International Environmental Modelling and Software Society (iEMSs)
2010 International Congress on Environmental Modelling and Software
Modelling for Environment's Sake, Fifth Biennial Meeting, Ottawa, Canada
David A. Swayne, Wanhong Yang, A. A. Voinov, A. Rizzoli, T. Filatova (Eds.)
http://www.iemss.org/iemss2010/index.php?n=Main.Proceedings

Deceiving Feedbacks: The Challenge of Policy-Design for Inshore Fishery Activities in Complex Ecosystems. The Case of the Ciénaga Grande de Santa Marta

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Abstract: The Ciénaga Grande de Santa Marta is an estuarine lagoon located on the Colombian coast. Given the lagoons variability, its connections to adjacent ecosystems, and its biodiversity and anthropogenic activity, it has long been a challenge to managers and policy makers to maintain the lagoon for sustainable use. A one-year joint project with the Instituto de Investigaciones Marinas y Costeras (INVEMAR) research institute and the Universidad de los Andes resulted in the development of a system dynamics model to aid in the design of sustainable policies for fishing control. The study presented here underlines the deceiving characteristics of feedback processes like fishing and biological dynamics, which generate unexpected impact on the lagoon. According to environmental variations and the decision-making processes made by local fishermen, salinity changes and fish abundance scenarios were explored in a simulation model. Various technical tests were performed such as structure assessment, behavior analysis and numerical parameter sensitivity. We suggest that the interplay among the reproduction loop, effort loop and catch loop, shows that variations in catches are defined by decision making processes of the fishermen according to the ecosystem and hydrological conditions. Importantly, the simulation model provided useful and novel approximations to support policy-design processes and discussions among local and regional institutions.

Keywords: Ciénaga Grande de Santa Marta, simulation, estuary, system dynamics, policy-design.

1. INTRODUCTION

Appropriate decision and policy making for highly dynamic ecological systems is a challenging task in environmental management. In particular, degraded ecosystems are expected to have different ecological dynamics that might lead to the spread of large-scale changes due to stressors on ecosystems feedbacks and constraints on its biological processes [Benett, et al., 2003]. The Ciénaga Grande de Santa Marta (CGSM) is an impacted estuary located in Colombia, where research has focused on environmental conditions, fishery resources and activity, and mangrove behavior. Management plans and policy implementations are wanted for the sustainable use of this ecosystem [Rueda and Defeo, 2003b; Rueda and Santos-Martínez, 1999; Sánchez et al., 1998]. We developed a simulation model of the CGSM as part of a one-year joint research project with the INVEMAR research institute and Universidad de los Andes. The main purpose of this model was to understand the relevant systemic interactions of the mangrove, fish, and human populations to help understand the complex dynamics that are observed in the lagoon, in order to support decision-making processes to develop sustainable policies for this ecosystem. This document presents the role of important feedback processes that seem to drive the dynamics of the CGSM. The next section describes the ecosystem of the CGSM, while the third section discusses the relevant literature on feedback complexity. The fourth section introduces the primary feedback structures that are proposed to explain the dynamics of fish and crustacean populations; these structures were mapped in a system dynamics simulation model. Finally, the last section presents the feedback-grounded hypotheses, which might explain the behavior of key variables as a result of the feedback processes interaction, and major results and the lessons that were derived along with implications on future research.

2. A COMPLEX ECOSYSTEM: THE CIÉNAGA GRANDE DE SANTA MARTA

The Ciénaga Grande de Santa Marta is a lagoon estuarine ecosystem located along the northwestern coast of Colombia [Botero and Mancera, 1998]. The estuarine is naturally variable, presenting challenging tasks for policy makers. Several factors, such as its multiple connections with adjacent ecosystems, its biodiversity, the extreme poverty of its human population, the alterations in its hydrological regime, the increase in the mangrove death rate, the reduction of fishery resources, the degradation of water quality, and the lack of commitment by the government and society, have all provided motivation to ensure the sustainable use of this ecosystem via environmental management plans and methods [Rueda, 2001; Rueda and Defeo, 2003b; Rueda and Santos-Martínez, 1999; Botero and Salzwedel, 1999]. However, despite several rehabilitation initiatives put in place since 1981, salinity upsurge, mangrove defoliation, fishery resource variations, intermittent institutional management and government presence, and social problems are still persistent in the lagoon [Vilardy, 2007]. Above all, past interventions have not taken into account the ecosystem feedback structures. We suggest that knowledge of these structures will likely improve the understanding of the behavior of the ecosystem and thus support decision-making processes for ecosystem management.

3. FEEDBACK COMPLEXITY AND ECOSYSTEMS

Ecological changes and strong feedback processes, like reciprocal interactions between biotic factors and the physical environment, must be considered in environmental management and restoration projects [Benett et al., 2003; Suding et al., 2004]. Because the CGSM is a degraded wetland ecosystem as a consequence of different anthropogenic activities [Botero and Salzwedel, 1999; Rueda and Defeo, 2003a], it is expected to have very different ecological dynamics than less impacted ecosystems [Suding et al., 2004]. For this reason, an understanding of the ecological processes (feedbacks and constraints) in a degraded system is critical. Different stressors on ecological feedbacks lead to the spread of ecological responses that cause large-scale changes [Benett et al., 2003]. For instance, an anthropogenic impact on an ecosystem can lead to soil loss and reductions in water quality and quantity, causing a dramatic change in biodiversity, such as a reduction in the commercial fish stock. In general, self-reinforcing and self-regulative processes driven by positive and negative feedback loops might help to explain the persistence of specific dynamics that usually challenge our understanding of these systems, either by amplifying or stabilizing behaviors [Sterman, 2000]. Hence, ecological feedbacks might become one of the most important factors for ecological decision- and policy-makers [Benett et al., 2003; Cumming et al., 2005].

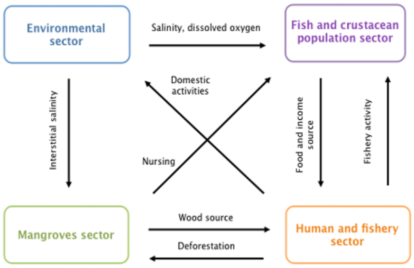
A relevant tool for understanding these special ecological interactions (feedbacks) is predictive modeling through simulation, which is appropriate for well-understood systems over short time frames [Benett, et al., 2003]. However, most ecological systems are complex, highly dynamic and not well understood [Jorgensen, 1999; Wu and Marceau, 2002]. Simulation models, and software for environmental management, have been constructed for different ecosystems [Woodwell, 1998; Güneralp and Barlas, 2003; Rai, 2008; Gal et al., 2009]. STELLA^{TM} (*isee systems*) is one of the most versatile tools and has been widely used for ecological modeling in diverse ecosystems around the globe [Costanza and Ruth, 1998; Costanza and Gottlieb, 1998; Ray and Straskraba, 2001; Hulla, et al., 2008]. This tool is based on system dynamics, a methodology suitable for dealing with complex systems driven by accumulation and feedback [Sterman, 2000].

The CGSM has not been studied from the perspective of system dynamics. Research has mainly focused on mangrove ecosystem, economically important ichthyic species, environmental conditions, and some human activities over the past years [Perdomo et al., 1998; Rueda, 2001; Blanco et al., 2006; Rueda, 2007]. Nonetheless, there are no ecological modeling studies that combine all of these variables together, or in pairs. Currently, only Twilley et al. [1998] have studied the CGSM with a modeling approach. In this work, the mangrove ecosystem of the CGSM was evaluated using the FORMAN model, which was developed to simulate the demographic processes of mangroves in a 0.05 ha plot. The model was used to establish trajectories of mangrove recovery according to different restoration criteria at geographically specific conditions and on a decadal time scale, hence contributing to the design and implementation of restoration projects. The simulations were based on differential equations but feedback processes were not taken into account.

Our work introduces a system dynamics model built in iThink^{TM} (*isee systems*), a software tool similar to STELLA, which allows for the inclusion of diverse variables to capture relevant feedback processes that might help to explain the complex dynamics of the CGSM. The system dynamics method provides a framework to explore and understand the feedback characteristics of a particular system, linking policy decisions to actions, and linking particular behavior to delays in the decision-making process and system response. [Forrester, 1961; Sterman, 2000]. This method can be used for understanding problems in industrial, urban, economic, politic and ecological systems, such as a declining market or industrial productivity, the flux of populations, rising salinity levels and unemployment [Saysel and Barlas, 2001]. An emphasis is made in understanding the system structure, that is, how interactions among physical and decision-making feedback processes produce system behavior. Patterns such as exponential growth or decay, s-shaped behavior, and oscillation and decay can be understood with positive and negative feedback loops [Saysel and Barlas, 2001; Sterman 2000]. Two different tools are available to represent the feedback processes in system dynamics, Causal Loop and Stock-and-Flow diagrams. Causal Loop diagrams are qualitative tools for representing relationships among variables, while Stock-and-Flow diagrams quantitatively describe the system structure using accumulations and rates [Sterman, 2000]. Thus, computer simulation is used to build explanations of structure-behavior relationships with the aim of enhancing the understanding of policy-makers.

4. FEEDBACKS IN THE CGSM

Our model is defined in four sectors (Fig. 1). The environmental sector models the habitat for fish and crustaceans as well as the abiotic (chemical and physical) conditions that are suitable for species survival, such as salinity, and dissolved oxygen. The population sector addresses the most economically and ecologically relevant fish and crustacean species for fishery management at the CGSM (Fig. 1), including reproduction, mortality and migration processes influenced by environmental conditions. The human and fishery sector concentrates on the local human population whose main economic activity is artisanal fishing, which employs many different pieces of fishing equipment, described in Figure 1. The last sector models the mangrove dynamics of the three main species (*Rizophora mangle, Laguncularia racemosa* and *Avicennia germinans*) that are locally used to build houses, and for firewood and fishing tackle. The simulation model uses arrays to encapsulate parallel model structures in a single visual arrangement to represent different fish and crustacean species and fishery gear under the same causal structure.



Fish and Crustacean Species	Inshore fishing gear
Eugerres plumieri	Cast net and encircling gillnet
Oreochromis niloticus	Drag net, cast net and trammel net
Mugil incilis	Trammel net, cast net and encircling gillnet
Elops saurus	Cast net, trammel net and encircling gillnet
Ariopsis sp.	Long lines
Callinectes sapidus and *C. bocourti*	Crab traps
Family Penaidae	Shrimp net

Figure 1. Model sectors (left side) and Fishing gear considered in the model and its target species (right side)

4.1 Conceptualization

The four different sectors generate sixteen feedback causal loops. We will describe only the most pervasive feedbacks that directly affect fish populations by means of generic Causal Loop Diagrams (CLD). CLD use arrows (causal links) to describe the relationship between two variables, and an effect of one variable on another is indicated by the direction of the arrow. Each arrow has an associated polarity sign; a positive sign means that an increase or decrease in the independent variable causes a similar change (further increase or decrease) in the dependent variable, and a negative link means that there is a change in the opposite direction, e.g. an increase produces a decrease in the dependent variable [Sterman, 2000]. Feedback loops are formed when the effect of any variable is fed back as a new cause by passing through any other variables that are connected with causal links. When an increase in the initial variable, for example, fish and crustacean population (Figure 2), results in a further increase in the same variable after going through a loop, or vice versa, it is considered to be a self-reinforcement loop and is denoted with a positive sign surrounded by an arrow (Fig. 2). If an initial decrease in a particular variable results in an increase in the same variable, or vice versa, the loop is labeled as a self-regulating loop denoted by a negative sign (population and carrying capacity interaction in Figure 2). Behavior patterns can be associated with these two types of basic feedback structures; positive feedback loops promote exponential growth while negative loops produce exponential-decay and goal-seeking behavior. Delays and interactions among diverse loops produce more complex patterns such as oscillatory and sigmoidal curves [Sterman, 2000]. Computer simulation helps to build these types of structure-behavior hypotheses.

Figure 2 shows the mutual interactions generated by fish and crustacean populations. A typical self-reinforcement feedback drives the growth or decay of specific species according to its reproductive behavior (*Reproduction loop* L2). The other feedback process is a negative loop that self-regulates the population and the ecosystem carrying capacity (*Fish and crustacean carrying capacity*, L1) [Monte-Luna et al., 2004]. Additionally, the reproductive behavior is affected by environmental conditions, and we considered the most relevant factors to be salinity, dissolved oxygen, and the nursing and feeding areas that mangroves provide.

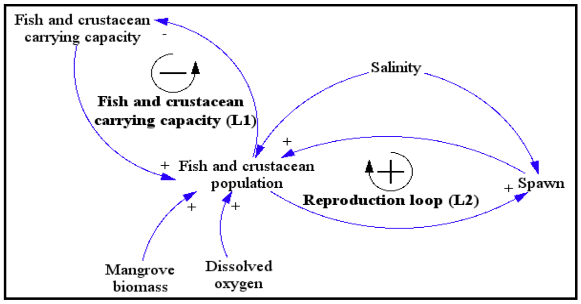


Figure 2. Fish and crustacean reproduction loops

The human population interacts with fish and crustaceans via fishery activities (Fig. 3). The available fishery resources define the total catch, which in turn controls the quantity of those resources due to extraction (*Catch loop* L3). The total catch is also affected by fishing efforts, in other words, the number of fishery trips is reinforced when the total catch is abundant enough to maintain use of the fishing gear (*Effort loop* L4). The fishing effort is also affected by fishery resource prices and follows normal supply-demand market dynamics, i.e. price changes modify the effort made by fishermen according to the highest price, which in turn is driven by the resource supply (*Price loop* L5).

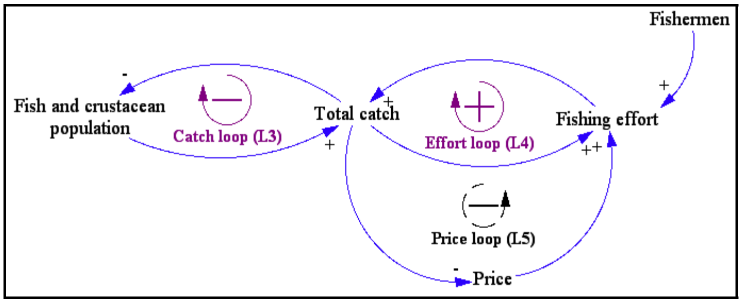


Figure 3. Fishery activity and human population loops

Mangrove dynamics can also be characterized by reproduction and carrying capacity loops (Fig. 4). The growth of mangroves is controlled by available resources (*Mangrove carrying capacity loop* L6) and their regeneration is defined by seedling production, which in turn also generates further mangrove biomass (*Mangrove regeneration loop* L7). Growth is also affected by environmental conditions such as the interstitial salinity and water level, depending on the tolerable range for mangrove species. Finally, mangrove biomass is also affected by deforestation. The causal relationships associated with salinity and water level in Figures 2 and 4 do not have causal polarities because they depend on the different range of tolerance for salinity by specific species of fish, crustaceans or mangroves.

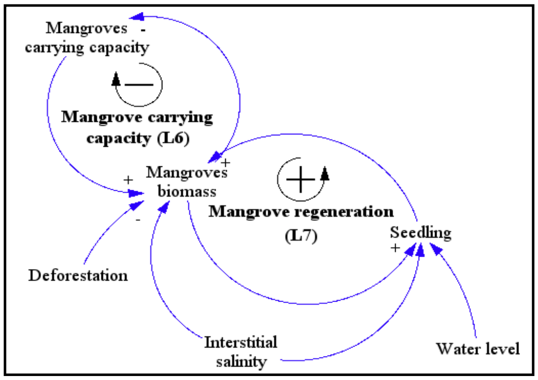


Figure 4. Mangrove loops

4.2 Simulation

Based on the previous conceptualization, a simulation model was built. Technical tests were made such as boundary adequacy, extreme conditions, structure assessment, behavior reproduction, equation formulation, and numerical parameter sensitivity [Forrester, 1961; Sterman, 2000]. Afterwards, we ran simulations to explore various hypotheses to understand structure-behavior relationships. The time horizon was defined as 20 years (2000-2020). Illustrative results are shown in section 5. Simulated and available data were compared. The model showed reliable behavior for aggregated fish and crustacean captures, effort and mangrove density according with seasonal changes in salinity, and trends found in historical data (results are not included in this document).

5. DISCUSSION

Simulations are shown in Figure 5. Four scenarios are proposed to test hypotheses about feedbacks interactions. The first scenario is based on salinity historical data provided by INVEMAR from the years 2000 to 2009, while the data for the future years were selected based on that data which shows salinity periodicity associated with two annual climatic seasons in the ecosystem, one dry and one rainy [Blanco et al., 2006]. The amplitude is estimated according to SOI intensity. The second scenario makes changes to the amplitude in salinity. Seasonal changes in fish abundance are associated with spawning periods and salinity variations, i.e. the ability of fish to cope with stressor conditions. We suggest that the *Reproduction loop* (L2) reinforces population growth during those spawning seasons, which is simultaneously controlled by the limiting resources in the ecosystem through the *Carrying capacity loop* (L1) (see Figure 2). The population growth rate is influenced by environmental conditions; for instance, seasons with lower salinity are associated with a higher abundance of fish and vice versa. In Figure 5 (left side), for the first scenario, a variable fish catch is different from the second scenario, where fluctuations are more associated with the reproduction loop than with salinity changes.

We also suggest that the *Catch loop* (L3) controls the extraction and total catch; this is reflected in changes in the fishing effort when the *Effort loop* (L4) reinforces the increase or decrease in the number of fishing trips according to the interest of fishermen, i.e. to make the most of fishery. Nevertheless, the interplay among the reproduction loop, effort loop and catch loop shows that the variations in specific catches are defined by decision making of the fishermen and by the hydrological conditions of the ecosystem (see Figure 5 left side).

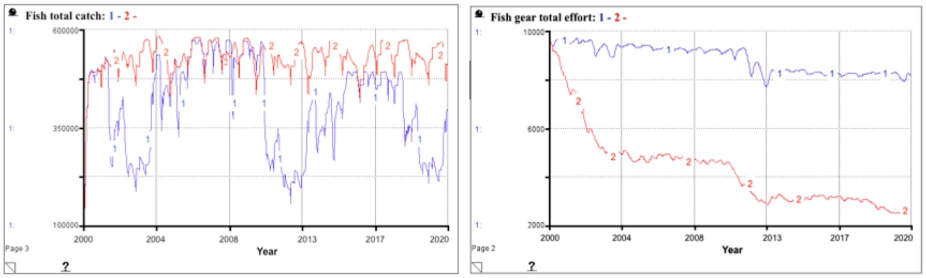


Figure 5. Left side: Fish total catch (kilograms/month) behavior with regular salinity, scenario one (1) and modified salinity, scenario two (2). Right side: Changes in fish gear total effort (number of trips per month) with all the species for scenario three (1) and leaving out two fish species (2) for scenario four

Furthermore, to explore the previous hypotheses, we ran two more scenarios with regular salinity values taken from scenario one. The third considers all of the species shown in Figure 1 and the fourth scenario leaves out the two most captured fish species from 2000 to 2008 (*O. niloticus* and *M. incilis*). Figure 5 (right side) shows the simulation results for the fish gear efforts. The interaction between the *Catch loop* (L3) and *Effort loop* (L4) for both scenarios influences the total effort of the fish gear in accordance with seasonal variations of the fish population, promoting an increase or decrease in effort, depending on the abundance of fish captured, which is regulated by the *Catch loop* (L3). We suggest for the fourth scenario that the *Effort loop* (L4) reinforces the decrease in the total effort of fish gear due to less abundance (L3). The *Reproduction loop* (L2) still operates, but the dominance of the *Catch loop* is stronger, as the fourth scenario emphasizes. In addition, the decrease in fish abundance promotes an increase in crustacean fishing efforts, because fishermen are looking for more abundant captures according to the ecosystem supplies. This leads to the hypothesis that fishing trips using certain gear are higher than for others gears based on the resource abundance of the fishery (Fig. 5, right side).

The simulation model is a first approach to explain and understand the interactions and resulting behavior among fish, crustaceans, mangroves and fishermen in the complex ecosystem of the CGSM by means of feedback loops. The model provides a new and available management tool to enhance system thinking and to support policy-decision making among institutions, government and local inhabitants. Additionally, it provides a novel perspective to approach sustainable management in the CGSM, where policy-making can be based on the selection or simulation of certain desirable dominant feedback structures.

However, further work on the understanding of feedback processes in the CGSM is desirable. A detailed discussion of model assumptions and non-linear relationships among the variables is still necessary. The sensitivity of the model in the change-effort function is significant; functions that describe changes in species price, fish, crustaceans and human population migration behavior should also be further explored. Finally, it is important to test alternative measurement unities for mangroves.

In summary, we provide an ecological simulation model for enhancing the comprehension of complex interactions of biological, chemical and human factors in the CGSM. Here, computer simulation is used as a tool to examine the consequences of the interaction of feedback structures and to support the decision-making processes regarding the management of the lagoon. An explanation of behavior that is based on feedback processes provides a better and more structured understanding of the ecosystem to enrich decision-making and management approaches used in the CGSM.

ACKNOWLEDGEMENTS

Instituto de Investigaciones Marinas y Costeras INVEMAR and the Research Center of the Engineering Faculty (CIFI) at Universidad de los Andes provided the financial support for the development of this joint project. We would like to especially thank Dr. Mario Rueda, the marine resource use and assessment program coordinator at INVEMAR, for his continuous support, willingness and experience to make this project possible.

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