stabilization loop dominates the dynamics of system before the tipping point. The death spiral loop, on the other hand, dominates but only as a shadow structure, that is the system has its behavior changed only when the two loops are simultaneously deactivated. This indicates that either loop can constrain the decline of infrastructure to a logarithmic pattern between years 25–49. From year 50 on, however, the system's dynamics is entirely dominated by the death spiral loop (loop stabilization does not dominate not even as a shadow structure).

The results therefore seem to support the hypothesis that the loss of sustainability of an irrigation system loop takes place when the death spiral starts to dominate (with no constraints) its dynamics over time. By the same token, the system will be sustainable as far as stabilization loops dominate dynamics.

4.2. Validation tests of the model

By applying the VENSIM tool *units check* we conclude that the model is dimensionally consistent without the use of arbitrary parameters or scaling factors and presents no preposterous combinations of units such as US$/year^2 (see Appendix). This is regarded as one of the most basic tests of model validation (Sterman 2000, 866). The model also gives plausible responses to extreme conditions. As an example, the variable infrastructure never assumes negative values even for very low values of the parameter rain regime; for the latter, however, there will not be output, benefits and maintenance of the irrigation infrastructure. The next step was testing, by using the VENSIM tool *reality check* whether the system endogenously generate the central problem of the interest to this work, namely whether it may lose resilience due to its own endogenous dynamics even in the absence of large exogenous events.

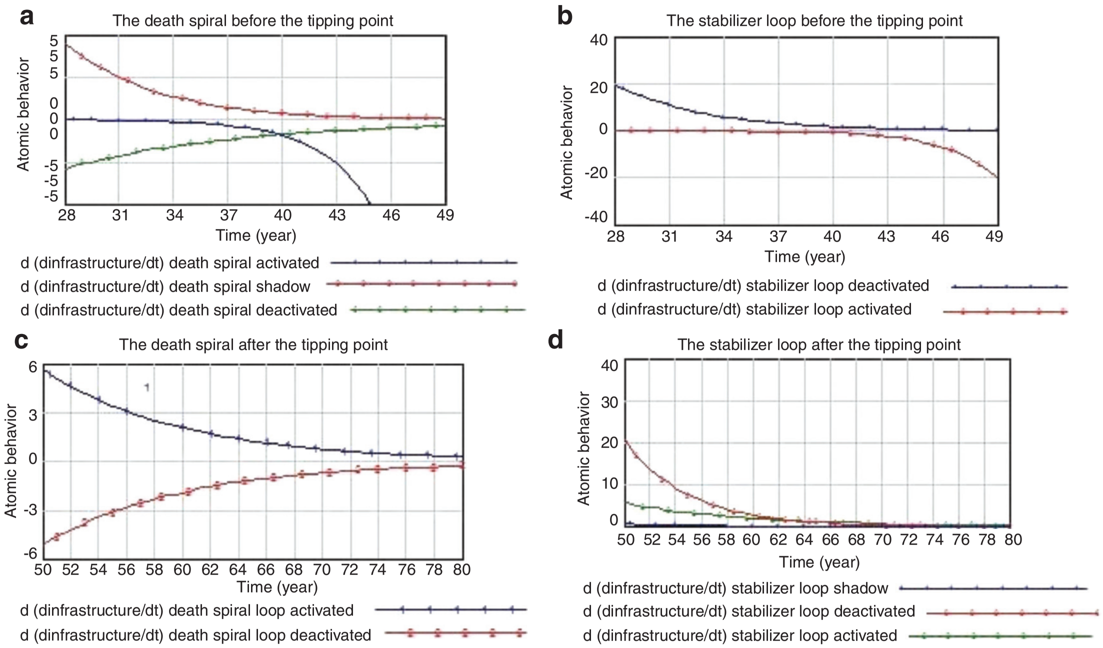

Figure 5: Loop dominance shifts in unsustainable irrigation systems.
The death spiral and the stabilizer loop are respectively deactivated between years 25–49 in graphs 5a and 5b, while in Figures 5c and 5d each loop is deactivated between years 50–80. The death spiral loop is deactivated by assuming the maintenance costs equal the maintenance dues after the drought. The stabilizer loop is deactivated by assuming the depreciation rate as zero. As a loop dominates the dynamics of the system when its behavior changes in response to loop deactivation, Figure 5b indicates that the stabilizer loop dominates the dynamics of system before the tipping point. The death spiral loop, on the other hand, dominates but only as a shadow structure, that is the system has its behavior changed only when the two loops are simultaneously deactivated. This indicates that either loop can constrain the decline of infrastructure to a logarithmic pattern between years 25–49. From year 50 on, however, the system's dynamics is entirely dominated by the death spiral loop (the stabilizer loop does not dominate not even as a shadow structure).

Below, we exemplify how we proceeded to the reality checks. In doing so, we first defined the test variable – no rain no maintenance – through which we forced the system into a drought regime. The condition *rain regime* <882 acre-feet (corresponding to a 35.2% decrease in rains) means that the mean flow decreases by less than this amount during the drought period.

No rain no maintenance: THE CONDITION: Rain Regime <882: IMPLIES: Maintenance ≥Depreciation
Starting testing of Constraint – no rain no maintenance
Test inputs:
rain regime <882
The constraint – no rain no maintenance – violated at time 20
The constraint – no rain no maintenance – not violated at time 25
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The test result indicates that maintenance becomes higher than depreciation after year 25, which leads the system to eventually return to its initial conditions, in which maintenance equals depreciation, as shown in Figure 6.

The next step is testing whether the system loses sustainability when it crosses the tipping point. T

No rain no maintenance: THE CONDITION: Rain Regime >882: IMPLIES: Maintenance ≥Depreciation
Starting testing of Constraint – no rain no maintenance
Test inputs:
rain regime >882
The constraint – no rain no maintenance – violated at time 20

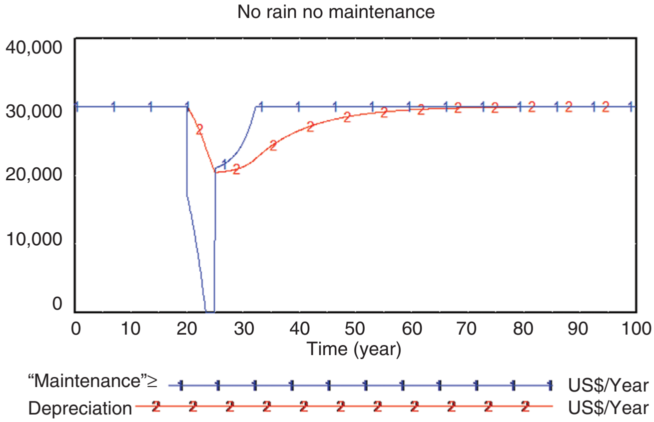

Figure 6: Reality check for variation in rain regime.

This means that the system will collapse, never returning to its initial conditions once hit by a severe enough drought (at year 20). The constraint will remain being violated through the entire rest of the simulation (maintenance <depreciation). The reality checks performed, therefore, confirms that the model endogenously generates the basic tipping points theoretical properties summed up in Figure 3.

While the model boundaries seem appropriate for the purpose at hand, it nevertheless leaves unanswered a number of important questions on how information flows through actual social networks in which irrigation systems are embedded. For example, who are the key actors for the diffusion of the information that systems are approaching their tipping point? What is the role of the government agencies in that process? A related question is how to gather and process empirical data for an actual irrigation system, which normally involves a large number of farmers? Next section explores a method to enhance our approach in order to allow starting to answer those critical questions for irrigation systems sustainability.

5. Discussion

Simulations performed in the last section suggest that, in general, the failure of an irrigation system is not due to the variance in water supply by itself. The loss of resilience of irrigation schemes as in many others socio-ecological systems (Bueno 2012), instead, may have an endogenous origin whereby environmental shocks serve only as triggering factors. According to this view, a major reason for the loss of sustainability of an irrigation system is the inability of farmers to perform O&M properly. At the system's tipping point, that is, at 882 acre-feet decrease in water supply, maintenance eventually equals infrastructure losses. Beyond that point, slight further decreases in water supply can lead irrigation systems to collapse due to the farmers' inability in paying maintenance fees.

Now imagine that having realized that the system is locked in a collapse trajectory government agencies decide to intervene, by financing the total annual spending on maintenance costs in a particular year. In Figure 7, we assume that agencies raise the maintenance level to the normal level alternatively at year 47 or year 51, that is 2 years before or 2 years after the system has crossed the tipping point. It is easy to see that the outcome of the intervention will be very different in each case. If government acts timely by complementing private maintenance spending, the system will be able to recover relatively easily, which means that the year 47 is a leverage intervention point of the system. On the other hand, if government postpones intervention, even for just 1 or 2 years, the system will collapse, as it may already be dominated by the death spiral loop.

Our approach, however, does not provide rigorous answers on the role played for farmers and government agencies in the diffusion of information about the sustainability conditions of irrigation systems. Traditional models of information diffusion, on the other hand, have shown that the process is susceptible to interpersonal influence, but, strictly speaking, they are based on what is happening in the population as a whole and, hence, they also do not differentiate among

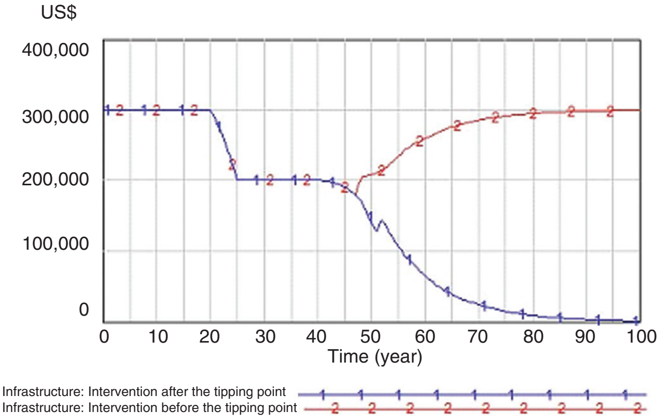

Figure 7: Leverage government intervention points.
After realizing that the system is on a collapse trajectory, government decides to intervene by complementing private maintenance spending. If it acts before the tipping point, the system is able to recover, which means that the year 47 is a leverage intervention point of the system. But if it postpones intervention, even just for 1 or 2 years, the system will collapse, because it may already be dominated by the death spiral loop.

central and peripheral agents in terms of information diffusion. A more realistic approach to understand the actual role of different agents in the process, therefore, should take in account the fact that interpersonal influence operates through persons who are closer in a social or physical sense. This means that a more realistic model should incorporate more detailed analyses of the social networks in which agents operate (Tutzauer et al. 2011).

In order to tackle these issues, we first created a NetLogo version (Wilensky 1999) of our basic VENSIM model, with the sole purpose of distributing agents through a landscape in order to show how to develop the analyses above mentioned. Information to build the landscape was obtained from an actual irrigation project – The Gorotuba River Irrigation District – in the Northwest region of the State of Minas Gerais/Brazil. The landscape was populated with 450 families (agents belonging to Group B in the basic model) and 40 firms (Group A), represented respectively by people and houses in Figures 8 and 9. The thicker line represents the main irrigation channel while the thinner ones represent the secondary channels of the project. Families and firms were placed in their actual locations in the district. We assumed that firms differ from families in that they are less lazy statistician than families, in the sense they search around by a larger radius to get information about the environment before taking actions. The number of the agents located within the searching radius, measured for the geodesic distance among cells in the grid, was used as a proxy to each agent's degree centrality in the social network in which agents interact. The agent's degree centrality is the number of relations he has within the network. The network's degree of centrality,

Figure 8: The Gorutuba river irrigation district – wide view.

on the other hand, is the average number of relations between each agent member of the network. Based on these assumptions we built a binary social matrix in which each cell assumes value zero if agents are not related to each other and 1 otherwise. By using the computer program UCINET (see Prell 2012), we finally built the graph for the social network of the Gorotuba District based on the social matrix above. This graph and its main measures, such as agent's degree, are shown in Figure 10.

As network ties serve as a conduit of information, the graph gives hints on a number of important issues related to the diffusion of information in irrigation systems similar to the system above. For instance, the social network of the Gorotuba District is characterized by relatively low density, low connectivity,

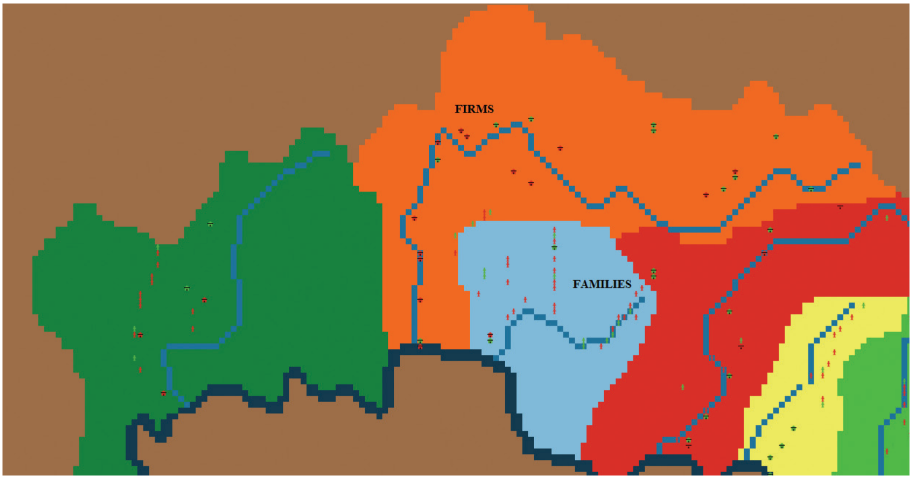

Figure 9: The Gorutuba river irrigation district – wide view.

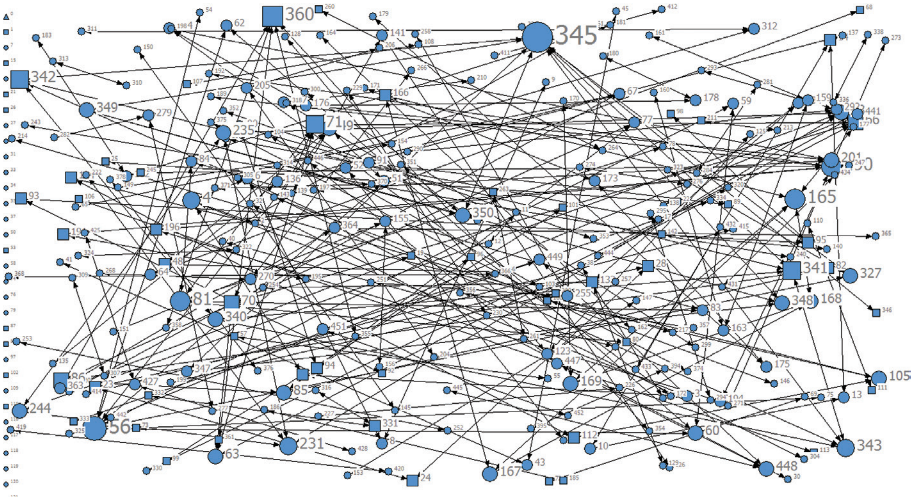

Figure 10: Social network of the irrigation district of Gorotuba river – degree of centrality. Families are represented by ellipses and firms by squares. The size of the symbols and labels is given by each agent's degree of centrality. The main measures of centralization of the social network of the Gorotuba district are: network's degree of centrality=0.961, density 0.002 and (Freeman) network centralization=1.54%.

and low centrality degree (for a very detailed explanation of these concepts see Newman 2012). In this kind of sparse and poorly connected network, according to the modern science of networks, the principal obstacle to implement successful sustainability policies lies in network's connectivity rather than in the resilience of individual decision-makers (Watts 2002a, Chap. 8). Highly connected individuals, in those settings, tend to be disproportionately effective in propagating new ideas and practices compared to nodes with average connectivity (Watts 2002b). Yet, as such social networks are also little centralized – that is, there are no especially influent individuals – they do not support cascades of social influence because eventual individual initiatives have no way of jumping from one cluster of producers to another. This suggests that private or government agencies should act preferentially as group connectors, by focusing, for instance, on convincing some producers located in strategic positions of the social network, e.g. in structural holes, to become early adopters of more resilient practices of management. The term is used in the network literature for indicating the separation between non redundant contacts, which are connected by a structural hole (Burt 1992, 18). The metric commonly used to assess the importance of structural holes in networks is the betweenness centrality, which measures who sits on the most routes between two actors, and thus might be considered a good way to find out who influences information flow. This metric is important in that a point that falls between other points exhibits a potential for controlling and, in some cases, distort information (Freeeman 1978/1979). Figure 11 indicates that there are some families and firms

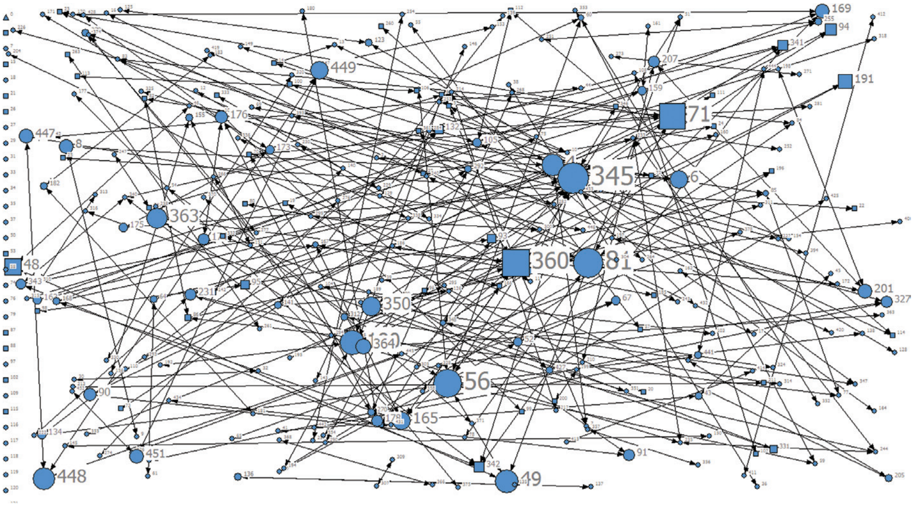

Figure 11: Social network of the irrigation district of Gorotuba river – degree of betweenness. Families 345 and 81 and firm 360, for example, present relatively high betweenness centrality and thus might serve as bridges of information among relatively isolated parts of the social network.

that present a relatively higher degree of betweenness centrality in the Gorotuba District. However, it is easy to notice that the network as a whole is poorly connected. For instance, agents represented on the far left side of the Figure 11, e.g. family 7 and firm 15 are completely disconnected from the rest of the social network.

That probably helps to explain why sustainability measures in irrigation systems based only, or mostly, in reforms that focus on participatory management, as it has been traditionally suggested in several applied studies on the subject (Simas 2002), rather than in bridging structural holes, have been so little effective in promoting sustainability in irrigations systems (World Bank 2007). In a nutshell, it seems that the empowerment of average producers has not been effective because those producers are too weakly connected to trigger cascades of adoption of more sustainable behaviors through their underlying social networks.

Interestingly, this seems to be a problem even in developed countries in which farmers are supposed to be more informed and conscious on the need to adopt sustainable irrigation practices. In Australia, for example, while the level of uptake of drought prediction is high within government agencies, less than one-third of farmers take drought predictions into account. Furthermore, farmer's preparedness to change major decisions is not generally influenced by this information. This is true even in extreme situations such as El Niño events, and despite the fact that drought link is widely known and accepted within the Australian agricultural community (Wright 2005).

However, as the social matrix from which Figure 10 is based on very simplifying assumptions, we need to take the analyses made only as a very preliminary attempt to make system dynamics irrigation models more realistic. Nevertheless, it is easy to think in more accurate ways to get empirical data from social and economic relations to feed such models. Prell (2012), among several other authors, suggests a number of straightforward ways to gather information in order to build social matrices through field research, for example by applying questionnaires in which producers are asked to answer a few simple questions.

6. Conclusion

There are currently a number of very powerful techniques to forecast natural disaster and extreme events in agriculture (Zhao et al. 2005). The purpose of this paper was to show that agricultural systems based on irrigation schemes can be also catastrophically disabled by cascading failures initiated by very tiny perturbations. The argument, in a nutshell, is that agricultural systems are “robust, yet fragile” in the sense of being robust to what is common or anticipated but potentially fragile to flaws in maintenance that may arise because farmers misperceive key feedback loops that drive their systems. In this context, farmers can be unable to prevent systems crossing tipping points beyond which stabilizing (negative) feedback loops stop dominating dynamics, triggering income downward trajectories, which impair their ability to carry out the necessary maintenance expenses. Problems of maintenance of irrigation systems operating near tipping points can then, many times, be explained by the inability of users to pay for the maintenance of infrastructure and not for their refusal to participate in maintaining systems integrity.

Recent developments in the field of dynamical systems have suggested that approach can help identify symptoms of loss of resilience not only in irrigation schemes but in all potentially fragile socio-ecological systems approaching tipping points. However, studies to support environmental decision-making often do not involve the relevant stakeholders, who consequently do not accept the results because they don’t understand or don’t agree with the underlying assumptions. This suggests that stakeholders should be involved in the overall decision-making process based on a mediate modeling approach (Ford 1996a,b; Van den Belt 2004), which emphasizes the interactive involvement of affected stakeholders in the learning process about their systems in a system dynamics computational environment that can generate relatively straightforward procedures to identify symptoms of loss of resilience (Bueno 2012).

One of those symptoms, which can actually be considered as a universal property of dynamical systems approaching tipping points, is a phenomenon known in dynamical systems theory as critical slowing down. System dynamics in such case is dominated by a damped, driven effect created when positive and negative feedbacks operate in tandem (Cohen 1997). This implies that systems operating near tipping points become increasingly slow in recovering from small perturbations, due to the fact that amplifying (positive) feedbacks loops, such as the “death spiral”, start to offset the stabilizing effect of negative feedback loops as the stabilization loop in model presented in Figure 1. This means that systems have become less resilient, in terms of this work (for more details on this point see Martin et al. 2011). Figure 7 depicts this characteristic slowing down process in action as an irrigation system approaches its tipping point: the later the system recovers original characteristics, the longer the return time to a sustainable exploitation path. Applied literature has tested a number of techniques, such as sensitivity and time series analyses, to check whether the theoretically predicted critical slowing down can indeed be identified in actual complex systems. For instance, a way to test whether a system is slowing down is to interpret fluctuations in the state of the system in response to natural perturbations. Slowing down should be reflected as a decrease in the rates of changing of the system near systems’ tipping point, which may be measured by an increase in the short-term correlation in key variables time series (Ives 1995), such as farmer’s income.

Unfortunately, there are signals that this process is already taking place in several regions of the world. Growth in irrigation, mainly in arid countries in the Middle and Near East, has dramatically slowed over the last decades to a rate that is inadequate to keep up with the expanding food requirements. Furthermore, extensive areas of land in a number of countries have been degraded by water logging and salinization resulting of poor agricultural management and maintenance, which has led to major environmental disturbances and raised doubts about its very sustainability in many places in the world (Rhoades 1997). Between 1998 and 2008, the World Bank changed its focus, providing US$ 6.2 billion for irrigation and drainage mostly to Asian countries. This increased farmers’ access to water, but the cost recovery of the projects remained challenging like in Middle and Near East countries before that, largely due the operation of the same vicious circle of low operation and maintenance expenditure proposed in this work (IEG World Bank 2011). This positive feedback loop leads to poor performance and increasing reluctance of farmer to pay for water use. Hence, fewer investments in new and existing irrigation projects are expected in the future, unless major improvements in the operation and maintenance of existing projects can bring those systems back to sustainable patterns of use, particularly in the poorest regions of the world.

Appendix: Full VENSIM Model Documentation

In this working version of the model, there are two groups of farmers (A and B) in order to take into account farmers’ different economic and social traits. In this version, however, farmers are assumed as being identical in all traits, except in their land endowment.

Farmers in group A

A’s Non-Irrigated Land=A’s Arable Land–A’s Irrigated Land

Units: acre

A’s Arable Land=Arable Land*“A: Land Share”

Units: acre

A’s Domestic Expenditures=35,000–STEP(15,000, 40)*0

Units: US$

A’s Irrigated Land=“A: Fixed Water Share”*Amt Apropriated/Recom Water Appl

Units: acre

A: Output Produced=Y max *A’s Irrigated Land

Units: US$

A: Before Maintenance Net Benefit=“A: Output Produced”*(1–Input Cost)

Units: US$

Farmers in Group B

B’s Non-irrigated Land=B’s Arable Land–B’s Irrigated Land

Units: acre

B’s Arable Land=Arable Land*(1–“A: Land Share”)

Units: acre

B’s Domestic Expenditures=35,000

Units: US$

B’s Irrigated Land=(1–“A: Fixed Water Share”)*Amt Apropriated/Recom Water Appl

Units: acre

B: Before Maintenance Net Benefit=“B: Output Produced”*(1–Input Cost)

Units: US$

B: Output Produced=Y max *B’s Irrigated Land

Units: US$

The Atomistic Behavior of the Infrastructure

The following equations give the atomistic behavior of the value of the infrastructure which shifts from negative to positive in year 49. They indicate when the system has started to be dominated by the death spiral at this point.

d (d infrastructure/dt)=(Infrastructure–“infrastructure t–1”)–(“infrastructure t–1”–“infrastructure t–2”)

Units: US$

Infrastructure=INTEG [(+Maintenance-Depreciation), 300,000]

Units: US$

Infrastructure t-1=DELAY FIXED(Infrastructure, 0.0625, 0)

Units: US$

Infrastructure t-2=DELAY FIXED(“infrastructure t–1”, 0.0625, 0)

Units: US$

Depreciation and Maintenance

The specification for the variables Depreciation and Maintenance is adopted in order to allow to test for loop dominance. The stabilizer loop, for example, is deactivated by substituting 1 for zero in the equation for the Depreciation Rate below. The “Death Spiral”, at the other hand, is deactivated by assuming that total actual maintenance equals total maintenance dues after the beginning of the drought period.

Depreciation=(Depreciation Rate/Depreciation Appropriation Regime)*Infrastructure

Units: US$/Year

Depreciation Rate=0.1–STEP(–0.1, 49)*0

Units: Dmnl

Depreciation Appropriation Regime=1

Units: Year

Maintenance=MAX(“A: Actual Maintenance”+“B: Actual Maintenance”, STEP(30,000, 49)*0)/Depreciation Appropriation Regime

Units: US$/Year

A: Maintenance Dues=15,000

Units: US$

A: Actual Maintenance=MAX[0, MIN("A: Maintenance Dues", "A: Before Maintenance Net Benefit"–A's Dom Exp)]

Units: US$

B: Maintenance Dues=15,000

Units: US$

B: Actual Maintenance=MAX[0, MIN("B: Maintenance Dues", "B: Before Maintenance Net Benefit"–B's Dom Exp)]

Units: US$

Simulation Parameters

Initial Time=0

Units: Year

Final Time=100

Units: Year

Time Step=0.0625

Units: Year

The Rain Regime

The specification for the rain regime allow for testing different assumptions about droughts severity. For example, larger values for td and r mean more severe drought periods.

Availability of Water=Mean Flow

Units: acre-foot

Mean Flow=2500

Units: acre-foot

Rain Regime=-PULSE(y, td)*r

Units=acre-foot

Environmental, Technological and Factors Endowment Parameters

A: Fixed Water Share=0.5

Units: Dmnl

A: Land Share=0.25

Units: Dmnl

Appropriation Rate=0.36*Infrastructure/Desired State of Infrastructure

Units: Dmnl

Arable Land=2000

Units: acre

Desired State of Infrastructure=300,000

Units: US$

Input Cost=0.33

Units: Dmnl

Recommended Water Application=1.8

Units: acrefoot/acre

Total Irrigated Land=A's Irrigated Land+B's Irrigated Land

Units: acre

Water Released=Availability of Water–Amount of Water Appropriated

Units: acre-foot

Y max=400

Units: US$/acre

Amount of Water Appropriated=Appropriation Rate*Availability of Water

Units: acre-foot

Literature cited

Anderies, J., M. Janssen, F. Bousquet, J. Cardenas, D. Castillo, M. Lopez, R. Tobias, B. Vollan, and A. Wutich. 2011. The Challenge of Understanding Decisions in Experimental Studies of Common Pool Resource Governance. *Ecological Economics* 70:1571–1579.

Bueno, N. P. 2012. Assessing Resilience of Small Socio-Ecological Systems Based on the Dominant Polarity of Their Feedback Structure. *System Dynamics Review* 28(4):351–360.

Burt, R. 1992. *Structural Holes: the Social Structure of Competition*. Cambridge, MA: Harvard University Press.

Cohen, B. 1997. *The Edge of Chaos, Financial Booms, Bubbles, Crashes and Chaos*. Chichester: John Willey & Sons.

Coyle, R. G. 1996. *System Dynamics Modeling: a Practical Approach*. London: Chapman and Hall.

Dakos, V., M. Scheffer, E. Van Ness, V. Brovkin, V. Petoukhov, and H. Held. 2008. Slowing Down as an Early Signal for Abrupt Climate Change. *Proceedings of the National Academy of Sciences USA* 105:14308–14312.

Férnandez, J. and M. Selma. 2004. The Dynamics of Water Scarcity on Irrigated Landscapes: Mazarrón and Aguilas in South-Eastern Spain. *System Dynamics Review* 20(2):117–137.

Ford, A. 1996a. Testing the Snake River Explorer. *System Dynamics Review* 12(4):305–329.

Ford, A. 1996b. System Dynamics and the Electric Power Industry. *System Dynamics Review* 13(1):57–85.

Ford, A. 1999a. *Modeling the Environment – an Introduction to System Dynamics Models of Environmental Systems*. Washington: Island Press.

Ford, D. 1999b. A Behavioral Approach to Feedback Loop Dominance Analysis. *System Dynamics Review* 15(1), Spring.

Forrester, J. W. 1961. *Industrial Dynamics*. Portland, OR: Productivity Press.

Freeeman, L. 1978/1979. Centrality in Social Networks, Conceptual Clarification. *Social Networks* 1:215–239.

IEG World Bank. 2011. *Evaluative Lessons from World Bank Group Experience – Growth and Productivity in Agriculture and Agribusiness*. Washington, DC: The World Bank.

Ives, A. R. 1995. Measuring Resilience in Stochastic-Systems. *Ecological Monograph* 65:217–233.

Jones, W. 1995. *The World Bank and Irrigation*. Washington, DC: The World Bank.

Jopp, F., H. Reuter, and B. Breckling. 2011. *Modelling Complex Ecological Dynamics*. London, New York: Springer.

Martin, S., G. Deffuant, and J. Calabrese. 2011. Defining Resilience Mathematically: from Attractors to Viability. In *Viability and Resilience of Complex Systems – Concepts, Methods and Case Studies from Ecology and Society*, eds. G. Deffuant and N. Gilbert, 15–36. London, New York: Springer.

Meadows, D. 1989. Delays: Exercise and Supplementary Notes. In *Study Notes in System Dynamics,* ed. M. Goodman, 219–256. Walthan, MA: Pegasus.

Moxnes, E. 2000. Not Only the Tragedy of the Commons: Mispercetions of Feedback and Policies for Sustainable Development. *System Dynamics Review* 16(4):325–348.

Moxnes, E. 2004. Misperception of Basic Dynamics: the Case of Renewable Resource Management. *System Dynamics Review* 20(2):139–162.

Newman, M. E. 2012. *Networks, an Introduction*. Oxford: Oxford University Press.

Ostrom, E. 1992. *Crafting Institutions for Self-Governing Irrigation Systems*. California: Institute for Contemporary Studies.

Prell, C. 2012. *Social Network Analysis, History, Theory and Methodology*. Los Angeles: Sage.

Richardson, G. P. 1995. Loop Polarity, Loop Dominance, and the Concept of Dominant Polarity. *System Dynamics Review* 11(1):67–87.

Rhoades, J. D. 1997. Sustainability of Irrigation: an Overview of Salinity Problems and Control Strategies. In *Canadian Water Resources Association*

(*RWA*) *Annual Conference "Footprints of Humanity: Reflections of Fifty Years of Water Resource Development,"* Lethbridge, Alberta, June 3–6, pp. 1–40.

Rudolph, J. W. and N. Repenning. 2002. Disaster Dynamics: Understanding the Role of Quantity in Organizational Collapse. *Administrative Science Quarterly* 47(1):1–30.

Saysel, A. and Y. Barlas. 2001. A Dynamic Model of Salinization on Irrigated Lands. *Ecological Modelling* 139:177–199.

Sengupta, N., S. Swati, and E. Ostrom. 2001. Sustainability, Equity, and Efficiency of Irrigation Infrastructure. In *Institutions, Ecosystems, and Sustainability*, ed. R. Constanza, 77–118. Boca Raton: Lewis Publishers.

Scheffer, M., J. Bascompte, W. Brock, V. Brovkin, S. Carpenter, V. Dakos, H. Held, E. Van Nes, M. Rietkerk, and G. Sugihara. 2009. Early-Warning Signal for Critical Transitions. *Nature* 461(3):53–59.

Schlager, E., W. Blomquist, and S. Tang. 1994. Mobile Flows, Storage, and Self-Organized Institutions for Governing Common-Pool Resources. *Land Economics* 70:294–317.

Simas, J. 2002. Issues Affecting the Irrigation and Drainage Sectors in Latin America: Lessons from Mexico, Argentina, and Brazil. In *Institutional Reform for Irrigation and Drainage: Proceedings of a World Bank Workshop (World Bank Technical Paper N. 524*), eds. F. Gonzalez and S. Salman, 149–168. Washington, DC: The World Bank.

Sivakumar, M. 2005. Impacts of Natural Disasters in Agriculture, Rangeland and Forestry: an Overview. In *Natural Disasters and Extreme Events in Agriculture*, eds. M. Sivakumar, R. Motha, and H. Das, 1–22. Netherlands: Springer.

Sterman, J. 1985. A Behavior Model of the Economic Long Wave. *Journal of Economic Behavior and Organization* 6(1):17–53.

Sterman, J. 1994. Learning in and About Complex Systems. *System Dynamics Review* 10(2–3):291–330.

Sterman, J. 2000. *Business Dynamics – Systems Thinking and Modeling for a Complex World*. Boston: Irwin McGraw-Hill.

Sterman, J. 2002. All Models are Wrong: Reflections on Becoming a System Scientist. *System Dynamics Review* 18(4):501–531.

Sweeney, L. and J. Sterman. 2000. Bathtub Dynamics: Initial Results of a Systems Thinking Inventory. *System Dynamics Review* 16(4):249–286.

Taylor, T., D. Ford, and A. Ford. 2006. Tipping Point Failure and Robustness in Single Development Projects. *System Dynamics Review* 22(1):51–71.

Tutzauer, F., K. Knon, and B. Elbirt. 2011. Network Diffusion of Two Competing Ideas. In *The Diffusion of Innovations – a Communication Science Perspective*, eds. A. Vishwanath and G. e Barnett, 145–170. New York: Peter Lang.

Tversky, A. and D. Kahneman. 2000. Rational Choice and the Framing of Decisions. In *Choices, Values and Frames*, eds. D. Kahneman and A. Tversky. New York: Cambridge University Press.

Van den Belt, M. 2004. *Mediate Modeling, a System Dynamics Approach to Environmental Consensus Building*. Washington, DC: Island Press.

Watts, D. 2002a. *Six Degrees: the Science of a Connected age*. New York, London: W.W. Norton.

Watts, D. 2002b. A Simple Model of Global Cascades on Random Networks. *PNAS* 99(9):5766–5771.

Wilensky, U. 1999. NetLogo. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University. Evanston, Il.

World Bank. 2007. *Emerging Public-Private Partnership in Irrigation Development and Management*. Water Sector Board Discussion Paper n. 10. Washington, D.C.: The World Bank.

Wright, W. 2005. Significance of Training, Education, and Communication for Awareness of Potential Hazards in Managing Natural Disaster in Australia. In *Natural Disasters and Extreme Events in Agriculture,* eds. M. Sivakumar, R. Motha and H. Das, 219–239. Netherlands: Springer.

Zhao, Y., S. Li, and Y. Zhang. 2005. Early Detection and Monitoring of Drought and Flood in China using Remote Sensing and GIS. In *Natural Disasters and Extreme Events in Agriculture,* eds. M. Sivakumar, R. Motha and H. Das, 305–317. Netherlands: Springer.