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Operationalizing Social Ecological Systems
Resilience analysis using a Dynamic Index

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Abstract: Governance of social ecological systems (SES) is a difficult task. Embracing complexity, the coupled nature of social and ecological dimensions, feedbacks and non-linearity of its attributes and the necessity of dealing with society participation in the decision process make the challenge bigger. Resilience is a growing research field that can collaborate with this discussion. Resilience is a SES feature that enhance its capacity of maintain identity under different systems changes. This work uses system dynamics theory as foundation to build a Dynamic Resilience Index. This index uses Cobb-Douglas equation to encompass several resilience attributes as biodiversity, social networks, institutions, polycentric governance and others, and combine them with ecosystem services in a integrative and system based approach. The article concludes that system dynamics is a powerful tool to embrace resilience analysis and can collaborate with the social perspectives of social ecological systems analysis.

Key words: Social Ecological Systems, Resilience, System Dynamics, Governance.

1. INTRODUCTION

During last decades of 20th century most part of planning and policies regarding oceans and coastal areas were created by government (BURROUGHS, 2011). These policies were mostly created under “command and control” perspectives and water quality parameters, pollution control measures and licensing process were derived from those actions. Nowadays there is a different perspective that considers management of resources in a plural context, formed by several complementary forces habits and behaviors, with formal and informal institutions acting at same time, inside government and also spread in society diverse communities. This perspective assumes that to change human behavior, opportunities and problems need to be evaluated, institutions and arrangements need to be stablished, and acceptable behavior regarding resource and environmental use must be encouraged or sanctioned (JUDA, 1999).

In a comprehensive analysis Burroughs (2011) used three schemes of decision making processes: Sector-based management, Spatial Management and Ecosystem-based Management. Sector-based Management (SBM) is a fundamentally reactive approach to resources management. If a company desires to create an activity that includes natural resource management that may cause a potentially significant environmental impact, the government reacts showing norms and regulations to that kind of activity. The Spatial Planning (SP) emerges as an alternative and uses particular objectives for a determined area and expect to reduce the conflicts through allocation of activities only in regions they fit properly (zoning).

More recent perspective resulted in Ecosystem Based Management (EBM) (FOLKE et al., 2005; BURROUGHS, 2011; PARAMIO et al, 2015). This approach includes several distinct advances regarding environmental management. Starts considering economic activity (social) a human feature that occurs inside a larger and finite natural system (ecological). This perspective is also called social-ecological systems and considers that those subsystems are linked once they affect and are affected by each other in complex dynamic relations (feedbacks). Effective management must recognize these links as well as the limits of combined social-ecological system (BURROUGHS, 2011).

The ecological subsystem of Social Ecological System must be managed in a sustainable way in order to obtain continued yield of ecosystem services on the short and long term (DAILY et al., 2000; BEAUMONT et al., 2007). Adaptive Governance seems to be one way to connects individuals, organizations, agencies, and institutions at multiple organizational levels (FOLKE et al., 2005). Adaptive governance is considered governance that is able to work
properly under a system that changes across time (using other word: a resilient society). The behavior of ecosystems requires that the governance system adapt itself to nature’s regular behavior and changes, meaning that the management of the social ecological system must be coupled to ecosystems.

1.1 Resilience

Resilience concept has been used in several knowledge fields from business to medicine. The concept has turned into a prolific branch of science in the last few years with impressive numbers: less than 100 citations in 1995 turned into 20,000 citations in 2014 (FOLKE, 2016). Despite the increasing adoption of this concept as an investigative agenda, Resilience brings an important message in this concept: social ecological systems work properly under certain limits. These ecological and social limits (tipping points or thresholds) are boundaries and if they are trespassed, the system will be operating under a different regime, in a new attract basin. This new regime is unknown and its capacity to provide ecosystem services that support human wellbeing is also unknown, and this new situation can enhance risks. Actually, uncertainty is a key concept when complex adaptive system is at stake (BIGGS et al., 2015), because system tipping points (limits of regime) are also unknown.

In a narrow view, resilience is the capacity to return to a stable point after some perturbation. This view is narrow because underneath it the idea of stability of systems is implicit, and also the control over its behavior. Systems are not stable, they are dynamic, sometimes under gradual changes (when slow variables are influencing its behavior), sometimes in abrupt changes; sometimes changes are predictable, and sometimes they are not. Therefore Resilience thinking, in a broad view, is the “capacity of people, communities, societies, cultures to adapt or even transform into new development pathways in the face of dynamic change” (FOLKE, 2016). Resilience thus is related to transformation, not stability.

There is the distinction between Specific Resilience and General Resilience. First one is the answer to the question “Resilience to what?” meaning specific resilience is considered in relation to a specific menace. On the other hand, general resilience is a general feature of systems, not a reaction regarding some specific threat. It is the capacity to deal with uncertainty, complexity and surprises (FOLKE, 2016).

Operationalizing Resilience studies is occurring fast although modeling and measuring it is not an easy task. Specific Resilience is easier to handle and there are several experiences in literature (e.g. Resilience Alliance) but operationalizing the concept in a higher level is an operational challenge. Béné et al. (2016) also claims “none [study] provides an approach or a methodology that enables us to measure resilience simultaneously at several levels”.

The author also shows another operational challenge that is to consider the multi-dimensional character of the system made of social, ecological and economic dimensions. According to the author (BÉNÉ et al, 2016): “This means that, in theory, the framework proposed to measure resilience should be designed in a way that allows for integrating this multi-dimensional nature (even if we are interested in one particular dimension e.g., food security)”.

1.2 Modelling Resilience

In order to collaborate with the exposed, this work is an attempt to integrate several systems features into a Dynamic Resilience Index (DRI). A causality model like MIMES can be used in this task, once causalities presumed for the system are formalized in the model, simulated and tested, and finally assumed as probable drivers of the system or discarded or replaced by a different variable more adequate to explain the system behavior. MiMES is the acronym of Multiscale Integrated Model of Ecosystem Services (BOUMANS et al., 2002; ALTMAN, 2014; BOUMANS et al., 2015). This model is based on system dynamics and recently it was used in several cases worldwide with excellent results (BOUMANS et al., 2002; KERCHNER et al. 2008; BATKER et al., 2010; ALTMAN et al., 2014; BOUMANS et al., 2015).

2. OBJECTIVES
The main goal of this work is to make an approach how MIMES model can contribute to underpin the Dynamic Resilience Index (DRI), integrating social, ecological, economic and cultural variables.

3. EXISTING MODELING FRAMEWORK

The Dynamic Resilience Index was obtained using Cobb-Douglas equation. This is a method used in system analysis to integrate several different components of the system into one meaningful indicator. It has been used in economic modeling and is exemplified by one sub-model of GUMBO (BOUMANS et al., 2002). GUMBO (Global Unified Metamodel of the Biosphere) is a MIMES model applied to the planetary scale.

3.1 Anthroposphere sub-model from GUMBO

GUMBO embodies in the Anthroposphere sub-model, economic and social attributes. The model focuses on two different variables to assess value: Gross World Product (GWP) and Sustainable Social Welfare (SSW). The first is a conventional economic valuation of goods and services; the second assess the contribution of system elements in a "quality of life" assessment, represented by SSW function.

In the model, both variables (GWP and SSW) are mathematically obtained using Cobb-Douglas equation:

\begin{align*}
(1) \quad & \text{GWP} = HK^{\alpha_1} \cdot SK^{\alpha_2} \cdot BK^{\alpha_3} \cdot W^{\alpha_4} \cdot \prod_{i=1}^{10} NK_i^{\alpha_i + 4} \\
(2) \quad & \text{SSW} = BK^{\beta_1} \cdot C^{\beta_2} \cdot \prod_{i=1}^{7} NK_i^{\beta_i + 2} \cdot HK^{\beta_{10}} \cdot SK^{\beta_{11}} \cdot W^{\beta_{12}} \cdot M^{\beta_{13}}
\end{align*}

Where \( \alpha \) and \( \beta \) are the percentage increase in levels of output (GWP or SSW) starting with 1% increase in the corresponding input. HK is human capital (represented in the model by technology and labor); SK is social capital (measured by social networks and institutions); BK is for built capital (represented by investment in infrastructure); W is for waste (waste products of consumption and also from depreciated capitals); C is for consumption (measured as non-invested GWP); NK is for natural capital (considers 7 different ecosystem services in SSW and 10 different for GWP); M is for mortality. Coefficients for waste (\(\alpha_4\) and \(\beta_2\)) and for mortality are negative. All the others are positive. The values range from -0.2 to 2. For specific contents check Boumans et al. (2002)

The differences between the two equations are that GWP includes ecosystem goods and services (including oil reserves for instance) and SSW includes only ecosystem services; SSW also includes consumption (measured as a portion of production) and mortality (a proxy for human health indicator) and both act like indicators of human well-being.

GUMBO’s authors calibrated all \( \alpha \) exponents in order to create a curve that follow GWP data of the countries under study. The same step could not be made with SSW because this indicator is not usually measured by nations. Thus \( \beta \) are arbitrary statements of the researchers and reflect their individual preferences, which will always be biased by their individual point of view about the society. To deal with that bias they used two profiles of people (from COSTANZA, 2000) and adopted their choice preferences: one group is formed by technological optimists and the other is formed by skeptics. First one gives more importance (weight) to built capital, consumption and individual knowledge, and less importance to natural capital and waste. Social capital and mortality are weighted equally among both.

Four types of capital are used to build GWP and SSW indicators. Energy is also present as an underlying attribute to calculate social, built and human capitals. Waste reduces the value of GWP and SSW and Consumption increases SSW. Mathematically, Cobb-Douglas equation is used for three reasons (BOUMANS et al., 2002): 1) the marginal product of new inputs is positive but decreasing (meaning additional units of the same attribute will enhance the overall index at a lower rate every time step); 2) Because the equation allows replacement of its components; 3) it is mathematically treatable.

Cobb-Douglas advantages are very relevant to dynamic modeling.Marginal product of new inputs increasing at a decreasing rate must occur to be consistent with the expected behavior of the index. If there is more biodiversity, it is expected to have more SSW, but not with an exponential growth. Thus more biodiversity implies more SSW at lower growing rates.
3.2 Foundations of index development

Several authors have been studying which system’s properties interact, forming the substrate from which Resilience emerges. FIKSEL (2003) establishes a list of four components of Resilience:
1. Diversity - existence of multiple forms and behaviors;
2. Efficiency - performance with modest resource consumption;
3. Adaptability - flexibility to change in response to new pressures;
4. Cohesion - existence of unifying forces or linkages.

A similar approach is presented by BIGGS et al. (2015) with a deeper analysis and more detailed features underneath Resilience concept. They focus their understanding in Resilience of Ecosystem Services, meaning the “capacity of a social ecological system to continue providing some desired set of ecosystem services in the face of unexpected shocks as well as more gradual ongoing change”. This comprehensive approach brings seven components of Resilience:
1. Maintain diversity and redundancy – systems with high levels of biodiversity and redundancies tend to be more resilient in providing ecosystem services;
2. manage connectivity – ecosystem recover from disturbances using internal links of species and social actors. In social networks it can also provide new information and trust;
3. manage slow variables – identify slow variables and their feedbacks is a challenging effort, but understanding these general system features increase resilient behavior;
4. foster Complex Adaptive Systems (CAS) thinking – comprehension of the need of integrated approaches, non-linearity and uncertainty regarding ecosystem services production in social ecological system increases the ability to deal with changes, and then increases resilience;
5. encourage learning – studying how systems works reduces the uncertainties and enlighten non-linearity behavior, experimentation and monitoring thus can enhance knowledge and foster resilience;
6. broaden participation – participation enhance relationships, can build trust, facilitate learning and make collective action possible. All these are directly related to governance and resilience;
7. promote polycentric governance systems – provides a structure in governance that allows the other principles to develop and also enhances participation and social networks.

Principles 1 to 3 are general systems features, and principles 4-7 are more related to governance of social ecological systems. There is a degree of overlap between all those concepts. Connectivity (principle 2) regarding social sphere and social networks (principles 6 and 7) are close related; foster CAS thinking and enhance learning is one form of bias development of scientific knowledge in order to pursue systems thinking.

Although all those components are still under construction, they form the actual state of the art in social ecological resilience studies. Comparing the suggested components of both authors (FIKSEL, 2003 and BIGGS et al., 2015) can be a way to understand common ground on the nature of Resilience and then make the process of building Dynamic Resilience Index founded in the best available scientific bedrock.

4. MODEL DEVELOPMENT

4.2 Proposed Dynamic Resilience Index

The following index needs to be tested. At this stage it is only a proposal of how DRI could be measured:

\[
DRI = (BK^{\gamma_1}. E)^{\gamma_2}. PG^{\gamma_3}. I^{\gamma_4}. SN^{\gamma_5}. CasK^{\gamma_6}. ES^{\gamma_6}. GE^{\gamma_7}
\]

Where DRI is dynamic resilience index; BK is built capital; E is for efficiency; B is Biodiversity; PG is for polycentric governance; I is for Institutions; SN is for Social Network; CasK is for complex adaptive thinking knowledge; ES is for ecosystem services; GE is for gender equality.
These variables embody most of the factors proposed by Fiksel (2003) and Biggs et al. (2015). Built capital is a proxy for the built environment of the society, but different from GUMBO, it is regulated by an Efficiency factor.

Biodiversity is a proxy for natural species availability, and must embody some food chain index that shows the links between the species. This variable is aligned to Principle 1 of Biggs et al. (2015) and to component 1 of Fiksel (2003).

Polycentric governance is a proxy for the organization of the society and the distribution of responsibility and power. It is aligned to principles 7 and 3 from Biggs et al. (2015) and component 3 of Fiksel (2003).

I is a proxy for institutional diversity. Institutions represent the overall interest of society to exercise its power about something, through the adoption of rules of use. Institutions thus will embody the knowledge about the system with participation of society in its application. It is aligned to principles 7, 6 and 4 from Biggs et al. (2015) and to component 4 of Fiksel (2003).

SN is social network proxy. Not only is the size of the network relevant but also its cohesion. There are some variables from social network analysis that can be embedded in this indicator (e.g. Centrality measures) in order to understand the participation of the stakeholders into decision making. This indicator is aligned with 1, 6 and 7 from Biggs et al. (2015) and to components 1 and 4 of Fiksel (2003).

CasK is a proxy for complex adaptive system knowledge of the society under study. It can be obtained from a small part of the education variables of the people, probably growing at slow rates over years. This is relevant because is a driver for changing the perception of old management types like sector based management and spatial planning (BURROUGHS, 2011) to a new one, more appropriate system that embodies complexity and uncertainty into the planning (Ecosystem Based Management). It also complies with principles 3, 4 and 5 from Biggs et al. (2015) and component 3 from Fiksel (2003).

ES is an indicator of ecosystem services. It is important because in the end all social ecological systems are embedded in a natural finite world responsible for provision of several services, most of them without any market value, that makes human societies feasible in this planet. This is well described in BOUMANS et al (2002) and complies with Principles 1, 2 and 3 from Biggs et al. (2015) and components 1 and 3 from Fiksel (2003).

GE is a proxy for gender equality. This is not directly present in any of previous recommendations (FIKSEL, 2003 and BIGGS et al., 2015) but it is clear that reducing inequalities in representation and enhancing gender equality are relevant aspects regarding SES governance (JOHNSSON-LATHAM, 20007; GROSSER, 2009).

5. DISCUSSION

Although Resilience is undeniably growing in scientific researches, there are those who discuss the adoption of the agenda (BROWN, 2014; CRETNEY, 2014; STONE-JOVICICH, 2015). All those authors agree that social sphere is underrepresented in resilience studies. In a broad view, they argue, as social scientists, that social ecological systems view (not only Resilience) lack of social perspective, being too ecological.

Using dynamical resilience index can contribute to enhance social perspectives regarding SES analysis once its embraces knowledge that from social sciences as social networks, polycentric governance and others. It is important to keep in mind that this index is not supposed to replace all the discussion and the qualitative analysis that is commonly done, on the contrary, it is an attempt to operationalize the concept and contribute to discussion.

Brown (2014) argues the idea of social and political features being underestimated in resilience practice and science. Cretney (2014) pursue a political criticism of the risk of adopting resilience thinking because it “justify projects informed by neoliberal ideologies that aim to decrease state involvement, increase community self-reliance and restructure social services”. The author also argues that the concept does not consider power, agency and inequality in the use of the term. One alternative could be the enhancement of social network measurements and integration of this knowledge with polycentric governance, enhancing power distribution and decreasing this overlook.

A deeper criticism is found in Stone-Jovicich (2015). The author draws attention to different perspectives (material-spatial world systems analysis, critical realist political ecology, and actor-network theory) from social sciences regarding social-ecological systems, arguing those to be more appropriate when compared to resilience.
World system analysis uses several approaches to investigate “emergence and dynamics of the capitalist world political economy over the past 500 years” (STONE-JOVICICH, 2015). Overall premise is that world system level processes are important to understand human-nature relations in long term and cross-scale. This approach also claims that considering only internal dynamics of a small or local society are insufficient to explain its own dynamic of change.

This criticism is pertinent on the understanding of system behavior. System dynamics has been dealing with this since its foundation and the way to do that is about delimiting system boundaries. Building a system dynamic model is an iterative process of enhancing complexity (STERMAN, 2000). In this process, the modeler will embody all those variables that are relevant for the overall behavior of the system. Variables that have their dynamics influenced by the behavior of other variables in the model are called endogenous variables and must be modeled in order to have a high quality output. Those variables that are relevant for the behavior of the system, but are not directly influenced by variables inside the model can be treated as exogenous variables.

Critical realist political ecology has different characteristics in its evolving stages (from 70’s structuralism, followed by 90’s poststructuralism). In a wide view, this approach claims that environmental problems are independent of human understanding (STONE-JOVICICH, 2015), and adopts a perspective that “reality” problems can never be understood in its totality by societies. With that perspective, scientific explanations of environmental degradation are considered to be always limited, to be able to provide only limited insights of the unattainable complexity of the system, and therefore, can “exacerbate environmental crises and social injustices” (Op. cit).

The position of political ecology resumes perfectly human condition towards complex systems. The lack of complete information and perfect knowledge about systems represent boundaries to human approach to SES. In system dynamics this limits of knowledge are called bounded rationality (STERMAN, 2000), and it is well known as a limit but also represents a boundary to be surpassed by scientific experimentation.

Actor-network theory perspective considers that social relations domain is always mediated (even enabled) by non-human entities and thus, at least at the beginning of the analysis, humans and non-humans have a similar potential role in the overall behavior of the system (what is called generalized symmetry). The focus is not in the structure of networks, but more on the “structure of networking” (STONE-JOVICICH, 2015), meaning the ways that actors interact and affect each other. This perspective also considers that change is always happening (this might justify the abandon of pursuing stable networks) and thus dynamics is the core of the analysis.

Structure of networking is probably the major contribution of system dynamics in order to collaborate with resilient thinking and modelling. The way that actors interact and affect each other is, in system dynamics terms, considered by causalities. Causalities are the expression that conditions the change in behavior of one variable (actor) in function of changes that already occur in other variable.

In the moment of validation of the model, scientists compare the obtained behavior of any variable of the model with the real behavior of that variable obtained by field measurements or other models. If the model variable present similar behavior of the real one, means that it is obtained by a set of premises that also occur in the real world, and then, causalities were discovered. This is a difficult process even to most experienced modelers, and also there is always the chance of some slow variable that was not embodied in the model, to be present in the real world and affect the expected behavior of the system. This is the main limitation of this science branch.

Considering resilience, the work of causalities discovery through validation embodies a challenge because there is no real world data to be used to validate, but also encompass a great opportunity to use DRI as a parameter for other assessments validation.

One interesting collaboration of Cobb-Douglas equation is that all exponents ($\gamma$) can be managed to enhance knowledge regarding scenarios (BOUMANS et al., 2002) or can be used in order to build specific resilience index for particular types of social ecological systems, as fisheries communities, hunter-gathering communities, coastal cities, rainforest watersheds, etc. This field must be explored and the possibility of standardized exponents should be tested.

Adoption of system dynamics models to build resilience dynamic index is at ultimate point justifiable considering that building a model is a process of learning about the system.
6. CONCLUSIONS

Social ecological systems (SES) are complex, adaptive systems with feedbacks, uncertainties and surprises that make the process of management far from trivial. Resilience appears though as a feature of SES that encompass several distinct system aspects which embodies uncertainties, feedbacks and complexity and thus can be an interesting way of dealing with complexity challenges and also increase society participation in the process.

This work presented a system dynamics based index for resilience: Dynamic Resilience Index (DRI). Far from presenting all the possibilities of calculations, the goal was to collaborate with the discussion regarding SES Resilience in at least two points. First to bring resilience in a treatable mathematical index that should not replace the qualitative assessments presented in literature, but enhance the application of the theory. Second, to provide a mathematical approach that can be useful in order to build an integrative index.

Enhancing the use and application of resilience concepts through measurement of DRI can enforce the awareness of society regarding complexities, uncertainties and feedbacks of SES and promote the development of this science field.

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