A practical procedure for assessing resilience of social-ecological system using the System Dynamics Approach

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ABSTRACT

While growing attention has been paid to the idea of resilience of social-ecological systems, it seems that there still are a number of gaps to bridge before we could really use this concept for practical purposes. The main problem is that the most of the works in the field are unclear on how to unequivocally measure the degree of resilience of particular social-ecological systems. In this paper, we suggest to be possible identifying the loss of resilience of social-ecological systems as a process of loop dominance shift. In order to illustrate the argument, we use a very stylized system dynamics model for irrigation systems developed by scholars associated to the Workshop in Political Theory and Policy Analysis at Indiana University.

Keywords: resilience; social-ecological systems, common-pool resource systems, system dynamics; loop dominance shifts

1. INTRODUCTION

The application of the concept of resilience to social-ecological systems is gaining popularity among scholars of different persuasions. The most widely cited definition states that resilience is the amount of disturbance a system can absorb without shifting into an alternate regime (Holling, 1973). A well-known analogy describes a system as a ball on a surface that represents the forces acting to change that state. Pits in this surface are analogous to stable states and the slope of the surface represents the strength of the forces moving the system in a given direction. Disturbances move the ball across the landscape's surface and so the resilience of a given state of the system corresponds to the width of a stability pit (Peterson, 2000). Scholars have criticized this view on the lack of clarity regarding what, exactly, is meant by being in one regime or another (Hanley, 1998), and because it is unclear how to measure that property in social-ecological systems (Batabyal, 1998). In this paper we offer a definition for resilience that attempts to help answer those two criticisms.

We define resilience as a second order condition for a social-ecological system's dynamics. By this definition, the system is resilient as far as it is able to maintain the capacity of keeping resistance to disruptive changes. Returning to the analogy of the ball on a surface, we can imagine a surface, say a table, that is divided in two parts or basins of attraction: a smooth side and a rough one composed by pits of different width. If the ball is on the smooth part and the table is moved, the ball will enter a collapse trajectory, that is, will fall from the table. But if the ball is inside a pit, on the other side of the table, it will stay in the bottom of the pit or if it jumps out it is likely that it will fall into a neighboring pit when the system is disturbed. Thus, we say that the system is resilient when it is on the second side of the table in which endogenous systemic forces work to keep it in an equilibrium dynamics while being capable of evolving, that is, passing from one pit to another. Otherwise, the system would be non-resilient because it would be subject to the dominance of a reinforcing loop that pushes it away from the equilibrium. The loss of resilience of a social-ecological system may be seen therefore as a process of tipping points crossing where a loop dominance shift occurs, that is the behavior of the system starts to be commanded by another dominant loop (Richardson and Pugh, 1981, p.285)[1].

There are presently a number of procedures for identifying systems' tipping points (Rudolph and Repenning, 2002; Repenning, 2001) . One of the simplest is that proposed by Ford (1999 a) that allows to identify changes of feedback loop dominance, by successively activating and deactivating the principal loops of a simulation model and verifying the effect on the variables of interest. In this paper we are going to apply this procedure to a very simplified version of the irrigation model proposed by Sengupta et al. (2001) in order to illustrate the argument.

The rest of the paper is organized as follows. In section two, we present the rudiments of the system dynamics methodology, including the irrigation model we used for illustrating how that methodology can help us to achieve a more operational definition of resilience. In section three we show how to identify loop dominance shifts in this type of model. In section four we discuss the importance of identifying resilience as tipping points where loop dominance shifts occur, showing particularly that they are thresholds beyond which social-ecological systems loose resilience.

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[1] This definition is very close to the definition of regime shift provided by Walker and Meyers (2004: p.2); the difference is that ours emphasizes the crucial concept of loop dominance. Accordingly to Walker and Meyers' definition , "a regime shift involving alternate stable states occurs when a threshold level of a controlling variable in a system is passed, such that the nature and extent of feedbacks change, resulting in a change of direction (the trajectory) of the system itself. A shift occurs when internal processes of the system (rates of birth, mortality, growth, consumption, decomposition, leaching, etc.) have changed and the state of the system (defined by the amounts of the state variables) begins to change in a different direction, toward a different attractor. In some cases, crossing the threshold brings about a sudden, large, and dramatic change in the responding state variables… In others… the response in the state variables is more gradual but, nevertheless, once the threshold has been passed, the feedbacks have changed and the dynamics of the system shift from one basin of attraction to another."

2 . METHODOLOGY

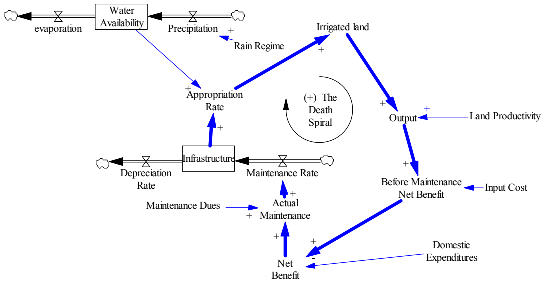
2.1 - The system dynamics methodology

The fundamental ideas of this paper come broadly from the field of system dynamics that originated in the 1960s with the work of Jay Forrester and his colleagues at the Sloan School of Management at the Massachusetts Institute of Technology. System dynamics allow the construction and analysis of mathematical models and simulation scenarios that identify critical feedbacks influencing systems (Costanza and Ruth, 1998; Stave, 2002). System dynamics has been increasingly used in a wide variety of environmental and resource settings (Cavana and Ford, 2004) such as global environmental sustainability (Meadows et al. 2004), water resource planning in irrigation systems (Ostrom*,* 2001), and ecological modeling (Costanza *et al.,* 2001; Costanza and Wainger, 1993). A detailed description of system dynamics methodology with special emphasis on social ecological systems is given in Ford (1999 b) and a very understandable general explanation about how to apply it can be found in Saysel *et al.* (2002). The procedure for identifying loop dominance shifts, finally, comes from Ford (1999 a).

2.2 - Model description

The starkest version of the Sengupta`s et al. model, used in this paper for illustrating the idea of resilience, can be summarized as the simple stock-flow structure depicted in figure 1. The fully documented Stella model is presented in Sengupta et al. (2001) and the VENSIM version is available upon request. In that structure, there is just one reinforcing feedback loop highlighted by the thicker line at the right side of the diagram labeled (by us) as “the death spiral” by reasons we present below.

Figure 1 : Basic feedback structure of the Segupta’s et al. irrigation model



Variables inside the boxes are level or state variables which accumulate the values of rate variables; for example, the state of the irrigation infrastructure depends on the irrigators covering the depreciation of the equipment. The amount of water appropriated for the irrigators – the appropriation rate - on the other hand, depends 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 production levels 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 maintenance in the model is given for:

Actual maintenance = MIN(Before Maintenance Net Benefit - Dom Exp, Maintenance Dues)

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, when profits are reduced, after deducing his domestic expenses, irrigators may not be able to reinvest the total amount required to recover the depreciation of the equipment. The amount invested in equipment maintenance therefore would be determined by the resulting difference between the actual profit earned and the domestic expenses.

The degree of resilience of the above system can be assessed in the following way: what level of disturbance, droughts for instance, can the system support before the agents stop investing the total amount needed for the integral maintenance of the equipment?

It is easy to see that as far as the irrigators are able to pay their maintenance dues the infrastructure is maintained in appropriate use conditions. But if they are forced to expend less than that value, the maintenance rate will be lower than the depreciation rate and the infrastructure will decrease in size. Hence, in the next period, the amount appropriated of water, output and profits will decrease and thus the investments in equipment maintenance. Once the irrigators are forced to pay less than right maintenance dues, therefore, the system can enter a snow-ball trajectory we have labeled “the death spiral” because the final outcome of the process is the complete deterioration of the existing infrastructure. Going back to the analogy we made in the beginning of this paper, we may say that the system has lost resilience because thereafter the ball has passed from the rough to the smooth part of the table and will jump out.

The process can be summarized as follows:

1) An exogenous environmental shock such as a decrease in the amount of rains decreases Availability of Water, Irrigated Land, Output, Profits and Actual Expenditures in Infrastructure Maintenance

2) If Actual Expenditures in Infrastructure Maintenance = Maintenance Dues, the infrastructure will be preserved at the present level

3) If Actual Expenditures in Infrastructure Maintenance < Maintenance Dues, Death Spiral will dominate de system dynamics

The question thus is how to identify the point where the death spiral starts to dominate the system dynamics. In the next sub- section a methodology to identify that critical threshold is presented.

2.3 - A simple procedure to identify loop dominance shifts

Ford (1999 a) proposes the following steps to determine if a system has crossed a loop dominance shift threshold.

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[2], 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. If the atomic behavior pattern is the same and there are no shadow feedback structures involved the loop does not dominate system dynamics in that time interval[3].

3 . RESULTS

By applying the procedure detailed in the last subsection to the irrigation model we can identify the interval in which the death spiral dominates system dynamics, that is the interval in which the system has lost resilience.

1) the variable of interest is the state of infrastructure and we simulate its dynamics over a period of 80 years, supposing that a permanent decrease of 10% in the precipitation level has occurred in the 20^{th} year of the simulation.

2) the reference time interval is given by the period comprehending the years beyond year 25 of the simulation where the system presents a clear logarithmic atomic behavior, that is where $d^2x/dt^2 < 0$.

3) as there is only one loop in the model this is chosen as the candidate loop.

4) feedback loop "death spiral" is deactivated by severing the causal link between Net Benefit and Actual Maintenance. This is done by changing the equation for Actual Maintenance from

Actual maintenance = MIN(Before Maintenance Net Benefit - Dom Exp, Maintenance Dues)

to

Actual maintenance = Maintenance Dues

5) The behavior of the variable of interest over the reference time is simulated with the death spiral deactivated. Behavior of the variable infrastructure with candidate loop activated and deactivated is shown in figure 2

6) the dynamics of the variable of interest in the reference time interval changes from logarithmic to linear (the atomic pattern changes from a negative value to zero), indicating that the death spiral dominates the behavior of de variable of interest – Infrastructure - from year 25 through year 80 under the conditions of the system identified in step 1. Notice that between years 20 and 24 the behavior of the system continues to be linear and therefore the atomic pattern does not change.

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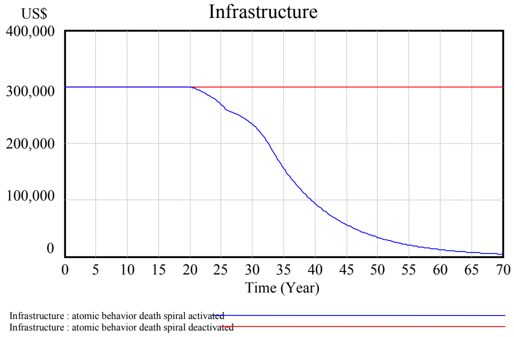
[2] There are three basic behavior patterns based on the net rates of change of the variable of interest: a) linear behavior, when the absolute value of the net rate of change of a system variable is constant, b) exponential growth or decay, when the absolute value of the net rate of change of a system increases over time and c) logarithmic growth or decay, when the absolute value of the net rate of change decreases over time.

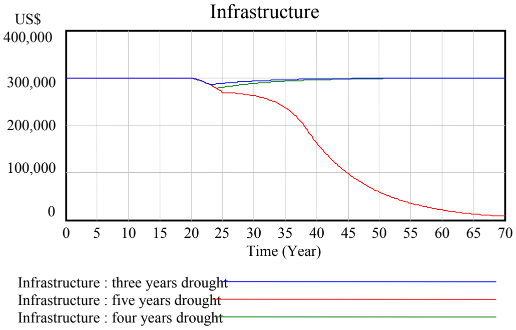
[3] Shadow feedback structures occur when two or more loops jointly dominate the dynamics of a system; in that case we should test for loop dominance deactivating all the linked loops at the same time. For the purposes of this work, we will consider only the simplest case where there are no shadows structures involved. For more details on how to identify shadow structures see Ford, 1999 a), pp. 18-23.

Figure 2 : Infrastructure dynamics with “death spiral” activated and deactivated



The conclusion is that the system looses the capacity to resist environmental shocks like droughts once a particular drought is severe enough to place in action the death spiral[4]. Figure 3 shows that while death spiral is not active the system is able to reorganize itself recovering its initial conditions, but once a critical tipping point is crossed, that is the drought lasts for five years or more, say until year 25, the system enters a collapse trajectory, that is looses which we have defined as resilience.

Figure 3: Infrastructure behavior under three different drought scenarios



4 . DISCUSSION

It might be argued that the model used for simulations in this paper is too simple and, therefore, does not represent not even approximately the dynamics of any actual complex system. That criticism would be fair if the purpose of the paper had been representing the dynamics of actual irrigation systems. Actual complex systems have many balancing and reinforcing loops which can jointly dominate system dynamics and thus we would need to perform much more sophisticated loop dominance analyses, taking in account the presence of possible complicated shadow structures, before reaching conclusions about their dynamics. However our objective here was not that one.

In studies of resilience like ours, we are interested in the magnitude of disturbance that can be tolerated before its dynamic behavior changes. Based on this definition, a operational concept of resilience should provide answers to three basic questions (Carpenter and Gunderson, 2001): 1) the amount of exogenous force the system can sustain; 2) the degree to which the system is capable of reorganizing in response to those exogenous forces and 3) the degree to which the system can build the capacity to learn and adapt.

It seems that the methodology presented in this paper helps to answer the first and, at least partially, the second of those questions. The third one is much more difficult to answer and perhaps our present knowledge is not large enough to go much farther than using metaphors like the adaptive cycle proposed by Gunderson and Holling (2001). Yet it seems that much insight on the actual systems` dynamics could be gained from the effort in reaching more operational concepts of resilience as we have tried to do in this paper.

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