Assessing Resilience of Complex Socio-ecological Systems through Loop Dominance Analysis

Newton Paulo Bueno, Federal University of Viçosa, Dep. of Economics, Viçosa, MG, Brazil, 36570-000, phone number: 553138991566, e.mail: npbueno@ufv.br

ABSTRACT

Although resilience is an important concept to assess the vulnerability of ecological systems, literature is still unclear on how to measure it in more complex social-ecological systems. This paper presents a practical procedure to assess the degree of resilience of fisheries which builds on system dynamics analysis, specifically on the recent field of research known as loop dominance analysis. It shows that such systems may lose resilience when they exceed certain thresholds beyond which shifts in dominance of feedback loops take place and suggests how to identify those thresholds.

Keywords: socio-ecological systems, resilience indicator, system dynamics, loop dominance analysis

1. INTRODUCTION

Although the field is considered by some to be fragmented, an emerging consensus on the critical importance of the concept of ecological resilience for assessing the vulnerability of social-ecological systems (SESs) promises even greater relevancy and utility of that concept for decision makers in the near future (Eakin and Luers [2]). As defined by Holling [8], ecological resilience refers to the ability to absorb change and disturbance and still maintain the same relationships that control a system’s behavior. However, questions regarding to operationalizing the concept of resilience for the analysis of complex social systems have been raised. This paper aims to help bridge that gap by proposing a practical procedure to assess the degree of resilience of SESs which builds on system dynamics analysis, specifically on the recent field of research known as loop dominance analysis. We suggest that SESs lose resilience when they cross tipping points, that is threshold conditions that, when crossed, shift the dominance of feedback loops that control the processes. For illustrating the argument, we use a very stylized system dynamics model developed by Bueno e Basurto [1] for a small Mexican fishery.

2. METHODOLOGY

2.1 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 [7]) . There are only three unique behavior patterns based on the net rate of change, or atomic linear behavior, of a variable of interest, say fish population. The first is linear behavior, when the variable grows or declines steadily. 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 dynamics 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 [6], p.8):

“A feedback 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 path) of that variable’s behavior.”

2.2 Definition of loop dominance

System dynamicists have been developing a number of new techniques for understanding complex systems’ behavior. One of the more illuminating existing studies is the classical Richardson’s [12] paper on loop dominance which we shall use in this paper to study the problem of assessing resilience in fisheries. Our conjecture is that the loss of resilience of social-ecological systems like fisheries can be seen as a bifurcation point in their dynamics through time caused by shifts in loop dominance. More precisely, we shall argue that systems lose resilience when their dominant polarity shifts from negative to positive. The development is in terms of continuous systems but a similar development holds for processes expressed in discrete terms.

The polarity of a single feedback loop involving a single level x and an inflow rate \( \dot{x} = dx/dt \) is defined by sign \( d^2x \), which is consistent with a more intuitive characterization as follows. The denominator of the fraction – dx – can be thought of as a small change in x, for instance a small change in fish caught in a particular fishery, which is traced around the loop until it results in a small change - d\( \dot{x} \) – in the inflow rate, say in the regeneration rate of the system, \( \dot{x} = dx/\Delta t \). If the change in the rate, d\( \dot{x} \), is in the same direction as the change in the level, dx, then they have the same sign. As \( \dot{x} \) is an
inflow rate and thus is added to the level, the loop is a positive one and hence reinforces the initial change. In such case sign \( \frac{dx}{dt} \) is positive and will be negative if the polarity of the loop is negative, that is if the resulting change in the inflow rate is in the opposite direction to the change dx. If \( \dot{x} \) is an outflow rate, all we have to do to extend the above definition for loop polarity is to attach a negative sign to the expression for \( \dot{x} \), since variation in the same direction in the outflow, e.g. in the death rate, and in the level, e.g. in the fish population means that the loop polarity is negative.

The basic mathematics of loop dominance analysis is as follows.\(^1\)

Taking the derivative of the input flow into the state of variable of interest, \( \dot{x}_k \), with respect to the state of the state variable of interest, \( x_k \), yields:

\[
\frac{d\dot{x}_k}{dx_k} = \frac{\partial f_k}{\partial x_1} \frac{dx_1}{dx_k} + \frac{\partial f_k}{\partial x_2} \frac{dx_2}{dx_k} + \ldots + \frac{\partial f_k}{\partial x_n} \frac{dx_n}{dx_k}
\]

Which simplifies to:

\[
\frac{d\dot{x}_k}{dx_k} = \sum_{i=1}^{n} \frac{\partial f_k}{\partial x_i} \frac{\dot{x}_i}{x_k} \quad \text{for } \dot{x}_k \neq 0 \quad (1)
\]

Each term in equation (1) represents all minor feedback loops (or pathways) leaving the \( i^{th} \) state variable and coming into the variable of interest \( x_k \). We can decompose the effect of each minor feedback coming into the state variable \( x_k \) by doing:

\[
\frac{d\dot{x}_k}{dx_k} = \sum_{i=1}^{n} \sum_{j=1}^{m(i)} \frac{\partial f_j}{\partial x_i} \frac{\dot{x}_i}{x_k} \quad (2)
\]

Where \( m(i) \) is the number of minor loops that leave the \( i^{th} \) state variable and come into the \( k^{th} \) state variable, \( \frac{\partial f_j}{\partial x_i} \) is the polarity of the minor feedback loop and the ratio \( \frac{\dot{x}_i}{x_k} \) represents the net changes in the \( i^{th} \) state variable and the net changes in the \( k^{th} \) state variable.

Thus, the system is dominated by negative feedback loops, that is presents an equilibrium behavior pattern, only if \( \frac{d\dot{x}_k}{dx_k} < 0 \). Furthermore, if the sign of \( \frac{d\dot{x}_k}{dx_k} \) shifts from negative to positive this indicates it has crossed a tipping point beyond which self-reinforcing loops start to control the process and the system loses resilience, as we have remarked before.

These ideas suggest a practical procedure for assessing resilience in fisheries which can be summarized in the following steps:

1) Identify the variable of interest (x) that will determine feedback loop dominance in the major loop of a system dynamics model, that is the loop that drives the dynamics \( x \rightarrow dx \rightarrow dx/dt \rightarrow x \), and compute the ratio \( \frac{dx}{dt} \) for the actual observed conditions of the system and over a chosen reference time interval, attaching a negative sign to \( \dot{x} \) if \( \frac{dx}{dt} \) is an outflow rate.

2) Identify a control parameter which affects an auxiliary variable and can vary the gain of the major loop. Use the parameter to vary the gain of the major loop until \( \frac{dx}{dt} \) changes sign in the reference time interval.

3) Compute the value of the variable of interest at the point where \( \frac{dx}{dt} \) changes sign and compare this value to the equilibrium value obtained in the last run before \( \frac{dx}{dt} \) changed sign; tipping point of the variable of interest is in this interval.

4) Repeat steps 2 through 5 for the other loops.

5) Select the larger among the critical values of the variable of interest as the critical resilience level of the system and compare this to the actual observed level (or the simulated level at the actual observed conditions of the fishery); resilience degree is computed as:

\[
\frac{\text{actual observed level} - \text{critical resilience level}}{\text{critical resilience level}} \times 100
\]

In section 3, we apply this procedure to a system dynamics model developed for a small Mexican fishery.

2.3 The model for the Seri fishery

The Seri fishery is one of many Mexican small-scale fisheries located in the Gulf of California. It exploits the Callos de hacha (CDH), a sessile bivalve mollusk that lives buried in sandy bottoms. The entire Seri CDH fishery takes place inside the Infiernillo Channel, a long, narrow, and shallow body of water flanked on the east by the Mexican state of Sonora. The basic model for Seri fishery is formalized as the simple stock-flow structure presented in Figure 1. The equations of the complete VENSIM model and other information regarding parameters description are provided in Bueno and Basurto (op. cit.).

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\(^1\) See Mojtabahzadeh et al. [9].
Figure 1. A simple model for CDH population dynamics. Variables inside the boxes are the state variables of the system while the others are either parameters, like the carrying capacity of the fishery, estimated by extrapolating observation in a sample of the total area, or auxiliary variables, like the harvest rate. The harvest rate is given by institutional rules which determine fishing effort, that is the number the days fishermen go to sea, and by the capture capacity, given by the average number of boats deployed in the fishery, which also depends on the specific institutional rules adopted by the community. Positive signs indicate there is a direct relationship between the variables and negative signs, an inverse one. Thus total amount of CDH caught increases with the harvest rate and with CDH density in the channel and decreases when the size of the area of the channel covered by marine vegetation rises. The R mark indicates the presence of a positive or self-reinforcing loop. Hence, increases (decreases) in CDH Mature Population increase (decrease) regeneration rate and thus the CDH Mature population next period. The B mark indicates the presence of a negative or balancing loop. Regeneration rate, thus, depends on the fertility rate of female CDH and on the survival rate given by the Beverton-Holt equation: the larger the total CDH population (CDH) in relation to carrying capacity (CC), in the x axis, the lower the survival rate, in the y axis, and the smaller the CDH population next period. The sign of the loop, that is whether it is of self-reinforcing or balancing type, is obtained by multiplying the signs of the relationships included in the loop. The system may collapse if the flow of total CDH caught exceeds a safety level beyond which the regeneration rate next periods will be lower than total harvests, which leads the self-reinforcing loop (in its collapse mode, in which decreases in CDH population lead to further decreases ) to dominate the systems dynamics.

3. APPLICATION OF THE LOOP DOMINANCE PROCEDURE TO ASSESS THE RESILIENCE OF THE SERI FISHERY

For assessing resilience of the Seri fishery, apply the procedure proposed in section 2 as follows.

1) Variable of interest is the Mature CDH Population, which is a key variable for the system regeneration; the ratio \( \frac{dx}{dx} \) over the chosen reference time interval is shown in Figure 2.

![Figure 2: ratio \( \frac{dx}{dx} \) for a 13 boats fleet size](image)

2) Parameter \( \text{carrying capacity} \) is chosen, assuming that this parameter influences positively the regeneration capacity of the fishery; the evolution of the ratio \( \frac{dx}{dx} \) is shown in Figure 3.

![Figure 3: Loop dominance shift caused by variation in the carrying capacity](image)

3) System undergoes a loop dominance shift somewhere in the interval cc 20500- 21000 millions of CDs, and the tipping point (at cc = 20500), that is the point beyond which \( \frac{dx}{dx} \) changes sign from negative to positive, is at time 78. Critical Mature Population is somewhere in the interval equilibrium population at cc=21000 and the Mature Population at the tipping point. Thus, an estimative for the critical mature population based on the carrying capacity is 3282 < critical mature population <4252.

4) Procedure is repeated for the parameters average boats deployed, productivity per man and fishing effort. Results are as follows. Tipping points: fleet size: year 89; productivity: year 67, and fishing effort: year 82. Critical mature CDH population forecasts: fleet size:
15.9 to 16 boats → 4081 Mature CDHs < Xc < 4255
Mature CDHs; productivity: 660 CDH/man/day and 670
CDH/man/day → 4048 Mature CDHs < Xc < 4282
Mature CDHs; fishing effort: 50.5 to 51% → 4075
Mature CDHs < Xc < 4308 Mature CDHs.

5) resilience degree is computed as:

\[
\text{resilience degree} = \left( \frac{\text{observed level} - \text{critical resilience level}}{\text{critical resilience level}} \right) \times 100
\]

The critical resilience level of the fishery (the larger one) is 4308 million of mature CDH and, hence, the
resilience degree of the system is:

\[
\text{resilience degree} = \left( \frac{8900 - 4308}{4308} \right) \times 100 \\
= \frac{4592}{4308} \times 100 \\
= \sim 107.7\%
\]

Which means that the observed value in the Seri fishery is a little more than twice the critical resilience value.

4. DISCUSSION

Formal loop dominance analysis tools are still in their formative phase. One of the main criticisms raised against these approaches is that they do not provide a unified theory that automatically provide modelers with dominant structures. While much progress is expected to be reached in the field, this is likely to remain as a permanent shortcoming of the system dynamics methodology, given the analytical intractability of non-linear high order actual social-ecological systems. So it seems that at least in part loop dominance analysis is likely to remain as much as science as art.

Despite its shortcomings, however, simple analyses such as the one presented in this paper might be very helpful for resource users.

For instance, assume that fleet has grown from a size nearly below the tipping point of the system, say the one obtained at the fleet of 15 boats, to a size nearly above that point, in which 17 boats are deployed. Assume also that fishermen, after realizing that the fleet is too large, decide to reduce it to the original level after 45 (return 45) or 55 years (return 55) as depicted in Figure 4. In the second scenario, mollusk population has fallen below the system’s tipping point (4308000 mature CDHs in the Seri fishery), which has led the fishery entering into an endogenously driven downward spiral. Once system is stuck in that path it will remain there, even if the fleet size returns to the status quo ante, that is to the previous set of practices and institutional rules. Thus, in order to prevent their system to collapse, fishermen would have to agree on a new set of rules restricting fishing effort until the mollusk population has been restored to its sustainable levels.

Several recent studies using the system dynamics approach have attempted to apply the concept of resilience to study processes of dominance shifts in different complex systems. A representative sample of these works is as follows. Rudolph and Repenning [13] show that the accumulation of routine events can shift organizations from a resilient, self-regulating regime which off-sets the accumulation of interruptions in to existing plans and procedures, to a fragile self-escalating regime that amplifies them. Taylor and Ford [16] 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 and thus lead them to failure. Sengupta et al. [14], in another context, show how an irrigation systems can lose resilience due to insufficient maintenance of equipment. Ford [5], finally, suggests that electric companies may be trapped in a spiral of losses for expanding capacity ahead of demand beyond a certain critical level. The basic idea of all these works is that systems lose resilience when they exceed certain thresholds in which shifts in dominance of feedback loops take place. Given the commonalities among the processes it seems plausible, while this is still an unexplored field by economists, that approach might also help to better understand regime shifts in economic processes as long wave cyclical movements in investments and output (Sterman [15]) and perhaps structural breaks in economic activity, as the recent financial crisis.

5. CONCLUSION

Usually one assumes that social-ecological systems respond to gradual change in a smooth way, but sometimes there are drastic shifts – bifurcation points - which are typically hard to predict in advance, and expensive or even impossible to reverse (Folke et al. [3]). Mostly because measurement or predictions of thresholds in SESs have low precision, the precise meaning of resilience and its identification remain a subject of debate. This work has attempted to bridge that gap by providing a relatively simple procedure to assess resilience in SESs based on loop dominance analysis.

Once a system dynamics model has been calibrated for a particular SES, the proposed procedure allow to identify critical intervals for the population which would prevent systems entering into downward trajectories as typically happens in loss of resilience.
processes. Those values thus could then be considered as benchmarks by users, who might assess resilience by forecasting actual population directly from collected samples in different parts of the systems.

Computing such benchmark values is a potentially useful tool because it might help to develop indicators of gradual change and early warning signals of loss of ecosystem resilience by monitoring only (at most) a handful of key ecosystem variables. To be aware of those signals is important since, as literature has related fishermen around the world prefer, simply and pragmatically, to grow the fleet until there is compelling evidence to stop (Morecroft, [10], p. 341). However, as experience that people have before crossing the tipping point is likely to misguide them when their systems start to be driven by positive downward feedback loops (Moxnes [11]), the level of fish population that they intuitively consider as a compelling evidence for reducing their fishing effort may indeed be quite bellow from the critical safe level of resource use.

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7. REFERENCES


