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Research

Identifying potential consequences of natural perturbations and management decisions on a coastal fishery social-ecological system using qualitative loop analysis

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ABSTRACT. Managing for sustainable development and resource extraction requires an understanding of the feedbacks between ecosystems and humans. These feedbacks are part of complex social-ecological systems (SES), in which resources, actors, and governance systems interact to produce outcomes across these component parts. Qualitative modeling approaches offer ways to assess complex SES dynamics. Loop analysis in particular is useful for examining and identifying potential outcomes from external perturbations and management interventions in data poor systems when very little is known about functional relationships and parameter values. Using a case study of multispecies, multifleet coastal small-scale fisheries, we demonstrate the application of loop analysis to provide predictions regarding SES responses to perturbations and management actions. Specifically, we examine the potential ecological and socioeconomic consequences to coastal fisheries of different governance interventions (e.g., territorial user rights, fisheries closures, market-based incentives, ecotourism subsidies) and environmental changes. Our results indicate that complex feedbacks among biophysical and socioeconomic components can result in counterintuitive and unexpected outcomes. For example, creating new jobs through ecotourism or subsidies might have mixed effects on members of fishing cooperatives vs. nonmembers, highlighting equity issues. Market-based interventions, such as ecolabels, are expected to have overall positive economic effects, assuming a direct effect of ecolabels on market-prices, and a lack of negative biological impacts under most model structures. Our results highlight that integrating ecological and social variables in a unique unit of management can reveal important potential trade-offs between desirable ecological and social outcomes, highlight which user groups might be more vulnerable to external shocks, and identify which interventions should be further tested to identify potential win-win outcomes across the triple-bottom line of the sustainable development paradigm.

Key Words: *ecosystem-based management; loop analysis; small-scale fisheries; social-ecological systems; trade-offs*

INTRODUCTION

Mounting evidence of ecosystem degradation and the resulting reciprocal effects on human well-being have led to calls for comprehensive ecosystem-based management worldwide. Natural resource management has moved away from approaches that focus on a single species or sector, view the environment as static, and separate social and ecological issues toward integrated, dynamic approaches that consider the entire ecosystem, including humans, interactions among social and ecological components, and the cumulative impacts of multiple activities (Hughes et al. 2005, McLeod et al. 2005, Leslie and McLeod 2007, Levin et al. 2009). This shift reflects the view that managing for sustainable development and resource extraction requires an understanding of the feedbacks between biophysical systems and humans, and thus requires an integrative, interdisciplinary approach. These feedbacks are part of social-ecological systems (SES), in which resources, actors, and governance systems interact to produce outcomes across these component parts (Berkes and Folke 1998, Ostrom 2009, Cox et al. 2010, McGinnis and Ostrom 2014).

Marine ecosystems and the fisheries they support are examples of complex SES, with numerous relationships among ecological, social, economic, and institutional components operating at multiple scales (Berkes 2006, Mahon et al. 2008, Levin et al. 2009, Berkes 2011, Halpern et al. 2012, Kittinger et al. 2013). Governance and financial systems interact with social systems to influence human behaviors, which in turn have an impact on the marine and coastal environments, while the marine environment and resource units can in turn influence the choice of operational and collective-choice rules, and economic and cultural values (Fig. 1). All of these elements interact to produce a set of dynamic outcomes (Berkes and Folke 1998, Mahon et al. 2008, Ostrom 2009, McGinnis and Ostrom 2014). Current marine resource management recognizes the importance of considering interactions among fisheries components to meet social, ecological, and economic sustainability, but it can be challenging to develop an explicit understanding of the direct and indirect effects of fisheries on the larger web of interacting species and the feedbacks among these components on the greater social-ecological network. The processes to be quantified and modeled are numerous and produce feedbacks whose effects are difficult to predict. These complex dynamics often exceed our current understanding and data availability. However, to inform decision making and guide future monitoring and management actions, managers must evaluate the consequences of management actions or of external perturbations to the system (e.g., drivers associated with climate change, market fluctuations) on the full SES to avoid unintended consequences and to adaptively manage.

A suite of modeling frameworks have been developed to examine biological and human responses to multiple external and internal drivers within coupled SES (MIMES, Boumans and Costanza 2007; InVEST, Nelson et al. 2009; Atlantis, Fulton et al. 2011). Most of these models require large amounts of data because system components are numerous and feedbacks are complex. An alternative to an in-depth, quantitative description of SES and

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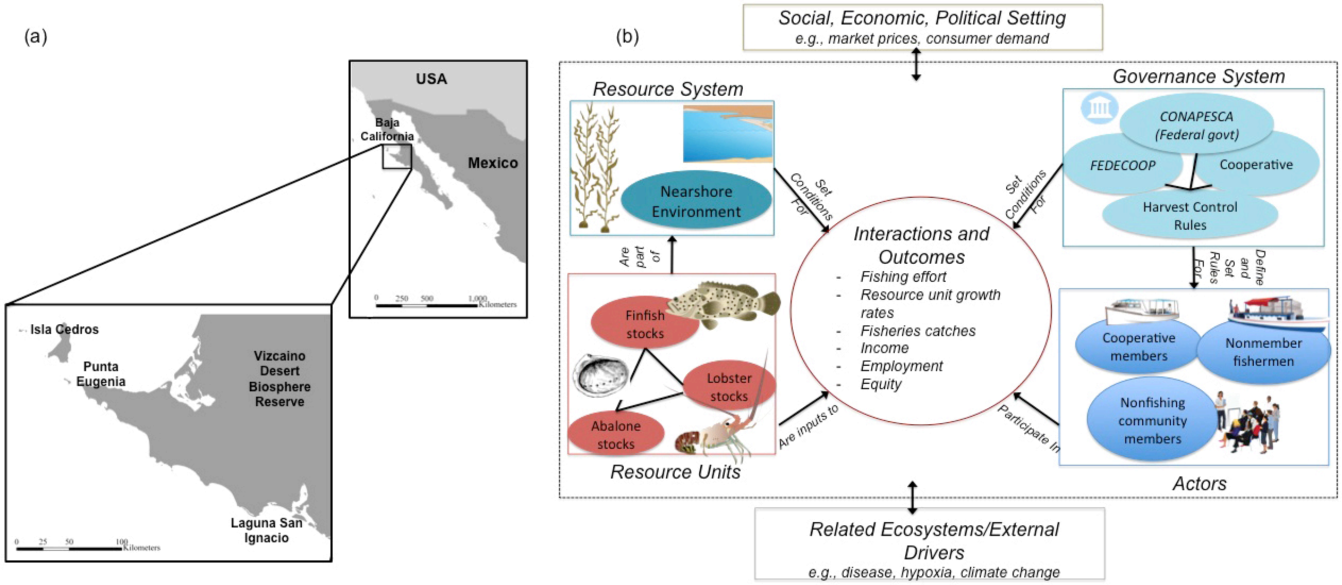
Fig. 1. The fishing cooperatives of the Vizcaino region in Baja California Sur, Mexico: (a) map of the study area showing location along the coastline from Punta Eugenia to Laguna San Ignacio; (b) conceptual representation of the social-ecological system (SES) based on the updated SES framework presented in McGinnis and Ostrom (2014).



their dynamics is qualitative modeling. Qualitative modeling approaches, including fuzzy cognitive mapping (Kok 2009), causal loop diagrams (Lane 2008), Bayesian belief networks (Woolridge and Done 2004), and loop analysis (Puccia and Levins 1986), can provide practical tools for evaluating external perturbations and management strategies, particularly under circumstances of limited data availability and uncertainty in the nature and strength of relationships within and between socioeconomic and biophysical components (Fishwick and Luker 1991, Dambacher et al. 2007, Espinoza-Tenorio et al. 2013, Carey et al. 2014). Furthermore, they can be developed using participatory approaches with multiple stakeholders and have conceptual appeal, are intuitive, and represent good communication tools. Loop analysis is one particular technique that allows for investigations of the dynamics of complex systems when the signs of interactions are known but other aspects of the linkages are uncertain, including strength of the interactions and their functional forms and parameters; in other words, whether a system component (e.g., species, actors, or user groups) has a positive, negative, or no effect on another component with which it interacts. Despite its limitations (see discussion of merits and limitations in Justus 2006), the limited data requirements of loop analysis make it a promising tool for investigating the dynamics of SES in data poor systems.

Loop analysis allows for an examination of how an external press perturbation (Bender et al. 1984) would potentially spread its effects in a system across multiple socioeconomic and ecological variables through the network of interactions among the variables. In loop analysis, linkages between variables are representations of the directional effect that one variable has on the rate of change of the other. For example, for predator-prey relationships, an increase in a predator population leads to a decrease in the growth rate of its prey. These linkages are expressed mathematically by the coefficients of the Jacobian matrix of a system of differential equations. The sign of these coefficients identify how any one variable qualitatively affects the others. By following the direction of links one can reconstruct the pathways of interactions through which management actions or natural perturbations propagate beyond the target variable. The abundance or level of any of the variables in the system may be predicted to increase, decrease, or remain the same following the natural perturbation or management intervention.

Thus, loop analysis offers alternatives to quantitative modeling for dealing with the complexities of SES in data poor systems and provides testable hypotheses regarding SES responses to perturbations and/or management actions (e.g., Carey et al. 2014). Although loop analysis offers an analytical framework for investigating the complexity of marine social-ecological systems (Espinoza-Tenorio et al. 2013, Carey et al. 2014, Reum et al. 2015), many applications of this approach to date have focused on the ecological elements of the system and have not included aspects of the social system and key SES linkages (but see Dambacher et al. 2007).

We apply qualitative loop models to examine changes in coastal SES of the Vizcaino Peninsula, Baja California, Mexico, in response to natural perturbations and management actions that have recently been implemented or are currently under consideration. These coastal fisheries are particularly relevant as a model system because fishing cooperatives of this region were granted exclusive access rights to a suite of invertebrate species starting in the 1930s (McCay et al. 2014), whereas fishing for finfish or by fishermen that do not belong to cooperatives has remained open access. Thus, this system allows for an examination of the ecological and socioeconomic consequences of allocating access rights for different species and to different users (e.g., Pomeroy et al. 2001, Costello et al. 2008), a management approach that is currently being implemented in small-scale fisheries globally (http://www.bloomberg.org/program/environment/vibrant-oceans/).

Using a case study of multispecies, multifleet, coastal, small-scale fisheries, we demonstrate the application of loop analysis to examine interactions among ecological and socioeconomic variables associated with territorial user right fisheries (TURF)-managed commercial fisheries and to understand the main feedbacks that drive the social and ecological performance of these coupled systems. We demonstrate how loop analysis can be applied as a method for examining potential outcomes from scenario analysis to inform planning and monitoring in SES. Through this approach, we examined a set of scenarios that mimic perturbations to the SES including the effects of climate perturbations that have recently been associated with observed decline in different stocks (e.g., Micheli et al. 2012), market-based initiatives such as an ecolabel, which was awarded to one of the fisheries (the spiny lobster trap fishery) operating in this region (Micheli et al. 2014*a*), and of changes in fisheries management and governance that are currently under consideration (Micheli et al. 2014*b*). Although these scenarios are designed to capture perturbations and management actions specific to the Vizcaino fisheries, they represent impacts faced by many coastal fishing communities worldwide and management options available to several of these communities. Because the application of loop analysis is relatively novel in the field of fisheries management (but see Espinoza-Tenorio et al. 2013, Carey et al. 2014), we emphasize, through the analysis of realistic scenarios in a case study system, the potential of loop analysis to evaluate complex social-ecological systems. Our analysis should provide useful insights for a suite of small-scale fisheries, in addition to the Vizcaino region cooperatives, to identify hypotheses and key variables for monitoring. Specifically, we ask: (1) What are the anticipated biological and socioeconomic consequences of external perturbations that result in the decline of specific stocks? (2) What market-based, governance, or local management actions may result in both biological and socioeconomic benefits? Which of these actions may result in resource declines or negative socioeconomic impacts? (3) How does the representation of the system (i.e., what specific linkages and feedbacks among system components are included) influence the predicted responses to perturbations?

METHODS

Study system/conceptual model

To illustrate and describe the components, linkages, interactions, and potential outcomes of the Vizcaino fisheries system, we developed a conceptual model based on Ostrom's social-ecological system (SES) framework (Ostrom 2009, McGinnis and Ostrom 2014), available literature describing the system, and the authors' knowledge of the system (Martone 2009, Shester and Micheli 2011, Micheli et al. 2012, 2014*b*, McCay et al 2014; Fig. 1). Components are organized as resource units, which interact among themselves and are part of a larger resource system that is subject to external forces that can influence the system, such as market or other socioeconomic drivers and global environmental change. The governance system defines a set of rules for a set of actors, some of whom are resource users. These systems and their components then interact in different ways to produce social and ecological outcomes. Finally, we indicate related drivers and conditions that are external to the system but which influence the components and their interactions.

Resource System

The study cooperatives are located along the Vizcaino Peninsula of the Pacific coast of central Baja California, Mexico, a region known as the Pacifico Norte (Fig. 1). The Pacifico Norte region can be characterized as temperate to subtropical, with sea surface temperatures ranging from 12-27 °C throughout the year. The region is a mosaic of rocky reef and sandy subtidal ecosystems that encompass the southern edge of the range of giant kelp (*Macrocystis pyrifera*) in which a zone of persistent upwelling maintains high biological productivity (Martone 2009).

Governance

The cooperatives belong to the Federacion Regional de Sociedades Cooperativas de la Industria Pesquera de Baja California (FEDECOOP), which acts as a comanagement agency with the national and regional fisheries agencies to monitor resources and develop management plans. The fishing cooperatives of the Pacifico Norte date back to the late 1930s, as a manifestation of the Mexican cooperative movement that was mainstreamed into national fisheries development policies (Ponce-Díaz et al. 2009, McCay et al. 2014). From the beginning of the cooperatives, access to high-value fisheries, such as lobster (*Panulirus interruptus*) and abalone (*Haliotis* spp.), in adjacent fishing grounds has been restricted by law to cooperative members. Since 1992, this special right has been in the form of 20-year concessions for exclusive exploitation rights for some species, including lobster and abalone.

The long-term exclusive concessions held by the cooperatives are examples of the assignment and comanagement of community-based access, withdrawal, exclusion, and management rights (Schlager and Ostrom 1992, Pomeroy et al. 2001). These community-based access rights have enabled cooperatives to add and enforce conservative management measures, including, but not limited to, regulation of catch composition, seasonal closures, and size limits in lobster fisheries (Vega 2001), reef-specific quotas, and the voluntary establishment of no-take reserves exclusively aimed at rebuilding abalone populations and other fisheries targets (Micheli et al. 2012, McCay et al. 2014). Both cooperative and noncooperative members are compliant with rules because of both positive and negative incentives that come with membership in the cooperative and ongoing investment in monitoring, enforcement, and infrastructure (McCay et al. 2014). However, the lack of concessions and associated rights for finfish may impede management of these stocks in this region, given that the incentives that often accompany comanagement and exclusionary rights are not in place for these species (Shester and Micheli 2011, Micheli et al. 2014*a*).

Resource Units

The Pacifico Norte fisheries target a wide variety of interacting species in rocky reef food webs, including predators, such as lobster and several finfish species, and their prey and competitors. Currently, in addition to lobster and abalone, cooperatives have exclusive rights to a set of other benthic species, including the wavy turban snail *Megastraea undosa*, the sea cucumber *Parastichopus parvimensis*, the red sea urchin *Mesocentrotus* *franciscanus*, and the red alga *Gelidium robustum*. The cooperatives also catch finfish, primarily barred sand bass (*Paralabrax nebulifer*), ocean white fish (*Caulolatilus* spp.), and California halibut (*Paralichthys californicus*) using nets and traps. In contrast with benthic invertebrates and algae, cooperatives do not hold territorial rights for finfish, so fishermen that are not members of the fishing cooperatives also have access to these species.

Actors

The FEDECOOP fisheries are located on the coastal edge of a vast desert protected by UNESCO biosphere reserve designation since 1988 (Fig. 1). The remote nature of these fisheries in combination with their unique institutional structure and history of occupation along the coast leads to the cooperatives playing a strong role in the community. Collectively, the cooperatives provide infrastructure, social programs, and employment to many residents in the communities, including both cooperative members and nonmembers, in jobs involving harvest, rule enforcement, resource monitoring, seafood processing, and transportation (Ponce-Díaz et al. 1998; Fig. 1).

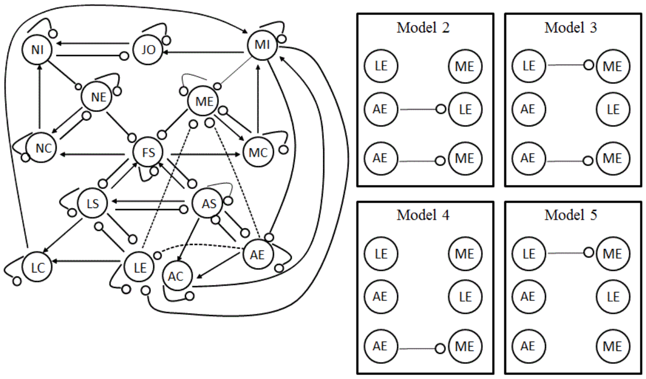
Socioeconomic and ecological interactions and outcomes

Membership in the cooperatives brings social and economic benefits. Abalone and lobster are the main targets and provide high value to the cooperatives because of high demand and market prices for these commodities (McCay et al. 2014). Finfish fisheries are also economically important in the region, representing additional, and in some cases the most important income source for cooperatives (Shester and Micheli 2011). Moreover, opportunities to engage in finfish fishing provide additional income for cooperative members during the closed fishing season for their main target species, as well as income and subsistence harvest for noncooperative members in the community, who do not have access to benthic fishery targets that are the purview of the cooperatives (Shester and Micheli 2011). However, despite delivery of important benefits to cooperative members and nonmember fishers, the gear types used by this fishery tend to have higher by-catch rates and may have adverse long-term effects on target populations, food webs, and habitats (Shester and Micheli 2011, Micheli et al. 2014*a*, *b*).

Loop analysis

The loop analysis first translates the conceptual model (Fig. 1) into a pictorial representation of interactions between the SES components, including resource units (e.g., species, fisheries catch), actors (e.g., cooperative members and noncooperative fishers), the governance system (e.g., harvest control rules, fishing effort), and socioeconomic factors (e.g., income, jobs for noncooperative members; Fig. 2). We assembled the SES interaction web capturing some of the main biological and socioeconomic components in our conceptual model (Fig. 1) and illustrated the linkages among them in a signed diagraph (Fig. 2; Appendix 1). We represent biological linkages as possible trophic relationships among target species or species groups, the linkages among species and fisheries operating in the study region based on harvest control rules, and key actors and some relevant socioeconomic components of the system (Fig. 2). The interaction web was assembled based on authors' experience and knowledge of the system and from relationships described in the published literature, including data from sampling and taxonomic identification of the benthic fauna and flora, stomach content analyses of fish and invertebrates, interviews with fishermen and cooperative members, and household surveys (Shester 2008, Martone 2009, Morales-Zárate et al. 2011, Ramírez-Sánchez et al. 2011, Shester and Micheli 2011, McCay et al. 2014, Leslie et al. 2015).

Fig. 2. Signed-digraph representation of the social-ecological system (SES) interactions in the Baja California fisheries case study. Variables are : MI (cooperative member income); JO (job opportunities for nonmembers); NI (nonmember income); ME (members effort on finfish); NE (nonmembers effort on finfish); MC (finfish catch by members); NC (finfish catch by nonmembers); FS (finfish stock); LE (lobster effort, by members only); LC (lobster catch); LS (lobster stock); AE (abalone effort, by members only); AC (abalone catch); and AS (abalone stock). Arrows represent positive interactions, where a variable leads to a positive rate of change in the other, and lines with open circles represent negative interactions, where a variable inhibits the rate of change in the other. The main model (model 1) includes predator-prey relationships among the three stocks, abalone, lobster, and finfish, and negative relationships among fishing effort between the abalone and lobster fisheries and the lobster and finfish fisheries. The other four model structures are variations on this primary model and remove some of the linkages among fishing efforts (models 2-5).



Loop analysis qualitatively predicts average changes in variables of interest (e.g., species abundance or catch) in response to varying conditions that modify their rate of change, i.e., variations in parameters governing the rate of change for the variables. One example is a stressor that increases the mortality rate of a species. This reduces that species' population growth rate, which in turn influences the abundance of that species as well as that of the other species to which the latter is connected in the network. The variation in the level of a component *j* due to a parameter change can be calculated by the loop formula:

$$\frac{\partial x_j}{\partial_c} = \frac{\sum_{i,k}\left\{\left[\frac{\partial f_i}{\partial_c}\right] \times \left[p_{ji}^{(k)}\right] \times \left[F_{n-k}^{(comp)}\right]\right\}}{F_n} \qquad (1)$$

where c is the changing parameter (e.g., mortality, fecundity, predation rate); $\partial fi / \partial c$ designates whether the growth rate of the *i-th* variable is increasing, decreasing (positive or negative input, respectively); $p_{ji}^{(k)}$ is the pathway connecting the variable that undergoes parameter change, *i*, with the variable whose equilibrium value is being calculated, *j*, and which includes *k* variables; $F_{n-k}^{(comp)}$ is the complementary feedback, which buffers or reverses the effect of the pathway. The denominator indicates the overall feedback of the system, which is a measure of the inertia of the whole system to change. A more detailed explanation of the method of loop analysis and the algorithm for predictions is given in Appendix 1. Loop analysis models were run in R using a code that is provided in Appendix 2.

Biological links

For our resource units, we included three main target species and species complexes in our loop analysis: lobster stocks, abalone stocks, and finfish stocks. We represent the following biological interactions in the social-ecological system: lobster are known predators of molluscs including abalone (Braje et al. 2009); finfish, such as gulf grouper (*Mycteroperca jordani*), cabezon (*Scorpaenichthys marmoratus*), and sheephead (*Semicossyphus pulcher*), are predators of both lobster, particularly the juvenile stages, and abalone (Braje et al. 2009; Fig. 1). Thus, abalone (AS), finfish (FS), and lobster (LS) form a tri-trophic system: FS preys upon both AS and LS, while LS preys upon AS. All stocks have negative feedback loops to themselves, representing density-dependent effects on population growth rate. Because these predators are all generalists and the degree to which these interactions drive top-down or bottom-up processes are unknown in this system, we tested the effects of including these interactions in the network in three different models, including top down and bottom up effects, bottom up effects only, and no biological interactions. This latter case explores the situation in which the biological interactions are completely obscured by socioeconomic links in determining the dynamics of fish variables.

Fisheries links

The Pacifico Norte cooperative fisheries target lobster using traps, abalone using hookah diving, and finfish using a variety of gear types, including traps, set gillnets, and driftnets (Shester and Micheli 2011, Micheli et al. 2014*b*). As in most fisheries, we assume that stock and effort have positive effects on catch, catch has a negative effect on stock, and effort and stocks have negative effects on each other (Fig. 2). The negative link from stock to effort considers that the larger the stock, the lower the effort required to obtain the same catch. Factors that control the fisheries are translated in the model as a self-damping term on effort and catch, representing the action of other variables that are not included in the model but can regulate model components (Bodini 1988). Although several factors, beside the density-dependent mechanism, can generate a self-damping term on variables (Puccia and Levins 1986), we do not include this mechanism in all of our variables, because the inclusion of all variables that play a regulative effect on the system in the model would make the model intractable. Because these fisheries are all conducted under the same cooperative system by the same fishers, and abalone and lobster are the main cooperative targets, we have linked effort among fisheries, such that both lobster and abalone effort negatively affect the rate of change of finfish effort, and abalone effort is negatively linked to lobster effort. We tested the effects of including these linkages on the outcomes of the SES by varying our model structure (Fig. 2).

In addition to the linkages among fishing efforts within the cooperatives, there are also nonmembers that have access to finfish stocks because the cooperatives do not hold exclusive access privileges for finfish. We captured nonmember effort separately by linking it negatively to the same finfish stock that is targeted by the cooperatives (Fig. 2). Nonmember effort is positively linked to nonmember finfish catch and is negatively linked to finfish stock size (Fig. 2).

Socioeconomic links

Both cooperative members and nonmembers gain income directly from the catch of stocks. Therefore, nonmember finfish catch positively affects nonmember income, whereas finfish, abalone, and lobster catch all positively affect member income (Fig. 2). In all of our models, income negatively affects effort. Furthermore, to capture the positive effect that cooperatives have on nonmembers in these communities through the provision of job opportunities (e.g., in seafood processing plants), member income positively affects job opportunities in the community and jobs positively affect nonmember income (Fig. 2).

Predicting change through loop analysis

The loop formula (1) allows predictions of how the level of system components might change because of external forcing (Puccia and Levins 1986). Predictions calculated with the loop formula can be arranged in a table with signs showing the expected direction of change (+, -, or 0). In Figure 3, signs for predictions are substituted by arrows for a clearer presentation. The entries in the table denote variations expected in the column variables when positive parameter inputs affect each row variable. Each row of the table indicates the variable that is subjected to parameter change. The responses of the variables to variations in the rate of change of a given row variable are reported in the columns. These responses concern the direction of change of the level of the variables (e.g., biomass, number of individuals, or amount of money). Predictions are conventionally obtained for positive input. In the case of a negative input, predicted directions of change along the row of interest are simply inverted.

Model variables are often connected to each other by multiple pathways. If such pathways have opposite effects, the model can yield ambiguous predictions. In these cases, model predictions are undetermined, and + or - signs in the table of predictions are replaced by question marks (?). To address these ambiguous predictions, we used a routine that randomly assigns numerical values to coefficients of the community matrix (i.e., the coefficients of the links in the signed digraph). Values for links are generated randomly by a routine within the interval (10^{-6}- 1). This procedure is executed *n* x *n* x 100 times, where *n* is the number of variables in the model. Therefore we created for each model community matrices ($n = 14$; Total runs = 19,600). Community matrices can then be inverted to understand how variables affect each other directly and through indirect pathways (Bender et al. 1984, Wootton 2002, Montoya et al. 2009). The coefficient (cij^{-1}) of the inverse community matrix shows the overall effect of variable *j* on variable *i* due to its direct link to variable *i* (e.g., predation, catch), as well as all possible indirect pathways through which variable *j* is connected to *i* via intermediate components. Hence, the net effect (the sum of the direct and indirect effects) of a perturbation on variable *j* on variable *i* is given by the element of the inverse community matrix.

Fig. 3. Table illustrating expected directional changes in the levels of the components of model 1 (Fig. 2). Alteration in the rate of change of any row variable results in expected variations in the level of the column variables. Green arrows indicate a positive change (75-100% of the linkages from the model runs were positive), whereas green triangles indicate a tendency toward a positive change (60-75% of the linkages were positive). Red arrows indicate a negative change (0-25% of the linkages from the model runs were positive), while red triangles indicate a tendency toward negative change (25-40% of the linkages were positive). Zeros (yellow dots) reflect compensation between positive and negative effects that result from the model runs and likely no change would be expected in the variable's level. Predictions are obtained by assuming positive inputs (i.e., increased rates of change of the variables) to the row variables. Predictions for negative inputs (decreased rates) can be easily obtained by simply inverting the direction of the arrows and of the triangles (and the colors). The first letter of the variable labels (in the rows and columns) identifies a system component (e.g., A for abalone, L for lobster, F for finfish), the second letter a specific descriptor of that component (e.g., S for stock size, E for effort, C for catch; see Figure 2 legend for a complete list of the variables and their acronyms).

	AS	AE	AC	LS	LE	LC	FS	ME	MC	NE	NC	MI	NI	JO
AS	⬆	⬇	●	▼	▲	●	⬆	▼	⬆	⬇	⬆	▲	⬆	●
AE	⬇	⬆	⬆	▲	⬇	▼	▼	●	▼	▲	▼	●	▼	●
AC	●	⬇	⬆	●	●	▼	⬆	▼	●	⬇	●	⬆	⬆	⬆
LS	⬇	⬆	▼	⬆	⬇	●	●	●	●	●	●	●	●	●
LE	⬆	⬇	●	⬇	⬆	▲	▲	⬇	▼	▼	▲	●	▲	●
LC	●	⬇	⬇	●	●	⬆	⬆	▼	●	⬇	●	⬆	⬆	⬆
FS	●	●	●	⬇	⬆	▼	⬆	⬇	●	⬇	⬆	●	▲	▼
ME	●	▼	⬇	⬆	▼	●	▼	⬆	⬆	●	⬇	⬆	▲	⬆
MC	●	▼	▼	⬇	▲	▼	⬆	⬇	⬆	⬇	▲	▲	⬆	●
NE	●	●	●	⬆	⬇	▲	⬇	⬆	●	⬆	⬆	●	⬆	⬇
NC	●	●	●	⬇	⬆	▼	⬆	⬇	●	⬇	⬆	●	⬆	⬇
MI	●	⬇	⬇	●	●	▼	⬆	▼	●	⬇	●	⬆	⬆	⬆
NI	●	●	●	⬇	⬆	▼	⬆	⬇	●	⬇	⬇	●	⬆	⬇
JO	●	●	●	⬇	⬆	▼	⬆	⬇	●	⬇	⬇	●	⬆	⬆

The community matrix *AH* must have a nonzero determinant and must admit an inverse matrix $(AH)^{-1}$. Of the n x n x 100 matrices created for each model, only those that satisfied the Lyapunov conditions of stability were kept and inverted. An overall table of predictions for each model was then obtained from the inverted matrices. In this table, each prediction was determined on the basis of the percentage of positive, negative, or zero signs in the array of the inverted stable matrices (Appendix 1, Table S2). We defined a set of rules to translate the percentage of cases obtained from loop analysis runs into signs in the overall prediction matrix (Puccia and Levins 1986). Specifically: - indicates that 0-25% of the relationships were positive; ?- indicates 25-40% of the relationships were positive; 0* indicates 40-60% positive change relationships; ?+ indicates 60-75% of linkages were positive; and a + indicates 75-100% of the signs obtained in the procedure were positive. This is based on Puccia's 3:1 ratio rule (Puccia and Levins 1986). Note that 0* are not real zeros but a neutral result that occurs when matrices have large numbers of opposite signs for a given variable's response. In fact, when multiple pathways have opposite effects to the same variable, positive and negative effects tend to compensate each other and the net result may be zero (no variation) or, more likely, a small change, which can be reasonably considered negligible.

Model structure and scenario testing

We examined the system dynamics and behaviors by conducting two different types of analyses. First, we explored the effects of different assumptions about model structure, particularly which linkages between variables are included or excluded (five model structures). Second, we investigated the system responses to perturbations (considering seven different perturbation scenarios).

To examine the sensitivity of model results to the specific linkages included, we varied model structure by including or removing different sets of biological and/or fisheries linkages. Models 1-5 (Fig. 2; Appendix 1, Table S2) include all of the biological linkages, in which both effects of predator and prey are represented, but each model varies the relationships among fishing effort, including or removing hypothesized links between abalone and lobster fisheries, lobster and finfish fisheries, and abalone and finfish fisheries.

We also varied the core biological structure to examine the robustness of outcomes to different assumptions about how species may affect each other through consumer-resource interactions. In a second set of models, we removed all biological linkages and varied the relationships among fishing efforts, as described above for models 1-5. In a third set of models, we included biological links but only in the form of the beneficial effect that prey exerts upon its predator, i.e., a bottom-up effect of resources on consumers. In all of these cases, the models yielded a zero matrix determinant and no predictions could be obtained. This means that the full set of biological interactions is needed for models to generate meaningful predictions. Thus, we present and discuss results only for models 1-5 (Fig. 3; Appendix 1, Table S2).

We investigated responses of single variables to parameter changes in the system by examining: (a) the table of predictions for each model to explore what relationships emerge between the ecological and socioeconomic components, and within the three fisheries; and (b) seven scenarios associated with specific external perturbations and management actions to examine the response of variables of interest, both biological (stock abundance) and socioeconomic (jobs, income).

Environmental perturbations

Disease, hypoxia, and climate change are major drivers of change in marine ecosystems and are associated with increased mortality of fisheries species in many coastal fisheries (Defeo and Castilla 2012, Micheli et al. 2012). In scenario 1, we simulated the external forcing of climate or other human impacts through decreased growth rate of abalone. Hypoxia, frequent or extreme El Nino-Southern Oscillation (ENSO) events, disease, or harmful algal blooms underlie observed abalone declines and may lead to further decline by increasing abalone mortality (Morales-Bojórquez et al. 2008, Micheli et al. 2012). In scenario 2, we modeled effects of disease or ocean acidification impacts on lobster populations as a negative input to lobster stocks, reflecting an increase in lobster mortality or a decrease in lobster growth and reproduction from these external drivers. Studies of the effects of ocean acidification on crustaceans indicate likely negative impacts on growth due to rises in [H+] in haemolymph and reduced oxygen delivery to the tissues (see Whiteley 2011 for review). Although disease has not affected lobster stocks in this system, it is a major concern for other lobster fisheries (e.g., Steneck et al. 2011).

Socioeconomic drivers

We examined the effects of market-based initiatives, such as the existing Marine Stewardship Council (MSC) ecolabel or proposed system-wide certification schemes that are implemented with the goal of increasing income to the fishing cooperatives (Micheli et al. 2014*a*). We modeled these drivers in scenario 3 as positive inputs to the cooperative member income, although in the case of the Vizcaino cooperatives, although the eco-label allows for some increased access to higher prices in the US market, it primarily functions as a source of empowerment and helps the cooperatives maintain their concessions (Pérez-Ramírez et al. 2012*a*, *b*). Other initiatives have been proposed for this region with the aim of increasing job opportunities for noncooperative members, such as abalone pearl culture and ecotourism. In scenario 4, we tested the effects of change to nonmember income through these opportunities accessible to nonmembers of cooperatives, designed to provide alternatives to fishing.

Fisheries management actions

Though not yet implemented, decreasing finfishing effort and phasing out of set gillnets has been highlighted as a possible option for decreasing the environmental impacts and improving the long-term sustainability of these cooperative fisheries (Peckham et al. 2007, Shester and Micheli 2011, Micheli et al. 2014*b*). In scenario 5, we examined how these management actions would influence other variables in the system using a negative input to cooperative member finfish effort. In scenario 6, we examined the effects of controls on nonmember finfish effort on the system. Finally, in scenario 7, we examined the effects of increased job opportunities through subsidies provided by the government, private foundations, or NGOs.

Sensitivity analysis

To examine whether model structure affected outcomes, we compared the tables of predictions from the five models to see whether there was concordance among them. We compared each prediction matrix, for each model, to all other matrices in a series of pairwise comparisons and determined the number of cases in which each prediction matrix differed from all others (Appendix 1, Table S3).

RESULTS

Model predictions: social-ecological systems (SES) dynamics

Loop analysis reveals that changes in input variables (e.g., stocks' growth rates, rate of change in member income) may influence other variables in the system in directions that often cannot be predicted based on known (or assumed) directional relationships. For example (see Fig. 3), an increase in the abalone growth rates (positive input to AS) is predicted to reduce lobster stock, which is counter to the notion that prey species should positively influence the abundance of their predators. This is because the influence of a variable on any other is mediated by the other variables in the system through indirect effects.

Another surprising outcome is changes in predators leading to no effects on their prey. The correlations between predators and prey vary depending on which stock is perturbed, because of feedbacks and compensation throughout the SES. For example, when the finfish stock's (FS) growth rate increases, FS itself is predicted to increase, but abalone stock (AS) does not change (Fig. 3). This result could be interpreted as a result of FS preying upon AS but also on LS, which, in turn preys upon AS. So the effect of FS on AS is at the same time positive and negative because this species also feeds on a predator of AS. However, the complexity of the SES increases the multiplicity of the pathways that connect FS and AS. The loop analysis indicates that FS is connected to AS by eight paths: four paths with a negative sign and four positive (the product of the signs of the links yield the overall sign for the path; see Appendix 1, Table S1). Thus, our simulations yielded the same percentage of matrices in which AS is expected to increase and matrices in which AS is expected to decrease (50%), resulting in a compensation of effects and a magnitude of variation that can be close to zero.

A positive input on FS causes lobster stock (LS) to decrease. This negative effect that LS experiences when a positive input affects the growth rate of FS could be due to the direct predation on LS and the predation on its prey. However, in a complex system like the one we describe in Figure 2, any effect of one variable on another is mediated by multiple pathways, so the full set of pathways must be examined to understand the effects.

Nine pathways connect FS to LS (Fig. 2; Appendix 1, Table S1). Five carry a negative effect to LS and four carry a positive effect. Although there is only one additional path indicating negative effects of FS on LS, the numerical simulation yielded that only 8% of the matrices predict an increase for the level of LS with a positive input affecting FS. But 91% of the matrices predict the population of LS to decrease following a positive input to FS. This is surprising, given that with the quasi-balanced number of pathways carrying opposite effects, we would expect the results of the simulation be more equilibrated. Likely this discrepancy between what we would expect looking at the number of pathways and what we obtain from the simulations depends on the following: random coefficients are taken in the range 10^{-6}- 1, but the product of link values in longer paths yields smaller numbers than the shorter paths; so that these latter contribute more to the final outcome from the loop analysis. If we consider the pathways from FS to LS (Appendix 1, Table S1), the two shortest pathways both have negative signs and we can understand why despite the numerical quasi-balance between opposite pathways, the response of LS to an increase in the growth rate of FS is negative.

In the previous case (input to FS and effect on AS), instead, the two shorter paths (Appendix 1, Table S1) have opposite signs. This relationship between FS and LS is consistent with what is anticipated from known predator-prey relationships, with some of the finfish species targeted by local fisheries (e.g., sheephead, *S. pulcher*) preying on lobster (i.e., an anticipated negative effect of increased FS on LS).

Despite expected negative effects on AS from FS and LS as predators, a positive correlation emerges between AS and FS when there is a perturbation to AS, whereas either no correlation or a negative correlation is predicted between AS and LS. As inputs enter the system through lobster stock (LS), LS becomes negatively correlated with AS, whereas no correlation exists between these two variables and FS, the abundance of which in all five models is predicted not to change.

The table of predictions can be used as a diagnostic tool to detect the entry point(s) of perturbations. For example, abalone stock (AS) changes only if perturbations enter the system through the abalone and lobster fisheries in the form of input to stocks and effort for both these fisheries. The only exception is model 4 (Appendix 1, Table S2), in which input to effort on finfish by members of the cooperative (ME) is predicted to affect abalone stock. According to these results, any variation in AS can be associated to alterations in the abalone or lobster fisheries but not in other variables of the system (i.e., economic variables).

Examining relationships between the fishery variables (catch, effort, and stocks) can also provide insights in the dynamics of specific fisheries. For example, the 3 x 3 submatrix that includes the relationships among variables AS, AE, and AC (abalone stock, fishing effort, and catch; Fig. 3) can be examined to glean information about aspects of the abalone fishery. As expected, abalone stocks are negatively correlated with effort: as effort increases, stock decreases and vice-versa. Effort and catch are positively correlated in one direction but negatively correlated in the other direction: as effort increases, catch increases, but as catch increases, effort is predicted to decrease. However, stock and catch show a neutral relationship, suggesting that effort is the key control variable. This submatrix is identical across all five models that we investigated (Appendix 1, Table S2), suggesting that conclusions based on this submatrix are robust to variations in model structure.

The table of predictions can also indicate which variables are most susceptible to external perturbation, either from environmental change or management interventions. For example, member income (MI) shows a greater inertia than nonmember income (NI) to parameter changes (Fig. 3). In model 1, 8 out of 14 possible responses of MI to external inputs are null (Fig. 3), and this pattern changes only slightly in the other models (the number of zeros varies between 6 and 8; Appendix 1, Table S2). Nonmember income remains unaltered only when inputs enter the system through AE, LS, and ME, in various combinations for the five models. Thus cooperative member income seems less vulnerable to perturbations than nonmember income, but it is also predicted to be less responsive to management interventions.

Predicted outcomes of natural perturbations and management actions

Collapse of target taxa (scenarios 1 and 2)

Disease and climate change are indicated as major drivers of increased mortality of target species and fisheries collapse. In scenario 1, we modeled the impacts of a disease, extreme ENSO, harmful algal blooms, or hypoxic events affecting abalone (Shepherd et al. 1998, Morales-Bojórquez et al. 2008, Micheli et al. 2012) as a negative input on abalone stock (AS; Fig. 4). Without effective effort control, a reduction in the abalone stock is accompanied by increased effort and no change in catch. However, income for both members and nonmembers is predicted to decrease, so that the increased mortality of abalone results in an overall economic loss for the local community. Biologically, the decline in abalone stocks is accompanied by a decrease in finfish stocks (FS) and an increase in lobster stocks (LS; Fig. 4). Interestingly, finfish effort is predicted to increase for both members (ME) and nonmembers (NE), but finfish catch for both groups (MC, NC) declines (Fig. 4). Job opportunities (JO) remain unaffected under all models.

In scenario 2, we modeled the negative impact of a disease on lobster stocks (Steneck et al. 2011). A negative input on lobster stock is predicted to lead to increases in abalone and no effects on finfish stocks (Fig. 2), assuming that disease would not simultaneously affect abalone and finfish stocks. The models reveal a substantial inertia of the system to lobster stock perturbation because no change is predicted for all other fishery and socioeconomic variables (Fig. 4). These simulations highlight a greater sensitivity of the system to perturbations on abalone than lobster, as suggested by more negative outcomes in scenario 1 than 2 (Fig. 4).

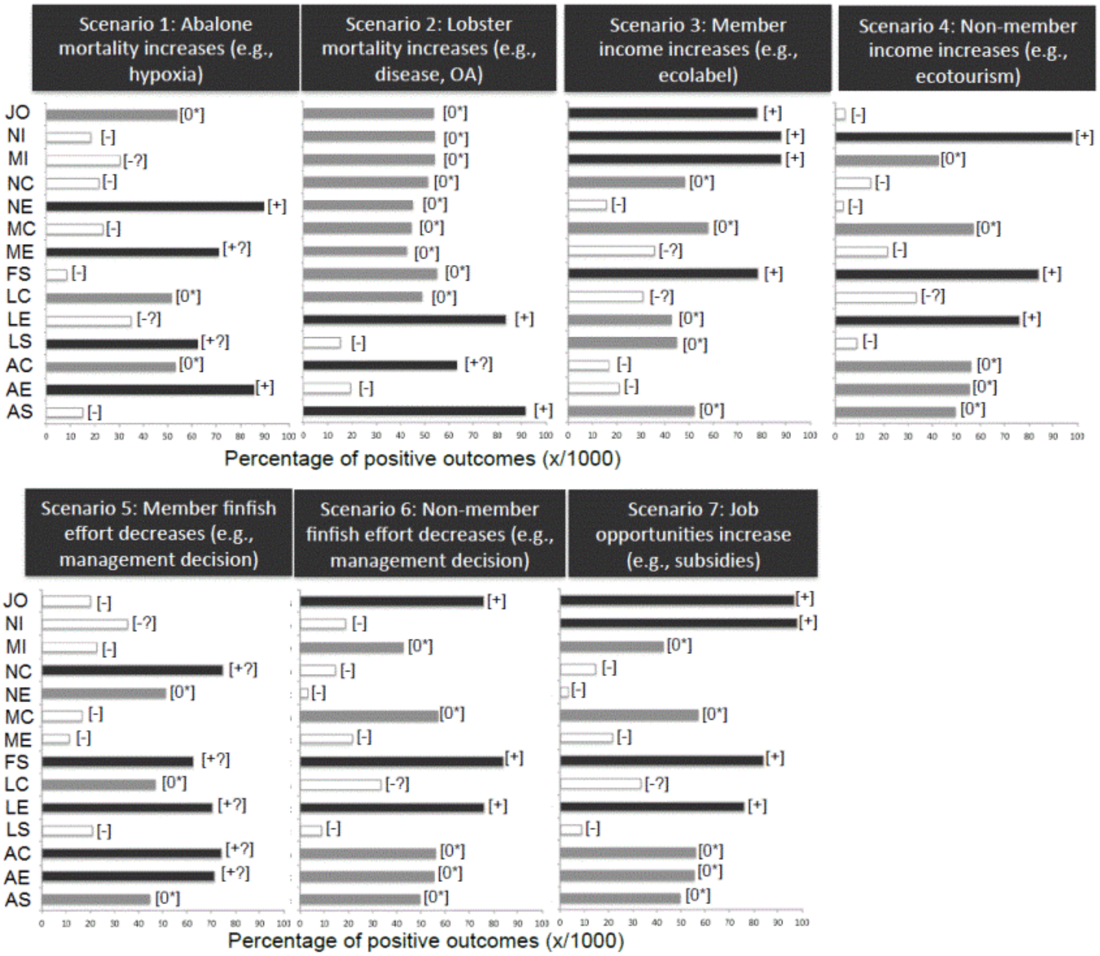
Results for scenarios 1 and 2 are relatively robust to the representation of the interactions in the system because removing links between fisheries through the effort variable does not change the directional responses of the variables (Appendix 1, Table S2).

Market-based interventions (scenarios 3 and 4)

In scenario 3, we examined the effects of the ecolabel, which is represented by a positive input to member income (MI). This is the only scenario that yields predictions of positive outcomes for both biological and economic variables, and for both user groups. Income and jobs are predicted to increase for both members and nonmembers, fishing effort is expected to decrease for all fisheries, abalone and lobster stocks are predicted to remain stable, and finfish stocks to increase (Fig. 4). Thus, improving member income through market-based incentives is predicted to have beneficial effects on the overall economy, with positive consequences on stocks that are either stable (AS and LS remain unchanged) or increase (FS).

In scenario 4, nonmember income is increased through opportunities from tourism development or other income opportunities not associated with fisheries. Under this scenario, benefits would accrue only for nonmembers, whereas member income is predicted to remain unchanged. This intervention would not have an impact on the abalone fishery, as indicated by no changes in AS, AE, or AC. Finfish stocks would increase because of decreased fishing effort associated with economic

Fig. 4. Results from loop analysis examining the effects of external drivers and management decisions from a suite of proposed scenarios, including: (1) increased abalone mortality caused by disease or climate change; (2) declines in lobster stocks from disease or hypoxia; (3) increases in member income from implementation of Marine Stewardship Council (MSC) certification; (4) nonmember income increase through external opportunities (e.g., price increase); (5) management decision that leads to decrease in member finfish effort; (6) management decision that leads to decrease in nonmember finfish effort; and, (7) increase in job opportunities (e.g., from subsidies). Outcomes for each variable from each scenario are given for the main model (Model 1, Fig. 2), which includes all linkages of the social-ecological system. Bar graphs indicate the percentage of positive outcomes from the loop analysis model runs.



alternatives, and lobster stock is predicted to decrease as a result of increased abundance of their predators. Thus, the main target stocks and the overall economy are not expected to benefit under this scenario.

Fisheries management actions (scenarios 5, 6, 7)
Management measures put in place to reduce member effort in the finfish fishery (ME) are predicted to lead to negative socioeconomic outcomes for all user groups (scenario 5; Fig. 4). Member and nonmember incomes and jobs are all expected to decrease. Thus, economically, this scenario has the most detrimental outcome among those considered. Finfish catch by members (MC) declines whereas catch by nonmembers (NC) shows a tendency to increase. Different consequences are predicted for abalone (AS) and lobster stocks (LS): LS is expected to decline, whereas AS is predicted not to change. Interestingly AS does not change despite both abalone effort and catch increasing. This highlights the difficulty of predicting outcomes using linear criteria of causation developed by focusing on the separate interactions between stock, effort, and catch in a single fishery.

A reduction in nonmember finfish effort (scenario 6) is also expected to result in economic loss for nonmembers and no income improvement for members. Nonmember income is predicted to decrease, likely due to finfish catch decrease because of reduced effort. Increased fish stocks result in decreased lobster stocks, whereas abalone stock is not affected and the abalone fishery seems insensitive to this input. As finfish stock increases, the feedback within this fishery results in constant catch, even with a decrease in effort. This does not hold for nonmembers because both catch and effort decrease.

Increasing the rate of change for job opportunities (scenario 7), for example through external subsidies or investments, leads to limited beneficial effects. As in the previous case (scenario 6), nonmember income is predicted to increase whereas member income would remain stable. Again the abalone fishery seems quite unaffected by this intervention whereas negative consequences are predicted for the lobster fishery (Fig. 4).

We further varied model structure to examine potential outcomes of other management interventions that might influence the system. Specifically, in our models 1-5 we represented the more general case of effort responding to changes in catch and stock, and did not consider regulatory controls that might influence this relationship, assuming that regulatory controls may not always be effective. From trends of catch and effort data on lobster in Baja California from 1960 to 2010 (Vega 2001), two phases can be identified in the historical records. During the first period (from 1970 to approx. 1990) effort increased while catch remained more or less constant, and in the second period (from 1995 to 2004), catch increased with constant effort. Predictions from our models indicate that an increase in effort may be accompanied by a constant catch only when we simulate a negative input on lobster stock, such as increased mortality or reduction in recruitment. Outcomes that reflect the second regime, in which a constant effort was accompanied by increased catch, requires a positive input to lobster catch, which may reflect improved catchability through, for example, implementing gear changes. However, during 1995-2004, effort was kept constant in the FEDECOOP cooperatives by maintaining the number of traps and length of the fishing season constant (Vega 2001). To examine how effective control of lobster fishing effort would influence outcomes, we introduced government agency as a controlling variable on lobster effort in additional models (Appendix 1, Table S4). Government agency (GA) is introduced as an external control of LE with no self-damping and with no other links to the rest of the system, so that GA responds to and acts solely on lobster effort (Appendix 1, Fig. S1). Interestingly, the table of predictions indicates that the presence of this variable makes LE resistant to all parameter changes except for input on GA itself (Appendix 1, Table S4). Models predict that increased catch can be obtained only with a positive parameter change on lobster catch, as in the case without control over effort (Fig. 3). In this latter case, a null value represents a true zero response and not compensation due to opposite forces. This zero response is typical of variables that are connected to a satellite variable (Levins 1974, Puccia and Levins 1986). Government agency is a satellite variable because it is connected to the system only through its linkage with LE and taken in isolation represents a system with zero feedback.

Sensitivity analysis

The largest difference in the frequency of predicted signs among the five models considered is between models 2 and 3, which differed in 28% of all pairwise comparisons (Appendix 1, Table S3). On average, comparisons among the five models yielded different signs in 20% of cases. However, if tendencies of signs (i.e., predictions such as ?+ and ?-) are considered as true signs (i.e., ?+ becomes + and ?- becomes -) differences are less pronounced: models 2 and 3 are still the most different but yield different predictions in only 17% of comparisons, and the average difference among models is 12%. Therefore, model structure can affect outcomes, but different predictions are obtained in a small fraction of simulations, suggesting that outcomes can be considered relatively robust to changes in the model structure that we tested.

DISCUSSION

Qualitative modeling approaches provide tools for learning about possible behaviors and responses to interventions in SES (Dambacher et al. 2007, Carey et al. 2014), as exemplified by this application of loop analysis to the coastal small-scale fisheries of the Vizcaino region in Baja California, Mexico. This approach can generate predictions and hypotheses about possible outcomes of management actions, new policies, or environmental drivers, and can highlight crucial links that need to be investigated to better understand the dynamics of complex SES. Loop analysis applied to the SES of coastal Baja California indicates how complex feedbacks among biological and socioeconomic components can result in counterintuitive and unexpected outcomes as a result of external perturbations. In general, our results suggest that possible trade-offs and cascading effects of management actions and new policies should be carefully considered when the goal of management is to simultaneously improve environmental condition and livelihoods of different user groups (Levin et al. 2009, Carey et al. 2014, Micheli et al. 2014*a*). Our results are consistent with broader scale analyses of Baja California small-scale fisheries applying the SES frameworks, which have highlighted trade-offs in achieving ecological and social sustainability, and high variability among different geographic regions of the Baja California Peninsula (e.g., Leslie et al. 2015).

Loop analysis helps highlight which components of ecosystems might be more or less vulnerable to perturbations and which interventions may be more beneficial than others for different components of the ecosystem and user groups. Our analysis of possible future scenarios of environmental or management change indicate that, under our assumptions for how system components interact, lobster stocks are predicted to be most vulnerable whereas finfish stocks are expected to benefit under most scenarios. Abalone populations appear to be generally insulated, showing relatively high resistance to changes in other components according to most scenarios. However, mass mortality of abalone (scenario 1) is predicted to have negative effects on catch and income for different user groups, with overall more negative outcomes than, e.g., disease or environmental conditions causing lobster mortality. In other words, abalone stock is rather insensitive to changes in other variables but changes in abalone's rate of change are likely to influence the whole system. Our models also show a negative correlation between lobster and finfish stocks. This negative correlation suggests that attempts to restore one of the two stocks or increasing its growth rate will negatively affect the other unless interventions are targeted to few variables (i.e., AC, LS, LC, ME, MI). These hypotheses need to be tested and should be carefully considered before management intervention.

Models produced specific predictions about the possible socioeconomic outcomes of different interventions or perturbations, and highlight what management interventions might be most beneficial or most detrimental to the local economy.

Only scenario 3, the ecolabel, shows positive effects on all three socioeconomic variables considered, i.e., member and nonmember income and jobs. The other six scenarios yield less positive outcomes for the economy of the system, where most predictions are negative (e.g., mass mortality affecting abalone stocks, the most valuable resource in this system, and a reduction of finfish effort within the cooperative) or show no consistent change (e.g., mass mortality affecting lobster, for which the cooperative, as for abalone, holds exclusive access rights). Thus, in this system, among the management interventions considered, the ecolabel is expected to have the greatest benefits whereas a reduction in finfishing effort by cooperative members the most detrimental. Moreover, the economic impacts of a mass mortality event of abalones are predicted to be greater than in the case of lobster.

Other studies conducted in this region have documented differential performance of fishers and fisheries in the face of change in environmental conditions. For example, Finkbeiner (2014) found that diversification of fishing activities was important for risk mitigation and stabilizing income, but the ability to specialize on high-value species during favorable conditions resulted in wealth accumulation. Thus, the flexibility to move across fishing strategies given changing environmental conditions is important for the adaptive capacity of small-scale fishing cooperatives. Further research on SES of Baja California and other regions should account for these dynamic responses to change, and how different governance frameworks and markets may enable or constrain adaptation.

Models also highlight what user groups might be more vulnerable to external shocks. In this SES, nonmember income is more sensitive than member income to environmental variability or the management decisions considered in these scenarios (Fig. 4; Appendix 1, Table S2). Interestingly, member income shows resistance to change when the system is perturbed through inputs that affect nonmembers, such as finfish stock, nonmember income, nonmember effort on finfish, nonmember catch, and job opportunities. Should these conclusions survive further scrutiny, they would indicate how management decisions might affect these communities because costs and benefits may be unevenly distributed. This is particularly important as perceived inequity in resource access, illegitimacy of process, and loss of social capital can influence how people comply with regulations, and, if ignored, can lead to unintended consequences, such as increased poaching and declines in species abundance (McClanahan et al. 2009). Ultimately, this can lead to poverty traps and affect the adaptive capacity of SES (Cinner 2011). An important next step will be to conduct in-depth analyses and modeling of social dynamics and possible unintended consequences of interventions in this and other coastal SES (e.g., Finkbeiner 2014). It is important to recognize that governance approaches addressing problems in one SES dimension could trigger unintended consequences in other dimensions if issues are not addressed in the whole system perspective. A comprehensive, integrative understanding of SES in this and other systems will enable sustainability science to more fully inform sustainability practice (Leslie et al. 2015).

Loop analysis can also reveal important potential trade-offs between desirable ecological and social outcomes, and can help identify which interventions may instead lead to potential win-win outcomes. In this case study, for example, management interventions, such as additional finfish fisheries regulation, are expected to have negative economic impacts, whereas creating new jobs through ecotourism or subsidies might have mixed effects on cooperative members versus nonmembers. Market interventions, like the ecolabel, are expected to have overall positive economic effects. Moreover, this positive economic impact is associated with a lack of negative biological impacts under most model structures, indicating that this market-based intervention poses the least trade-offs among those considered. Furthermore, under this scenario, the benefits are distributed across multiple stakeholder groups, in which both members and nonmembers are predicted to thrive. However, we caution applying outcomes from loop analysis without further modeling or empirical support for at least a core set of the variables. For example, our assumption that an ecolabel automatically increases the rate of change of member income may not be applicable in all systems. Although ecolabels can influence market price and increase income, and did result in documented benefits for FEDECOOP cooperative members and nonmembers in this region (Pérez-Ramírez et al 2012*b*), this is highly dependent on access to markets, infrastructure, and processing capabilities (Pérez-Ramírez et al. 2012*a*)

Loop analysis can identify what pathways may have greater influence on the outcomes, highlighting potentially important relationships to examine in future research and analysis. As described in our results, loop analysis may predict both expected and unexpected outcomes. For example, in this case study loop analysis predicts that an increase of fish stock abundance (FS) has a negative effect on the growth rate of its lobster (LS) but not abalone (AS) prey. As in any network analysis of complex systems, multiple pathways mediate the effects of one variable on another, so the full set of pathways must be examined to understand the effects. In each case (links from FS to LS and from FS to AS), there are multiple pathways carrying opposite effects, i.e., negative and positive. Thus, if only the number of pathways influenced the outcome of the loop analysis, we would expect the results of the simulation to lead to a neutral effect of FS on both AS and LS. Likely this discrepancy between what we would expect based on the number of pathways and what we obtain from the simulations depends on the fact that the product of link values, drawn from a random distribution, can yield small numbers in longer paths whereas the shorter paths tend to drive the final outcome of the loop analysis. In the example discussed above, the shortest paths are both negative from FS to LS but one positive and one negative from FS to AS.

This case study exemplifies the potential of loop analysis in SES applications and highlights the remaining weaknesses and caveats of this approach. In loop analysis, similar to other modeling approaches, predictions are strongly dependent on the specific assumptions about the relevant components of the SES, the nature of the linkages among these components, and the overall structure of the network. A major source of uncertainty is associated with our still limited ability to accurately represent the relationships between the variables. Although our depiction of the social-ecological system of the Vizcaino fisheries and decisions about the nature and direction of interactions are based on available knowledge of this and other similar systems, high uncertainty remains. For example, the observed negative impacts on lobster stocks that we obtained in several simulations are likely because of the assumption that predation by some finfish taxa (e.g., sheephead, which is targeted by local fisheries) controls lobster stocks. Although sheephead are major predators of lobster and sheephead control of benthic invertebrate populations has been demonstrated in kelp forests of southern California (Cowen 1983), there is no empirical evidence for top-down predatory control of lobster populations along the coast of Baja California.

Increasing the reliability of predictions can be obtained by designing alternative network structures and assessing the robustness of predictions to these different depictions of the linkages. This can help identify which structural differences matter. For example the abalone fishery subsystem (Fig. 3, columns labeled AS, AE, AC) appears to be quite resistant to environmental change. Of the 5 alternative network structures that we analyzed, 22 or more of the 42 predictions related to this subsystem show no response to parameter change (Appendix 1, Table S2). This robust outcome may be the effect of a core structure common to all models upon which few links added or removed do not change the predictions. Thus, it is particularly important that the core structure of models is carefully constructed, integrating all available sources of information and input from different stakeholders. In fact, an important benefit of loop analysis is that it provides a framework for integrating different types of information, thereby offering an opportunity to involve stakeholders in participatory model construction (Anthony et al. 2013). Both for qualitative and quantitative modeling approaches, model development will benefit from implementing participatory frameworks, in which different types of knowledge of the system from different users are included and tested to determine what variables and linkages are most relevant to the outcomes (Essington et al. 2016, Stier et al. 2016).

Our results, besides specific predictions in the different scenarios, highlight that patterns of correlation depend on the network structure and the entry point of the perturbation. For example, abalone (AS) and lobster stocks (LS) are negatively correlated with one another when biological stress enters the system (scenarios 1 and 2). However, when a press perturbation affects nonbiological variables (effort, income, job opportunities, scenarios from 2 to 7), the two stocks appear uncorrelated with one another. It follows that patterns of correlation from field data can be used to detect the entry points of perturbation in the system, and this highlights the potential of loop analysis as a diagnostic tool.

Loop analysis has been used in a few other cases of scenario analysis in the context of fishery (Anthony et al. 2013, Espinoza-Tenorio et al. 2013, Carey et al. 2014, Dambacher et al. 2015). Nevertheless, this technique presents several limitations that must be carefully addressed in management contexts. Justus (2006) outlined what outcomes from loop analysis are with regard to changes in the equilibrium level of the variables, but real systems are generally not at equilibrium, and nonlinearities often characterize variables' dynamics. Although previous studies (Lane and Collins 1985, Bodini 1988, 2000) have offered evidence that loop analysis can be applied to dynamic systems by considering changes in average values of the variables, dynamic changes remain a main challenge for qualitative modeling techniques. Another limitation of loop analysis concerns the time scale at which predicted effects may manifest themselves. For example, change can occur gradually, over long time frames, for some components of SES whereas others may experience sudden shifts. Variables that belong to different domains may show very different dynamics, thus time scales must be carefully considered and directly addressed by combining qualitative analysis and quantitative dynamic models.

Other qualitative modeling approaches can offer some advantages with respect to loop analysis. For example, fuzzy cognitive maps (FCMs) make the magnitude of links explicit through a semiquantification of the relationships between the variables (Özesmi and Özesmi 2004, Kok 2009). This approach resolves the ambiguities about the net effect of contrasting pathways discussed above. Another advantage of FCM over loop analysis is that it can make predictions about multiple simultaneous perturbations. However, the procedure for constructing FCMs requires experts to describe the structure and the interconnections of the network using fuzzy conditional (IF-THEN) statements. Such statements are of the type "if the level of variable A is high, that of variable B is low." This implies that experts define the relationships from correlations between the variables derived from observing the system (Stylios and Groumpos 1999). Our results highlight that patterns of correlation depend on the network structure and the entry point of the perturbation. For example, abalone (AS) and lobster stocks (LS) are negatively correlated with one another when biological stress enters the system through mass mortalities (scenarios 1 and 2). However, when perturbations affect the system through nonbiological variables (e.g., changes in effort, income, and job opportunities, scenarios 2-7), the two stocks appear uncorrelated with one another. It follows that defining interactions on the base of their correlations may be misleading (Levins and Puccia 1988).

Both loop analysis and FCMs allow for predicting changes in the level of the variables in a complex system following a perturbation to one of them. However, an advantage of loop analysis is that it models the effect of a perturbation to the rate of change of a variable, which isn't dependent on the initial state of the variable. For example, in scenario 1, we investigated the effect of an increased mortality of abalones due to climate change. Although we can expect heat waves and/or hypoxia to increase the mortality of abalone populations, based on available data (Morales-Bojórquez et al. 2008, Micheli et al. 2012), it is more difficult to predict the resulting abundance. In FCMs, instead, the perturbation is simulated as a change in the initial state of one or more variables (i.e., the abundance of a population), but changes in the level of the variables are difficult to predict (Levins and Puccia 1988). Therefore, in our case, loop analysis is more appropriate because it allows the incorporation of disturbances based on the knowledge of the direction of the variables' rates of change (negative, neutral, or positive). Given the strengths and weaknesses of each approach, there is great potential for fruitful integrations as shown by Ramsey and Veltman (2005).

Other qualitative modeling approaches include causal loop diagrams (CLD; Richardson 1986) and Bayesian belief networks (BBN; Borsuk et al. 2004; Pollino et al. 2007). Causal loop diagrams make predictions by logically reconstructing the causal chains of causes and effects between the variables on the basis of link polarities. However, predicting the behavior of complex networks, such as the one examined here, by identifying the feedback effects using link polarity is difficult and can lead to misleading interpretations of the effects, as previously highlighted by Richardson (1986). Similarly, specifying the relevant conditional probabilities as required by BBN can be a laborious and time-consuming process (Ticehurst et al. 2007). Moreover, including feedbacks via cyclic network structures requires dynamic time-explicit BBNs that depend on extensive parameterization. Hence, BBNs do not usually include feedbacks common to ecological systems (Marcot et al. 2001). Similar to FCMs, combining BBNs with loop analysis has great potential for improving predictions and model validation (Melbourne-Thomas et al. 2012, Anthony et al. 2013). However it must be emphasized that these applications of BBNs are based on the signs derived from the analysis of the qualitative models. As such, their outcomes are contingent on the assumptions and limitations of the signed diagraph models.

CONCLUSION

Managing fisheries under an ecosystem-based approach requires a shift in focus from single fisheries and sectors to a comprehensive strategy in which management considers multiple fisheries, multiple species, multiple aspects of local communities, and their linkages. Only by taking a holistic view of the SES can we begin to predict the consequences of multiple human activities, management interventions, and environmental shocks. Qualitative modeling approaches allow managers, stakeholders, and scientists to examine which of a suite of possible interventions has the greatest potential to influence other biological and socioeconomic components in the system, and which are more resistant to change. Furthermore, models and their outcomes can help identify key components and linkages, and prioritize data collection and management actions. However, qualitative models including loop analysis are subject to high uncertainty and outcomes of model perturbations are contingent on the assumptions about structural linkages. As such, qualitative models should be tested with empirical data and combined with quantitative dynamic models to increase certainty around model predictions. Despite their limitations, qualitative models that include linkages across the SES are integral to a comprehensive, system-wide approach that addresses ecological integrity, intergenerational opportunities, and economic efficiency, three key dimensions of the sustainable development paradigm.

Responses to this article can be read online at:
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Appendix S-A

Loop analysis: making predictions through signed digraphs

In what follows, we are showing how the loop analysis algorithm for predictions works using a simple model. In Figure S1 a simple tri-trophic linear chain comprises a resource (A), an intermediate consumer (B) and a final consumer (C). Loop analysis considers variations in the level of the variables as consequences of perturbations that permanently alter the rate of change of the variable. Suppose that c is the mortality of species A. If c is reduced (e.g. because of improved environmental conditions, or the establishment of a marine reserve), then the rate of change for A is expected to increase. We call this a "positive input". It is formally represented in Figure S1 as the derivative of the growth function for A ($\partial f(A)$ in respect to the variation ofc (∂c). Because parameters in the equations for the growth rate of variables (i.e. $dA/dt = f(A, B, c, d, e, \ldots)$ in which c, d, e are parameters) define the equilibrium points for the system, changes in parameter values define new equilibrium points with new values for the level of the variables. This parameter variation may influence the abundance of all variables in the model. Loop analysis algorithms predict the direction (increase, decrease, no variation) of change for the level of the variables.

The loop analysis algorithm and its structural elements, with examples of calculations, are visually represented in Figure S1.

The following formula summarizes the elements of the algorithm:

$$\frac{\delta x_j}{\delta c} = \frac{\sum_{i,k} \left[\frac{\delta f_i}{\delta c} \right] \times \left[p_{ji}^{(k)} \right] \times \left[F_{n-k}^{(comp)} \right]}{F_n}$$

Besides the sign of the input, determined by the term $\left[\frac{\partial f_i}{\partial c}\right]$, the loop formula makes use of the concepts of path, circuit, complementary feedback, and overall feedback. These refer to structural elements that can be identified in any graph. Their meaning can be fully understood by referring to the correspondence between matrix algebra and the formalism of loop analysis (see Levins 1975, Puccia and Levins 1985). In the above formula, *c* is the changing parameter (e.g., mortality, fecundity, predation rate); $[\partial f_i/\partial c]$ designates if the growth rate of the $i-th$ variable is increasing $(+)$ or decreasing $(-)$; $[p_{ij}^{(k)}]$ is the pathway connecting the variable that undergoes parameter change, x_i, with that whose equilibrium value is being calculated, x_j, and that includes (k) variables. The last factor of the numerator is the complementary feedback $[F_{n-k}^{(comp)}]$, which buffers or reverses the effect of the pathway; it is the feedback formed by the $(n-k)$ variables that remain in the system after the (k) variables that are on the path are excluded. The term $[F_n]$ indicates the overall feedback of the system, which is a measure of the inertia of the systems to change. Criteria to identify such elements in the example graph are provided by using the scheme depicted in Figure S1

Positive input on A: $\partial(f(A))/\partial c_A$

Overall Feedback (F_n) $-a_{AA}a_{BC}a_{CB} < 0$

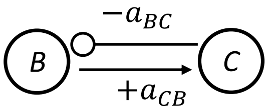
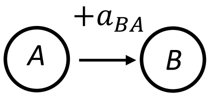
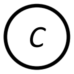
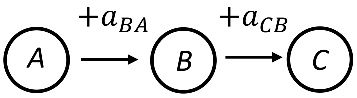
Effect on	Path	Complementary Feedback	Prediction
A	$+1$ $(variable\ on\ self)$	 $-a_{BC}a_{CB} < 0$	$\frac{\partial A}{\partial c_A} = \frac{(+)(+1)(-a_{BC}a_{CB})}{-a_{AA}a_{BC}a_{CB}} = +$
B		 $zero\ feedback$	$\frac{\partial B}{\partial c_A} = \frac{(+)(+a_{BA})(0)}{-a_{AA}a_{BC}a_{CB}} = 0$
C	 $(+a_{BA})(+a_{CB}) > 0$	-1 $all\ variables$ $on\ the\ path$	$\frac{\partial C}{\partial c_A} = \frac{(+)(+a_{BA}a_{CB})(-1)}{-a_{AA}a_{BC}a_{CB}} = +$

Figure S1. Signed-digraph of a three trophic level linear chain. Paths, complementary subsystems, and feedbacks used to calculate expected changes in the equilibrium level of the variables, in response to a positive input on A. The first term of the numerator in the formula under the Prediction header is the sign of the input (+).

Circuits and Feedbacks. In loop analysis, a pathway that starts at one node and, by following the direction of links, returns to it without crossing intermediate nodes more than once is called a loop, or circuit. Any circuit produces a feedback that can be either positive or negative, depending on the product of the signs of the links that form the loop. As there may be circuits of different length (with 1, 2, 3, ..., k variables involved), in a given system there are as many levels of feedback as variables. Each level of feedback considers all the circuits (feedbacks) involving that particular number of variables. In the system of Figure S1 there are 3 levels of feedback. The first level of feedback comprises the only one variable circuit that is present in the system: the self-damping on variable A.

Two resource-consumer interactions $[A\text{o} \rightarrow B]$ and $[B\text{o} \rightarrow C]$ produce two feedbacks of the second level, and the three variable feedback shown in Figure S1 (overall feedback) form the third level of feedback, which is created by two independent loops: the self-damping on variable A and the resource consumer interaction involving B and C.

Overall Feedback (*F_n*). The overall feedback is computed only once and corresponds to the highest possible level of feedback in a system. It can be calculated from single circuits linking all the variables in the system, or as a combination of shorter circuits involving smaller subsets of variables. In the hypothetical chain of three trophic levels depicted in Figure S1, the overall feedback corresponds to a third level of feedback (that is a feedback effect involving all three variables). Because the three variables cannot be connected simultaneously in unique circuits, the overall feedback comprises all the products of disjunct loops that have a combined number of variables equal to 3. That is, F_n is composed by the self-damping on A (a self-effect link is a loop of length 1) plus the two-node loop [B-C]. Its sign is obtained by multiplying the signs of the links involved, and this sign is further multiplied by (-1^{m+1}), where m is the number of disjunct loops entering the feedback. As the links involved are two negative and one positive, and there are two disjunct loops, the overall feedback is negative.

Path $[p_{ij}^{(k)}]$. A path is a series of links starting at one node and ending on another node, without crossing any variable twice. Suppose a positive input occurs on A (its rate of change increases, $\left[\frac{\partial f_i}{\partial c}\right] > 0$). To predict the new equilibrium of C, the path along which the effect travels is the positive link from A to B and the arrow from B to C. Its sign, given by the product of the signs of the links that form the path, is positive.

Complementary Feedback (*F_{n-k}*). The complementary feedback is the feedback that groups all the variables in the complementary subsystem. The complementary subsystem is what remains after the (k) variables in the path are excluded. In Figure 1, for a positive input on A and effect on B, the complementary subsystem is formed only by C (A and B are on the path). Because C has no self-effect link, in this example there will be a null (0) complementary feedback. A path from a variable to itself is equal to 1, while if all the variables are in the path (i.e., input to A and effect on C) there is no complementary subsystem, and the complementary feedback is equal to -1. These are two algebraic conveniences that are formally explained in Levins (1975) and Puccia and Levins (1986). Summation in the loop formula considers the fact that two variables can be connected by more than one path.

Using linear algebra, we obtain the same prediction as the graphic algorithm and the net effect (the sum of the direct effect plus all the individual indirect effects) on species i resulting from an input on species j is given by the element of the inverse community matrix:

$$\frac{\partial \vec{x}^*}{\partial c_h} = (A_h)^{-1}(-\frac{\partial \vec{F}}{\partial c_h})$$

$$if \quad \left(\frac{\partial \vec{F}}{\partial c_h} = +1\right) \quad then: \frac{\partial \vec{x}^*}{\partial c_h} = -(A_h)^{-1}$$

This means that (A_h) must have a non-zero determinant and must admit an inverse matrix $(A_h)^{-1}$ whose eigenvalues have to satisfy the Lyapunov condition of stability. For simplicity, the vector $(-\frac{\partial \vec{F}}{\partial c_h})$ is considered equal to one because there is no quantitative information about the inputs. A summary table of predictions can be produced from the simulated matrices that satisfy stability conditions. In the overall table, the variables' response is quantified as the percentage of positive signs, negative signs and zero values obtained from the matrices. The sign of the prediction is determined by a set of rules regarding the percentages of cases in which +, - and 0 appear in any given entry of the table, as we explained in the main body of the paper.

References

Levins, R. 1975; R. Evolution in Communities Near Equilibrium. M.L. Cody, J. Diamond (Eds.), Ecology and Evolution of Communities, Belknap Press, 16-50.

Puccia, C., and R. Levins. 1985. *Qualitative Modeling of Complex Systems*. Cambridge, MA: Harvard University Press.

Table S1. Example of pathways and their signs (Model 1).

a. Pathways from FS to AS:

FS⊸AS (-)

FS⊸LS⊸AS (+)

FS⟶MC⟶MI⊸AE⊸AS (+)

FS⟶MC⟶MI⊸AE⊸LE⊸LS⊸AS (+)

FS⟶MC⟶MI⊸LE⊸LS⊸AS (-)

FS⊸LS⊸LE⟶LC⟶MI ⊸AE⊸AS (+)

FS⊸LS⟶LC⟶MI ⊸AE⊸AS (-)

FS⊸LS⊸LE⊸ME⟶MC⟶MI ⊸AE⊸AS (-)

b. Pathways from FS to LS:

FS⊸LS (-)

FS⊸AS⟶LS (-)

FS⟶MC⟶MI⊸LE⊸LS (+)

FS⟶MC⟶MI⊸AE⊸AS⟶LS (+)

FS⟶MC⟶MI⊸AE⊸LE⊸LS (-)

FS⊸AS⊸AE⊸LE⊸LS (+)

FS⊸AS⊸AE⊸ME⟶MC⟶MI ⊸LE⊸AS (-)

FS⊸AS⟶AC⟶MI ⊸LE⊸LS (-)

FS⊸AS⊸AE⟶AC⟶MI ⊸LE⊸LS (+)

Table S2. Simulations' output. For each of the 5 models (see Figure 2 in the main article), the community matrix, the three matrices reporting the percentage of +, - and 0 obtained in the simulation, and the overall table of predictions are reported.

Model 1

```
 "Community matrix"

   AS AE AC LS LE LC FS ME MC NE NC MI NI JO
AS -1 -1  1  1  0  0  1  0  0  0  0  0  0  0
AE -1 -1  1  0 -1  0  0 -1  0  0  0  0  0  0
AC  0  0 -1  0  0  0  0  0  0  0  0  1  0  0
LS -1  0  0 -1 -1  1  1  0  0  0  0  0  0  0
LE  0  0  0 -1 -1  1  0 -1  0  0  0  0  0  0
LC  0  0  0  0  0 -1  0  0  0  0  0  1  0  0
FS -1  0  0 -1  0  0 -1  0  1  0  1  0  0  0
ME  0  0  0  0  0  0 -1 -1  1  0  0  0  0  0
MC  0  0  0  0  0  0  0 -1 -1  0  0  1  0  0
NE  0  0  0  0  0  0 -1  0  0 -1  1  0  0  0
NC  0  0  0  0  0  0  0  0  0 -1 -1  0  1  0
MI  0 -1  0  0 -1  0  0 -1  0  0  0 -1  0  1
NI  0  0  0  0  0  0  0  0  0 -1  0  0 -1 -1
JO  0  0  0  0  0  0  0  0  0  0  0  0  1 -1
```

```
Percentage of " + "
         AS       AE       AC       LS       LE       LC       FS       ME
AS 84.92683 14.34146 46.82927 37.31707 65.02439 48.34146 91.56098 28.92683
AE 14.19512 94.04878 76.00000 64.43902 19.70732 26.87805 29.46341 52.34146
AC 52.00000 20.92683 85.31707 44.82927 42.39024 30.92683 78.34146 35.46341
LS  8.48780 80.78049 36.68293 84.82927 16.58537 50.97561 44.97561 57.17073
LE 80.73171 26.00000 52.34146 11.31707 95.90244 73.60976 72.00000 19.31707
LC 52.00000 20.92683 16.78049 44.82927 42.39024 90.09756 78.34146 35.46341
FS 49.65854 55.17073 56.09756  8.68293 76.14634 33.36585 84.00000 21.41463
ME 55.41463 28.78049 26.04878 79.17073 29.56098 53.31707 37.60976 88.63415
MC 49.70732 37.41463 33.02439 19.07317 61.12195 28.87805 85.60976  8.97561
NE 50.34146 44.82927 43.90244 91.31707 23.85366 66.63415 16.00000 78.58537
NC 49.65854 55.17073 56.09756  8.68293 76.14634 33.36585 84.00000 21.41463
MI 52.00000 20.92683 16.78049 44.82927 42.39024 30.92683 78.34146 35.46341
NI 49.65854 55.17073 56.09756  8.68293 76.14634 33.36585 84.00000 21.41463
JO 49.65854 55.17073 56.09756  8.68293 76.14634 33.36585 84.00000 21.41463
         MC       NE       NC       MI       NI       JO
AS 76.68293 10.24390 78.24390 69.70732 81.85366 45.90244
AE 35.07317 66.14634 35.56098 47.70732 40.29268 56.34146
AC 57.75610 15.60976 47.95122 87.80488 87.85366 78.00000
LS 55.70732 54.87805 48.87805 45.90244 45.85366 46.34146
LE 32.09756 30.09756 61.70732 59.80488 65.36585 52.73171
LC 57.75610 15.60976 47.95122 87.80488 87.85366 78.00000
FS 57.07317 25.21951 82.04878 42.39024 60.29268 29.31707
ME 83.56098 48.87805 25.46341 77.51220 64.78049 80.00000
MC 87.46341 16.53659 69.70732 68.63415 77.85366 53.95122
NE 42.92683 96.92683 85.51220 57.60976 81.21951 24.00000
NC 57.07317  3.07317 96.92683 42.39024 82.73171 12.78049
MI 57.75610 15.60976 47.95122 87.80488 87.85366 78.00000
NI 57.07317  3.07317 14.48780 42.39024 97.90244  4.04878
JO 57.07317  3.07317 14.48780 42.39024 97.90244 96.78049
```

```
Percentage of " - "
         AS       AE       AC       LS       LE       LC       FS       ME
AS 15.07317 85.65854 53.17073 62.68293 34.97561 51.65854  8.43902 71.07317
AE 85.80488  5.95122 24.00000 35.56098 80.29268 73.12195 70.53659 47.65854
AC 48.00000 79.07317 14.68293 55.17073 57.60976 69.07317 21.65854 64.53659
LS 91.51220 19.21951 63.31707 15.17073 83.41463 49.02439 55.02439 42.82927
LE 19.26829 74.00000 47.65854 88.68293  4.09756 26.39024 28.00000 80.68293
LC 48.00000 79.07317 83.21951 55.17073 57.60976  9.90244 21.65854 64.53659
FS 50.34146 44.82927 43.90244 91.31707 23.85366 66.63415 16.00000 78.58537
ME 44.58537 71.21951 73.95122 20.82927 70.43902 46.68293 62.39024 11.36585
MC 50.29268 62.58537 66.97561 80.92683 38.87805 71.12195 14.39024 91.02439
NE 49.65854 55.17073 56.09756  8.68293 76.14634 33.36585 84.00000 21.41463
NC 50.34146 44.82927 43.90244 91.31707 23.85366 66.63415 16.00000 78.58537
MI 48.00000 79.07317 83.21951 55.17073 57.60976 69.07317 21.65854 64.53659
NI 50.34146 44.82927 43.90244 91.31707 23.85366 66.63415 16.00000 78.58537
JO 50.34146 44.82927 43.90244 91.31707 23.85366 66.63415 16.00000 78.58537
         MC       NE       NC       MI       NI       JO
AS 23.31707 89.75610 21.75610 30.29268 18.14634 54.09756
AE 64.92683 33.85366 64.43902 52.29268 59.70732 43.65854
AC 42.24390 84.39024 52.04878 12.19512 12.14634 22.00000
LS 44.29268 45.12195 51.12195 54.09756 54.14634 53.65854
LE 67.90244 69.90244 38.29268 40.19512 34.63415 47.26829
LC 42.24390 84.39024 52.04878 12.19512 12.14634 22.00000
FS 42.92683 74.78049 17.95122 57.60976 39.70732 70.68293
ME 16.43902 51.12195 74.53659 22.48780 35.21951 20.00000
MC 12.53659 83.46341 30.29268 31.36585 22.14634 46.04878
NE 57.07317  3.07317 14.48780 42.39024 18.78049 76.00000
NC 42.92683 96.92683  3.07317 57.60976 17.26829 87.21951
MI 42.24390 84.39024 52.04878 12.19512 12.14634 22.00000
NI 42.92683 96.92683 85.51220 57.60976  2.09756 95.95122
JO 42.92683 96.92683 85.51220 57.60976  2.09756  3.21951

Percentage of " 0 "
   AS AE AC LS LE LC FS ME MC NE NC MI NI JO
AS  0  0  0  0  0  0  0  0  0  0  0  0  0  0
AE  0  0  0  0  0  0  0  0  0  0  0  0  0  0
AC  0  0  0  0  0  0  0  0  0  0  0  0  0  0
LS  0  0  0  0  0  0  0  0  0  0  0  0  0  0
LE  0  0  0  0  0  0  0  0  0  0  0  0  0  0
LC  0  0  0  0  0  0  0  0  0  0  0  0  0  0
FS  0  0  0  0  0  0  0  0  0  0  0  0  0  0
ME  0  0  0  0  0  0  0  0  0  0  0  0  0  0
MC  0  0  0  0  0  0  0  0  0  0  0  0  0  0
NE  0  0  0  0  0  0  0  0  0  0  0  0  0  0
NC  0  0  0  0  0  0  0  0  0  0  0  0  0  0
MI  0  0  0  0  0  0  0  0  0  0  0  0  0  0
NI  0  0  0  0  0  0  0  0  0  0  0  0  0  0
JO  0  0  0  0  0  0  0  0  0  0  0  0  0  0


"Table of predictions”

   AS AE AC LS LE LC FS ME MC NE NC MI NI JO
AS +  -  0* ?- ?+ 0* +  ?- +  -  +  ?+ +  0*
AE -  +  +  ?+ -  ?- ?- 0* ?- ?+ ?- 0* 0* 0*
AC 0* -  +  0* 0* ?- +  ?- 0* -  0* +  +  +
LS -  +  ?- +  -  0* 0* 0* 0* 0* 0* 0* 0* 0*
LE +  ?- 0* -  +  ?+ ?+ -  ?- ?- ?+ 0* ?+ 0*
LC 0* -  -  0* 0* +  +  ?- 0* -  0* +  +  +
FS 0* 0* 0* -  +  ?- +  -  0* ?- +  0* ?+ ?-
ME 0* ?- ?- +  ?- 0* ?- +  +  0* ?- +  ?+ +
MC 0* ?- ?- -  ?+ ?- +  -  +  -  ?+ ?+ +  0*
NE 0* 0* 0* +  -  ?+ -  +  0* +  +  0* +  -
NC 0* 0* 0* -  +  ?- +  -  0* -  +  0* +  -
MI 0* -  -  0* 0* ?- +  ?- 0* -  0* +  +  +
NI 0* 0* 0* -  +  ?- +  -  0* -  -  0* +  -
```

```
JO 0* 0* 0* -  +  ?- +  -  0* -  -  0* +  +
```

Model 2

```
"Community matrix"
   AS AE AC LS LE LC FS ME MC NE NC MI NI JO
AS -1 -1  1  1  0  0  1  0  0  0  0  0  0  0
AE -1 -1  1  0 -1  0  0 -1  0  0  0  0  0  0
AC  0  0 -1  0  0  0  0  0  0  0  0  1  0  0
LS -1  0  0 -1 -1  1  1  0  0  0  0  0  0  0
LE  0  0  0 -1 -1  1  0  0  0  0  0  0  0  0
LC  0  0  0  0  0 -1  0  0  0  0  0  1  0  0
FS -1  0  0 -1  0  0 -1  0  1  0  1  0  0  0
ME  0  0  0  0  0  0 -1 -1  1  0  0  0  0  0
MC  0  0  0  0  0  0  0 -1 -1  0  0  1  0  0
NE  0  0  0  0  0  0 -1  0  0 -1  1  0  0  0
NC  0  0  0  0  0  0  0  0  0 -1 -1  0  1  0
MI  0 -1  0  0 -1  0  0 -1  0  0  0 -1  0  1
NI  0  0  0  0  0  0  0  0  0 -1  0  0 -1 -1
JO  0  0  0  0  0  0  0  0  0  0  0  0  1 -1


Percentage of " + "
         AS       AE       AC       LS       LE       LC       FS       ME
AS 86.74699 12.73666 45.78313 40.40448 63.42513 49.65577 91.52324 36.44578
AE 14.54389 94.44923 78.91566 51.46299 25.47332 26.24785 38.72633 28.61446
AC 51.41997 21.60069 84.50947 44.14802 39.02754 30.63683 80.76592 30.37866
LS  6.49742 86.61790 44.62134 80.37866 18.76076 49.91394 51.50602 33.73494
LE 90.74871  7.91738 38.72633 20.09466 94.79346 79.86231 64.58692 52.15146
LC 51.41997 21.60069 16.56627 44.14802 39.02754 92.03959 80.76592 30.37866
FS 53.91566 46.55766 48.92427  7.96041 79.25990 35.28399 84.50947 32.44406
ME 48.36489 36.53184 30.59380 83.26162 24.35456 50.30120 34.63855 89.37177
MC 54.08778 31.84165 31.84165 17.34079 63.51119 31.45439 85.92943 10.71429
NE 46.08434 53.44234 51.07573 92.03959 20.74010 64.71601 15.49053 67.55594
NC 53.91566 46.55766 48.92427  7.96041 79.25990 35.28399 84.50947 32.44406
MI 51.41997 21.60069 16.56627 44.14802 39.02754 30.63683 80.76592 30.37866
NI 53.91566 46.55766 48.92427  7.96041 79.25990 35.28399 84.50947 32.44406
JO 53.91566 46.55766 48.92427  7.96041 79.25990 35.28399 84.50947 32.44406
         MC       NE       NC       MI       NI       JO
AS 88.72633  9.29432 75.21515 73.10671 84.59552 50.60241
AE 16.17900 61.83305 45.95525 40.83477 39.19966 44.79346
AC 55.03442 13.94148 48.75215 89.54389 88.81239 78.14114
LS 34.81067 52.62478 58.39071 36.61790 41.82444 35.92943
LE 64.28571 29.30293 43.11532 80.24957 76.89329 73.92427
LC 55.03442 13.94148 48.75215 89.54389 88.81239 78.14114
FS 75.38726 22.03098 78.14114 51.80723 66.69535 36.44578
ME 81.11015 53.82960 24.82788 72.54733 59.98279 77.45267
MC 92.81411 14.97418 66.56627 73.02065 80.98107 57.18589
NE 24.61274 97.03098 86.53184 48.19277 79.43201 21.90189
NC 75.38726  2.96902 95.05164 51.80723 86.35972 17.16867
MI 55.03442 13.94148 48.75215 89.54389 88.81239 78.14114
NI 75.38726  2.96902 13.46816 51.80723 98.45095  5.59380
JO 75.38726  2.96902 13.46816 51.80723 98.45095 96.68675


Percentage of " - "
         AS       AE       AC       LS       LE       LC       FS       ME
AS 13.25301 87.26334 54.21687 59.59552 36.57487 50.34423  8.47676 63.55422
AE 85.45611  5.55077 21.08434 48.53701 74.52668 73.75215 61.27367 71.38554
AC 48.58003 78.39931 15.49053 55.85198 60.97246 69.36317 19.23408 69.62134
LS 93.50258 13.38210 55.37866 19.62134 81.23924 50.08606 48.49398 66.26506
LE  9.25129 92.08262 61.27367 79.90534  5.20654 20.13769 35.41308 47.84854
LC 48.58003 78.39931 83.43373 55.85198 60.97246  7.96041 19.23408 69.62134
FS 46.08434 53.44234 51.07573 92.03959 20.74010 64.71601 15.49053 67.55594
ME 51.63511 63.46816 69.40620 16.73838 75.64544 49.69880 65.36145 10.62823
MC 45.91222 68.15835 68.15835 82.65921 36.48881 68.54561 14.07057 89.28571
NE 53.91566 46.55766 48.92427  7.96041 79.25990 35.28399 84.50947 32.44406
NC 46.08434 53.44234 51.07573 92.03959 20.74010 64.71601 15.49053 67.55594
MI 48.58003 78.39931 83.43373 55.85198 60.97246 69.36317 19.23408 69.62134
```

```
NI 46.08434 53.44234 51.07573 92.03959 20.74010 64.71601 15.49053 67.55594
JO 46.08434 53.44234 51.07573 92.03959 20.74010 64.71601 15.49053 67.55594
         MC       NE       NC       MI       NI       JO
AS 11.27367 90.70568 24.78485 26.89329 15.40448 49.39759
AE 83.82100 38.16695 54.04475 59.16523 60.80034 55.20654
AC 44.96558 86.05852 51.24785 10.45611 11.18761 21.85886
LS 65.18933 47.37522 41.60929 63.38210 58.17556 64.07057
LE 35.71429 70.69707 56.88468 19.75043 23.10671 26.07573
LC 44.96558 86.05852 51.24785 10.45611 11.18761 21.85886
FS 24.61274 77.96902 21.85886 48.19277 33.30465 63.55422
ME 18.88985 46.17040 75.17212 27.45267 40.01721 22.54733
MC  7.18589 85.02582 33.43373 26.97935 19.01893 42.81411
NE 75.38726  2.96902 13.46816 51.80723 20.56799 78.09811
NC 24.61274 97.03098  4.94836 48.19277 13.64028 82.83133
MI 44.96558 86.05852 51.24785 10.45611 11.18761 21.85886
NI 24.61274 97.03098 86.53184 48.19277  1.54905 94.40620
JO 24.61274 97.03098 86.53184 48.19277  1.54905  3.31325
Percentage of " 0 "

   AS AE AC LS LE LC FS ME MC NE NC MI NI JO
AS  0  0  0  0  0  0  0  0  0  0  0  0  0  0
AE  0  0  0  0  0  0  0  0  0  0  0  0  0  0
AC  0  0  0  0  0  0  0  0  0  0  0  0  0  0
LS  0  0  0  0  0  0  0  0  0  0  0  0  0  0
LE  0  0  0  0  0  0  0  0  0  0  0  0  0  0
LC  0  0  0  0  0  0  0  0  0  0  0  0  0  0
FS  0  0  0  0  0  0  0  0  0  0  0  0  0  0
ME  0  0  0  0  0  0  0  0  0  0  0  0  0  0
MC  0  0  0  0  0  0  0  0  0  0  0  0  0  0
NE  0  0  0  0  0  0  0  0  0  0  0  0  0  0
NC  0  0  0  0  0  0  0  0  0  0  0  0  0  0
MI  0  0  0  0  0  0  0  0  0  0  0  0  0  0
NI  0  0  0  0  0  0  0  0  0  0  0  0  0  0
JO  0  0  0  0  0  0  0  0  0  0  0  0  0  0

"Table of predictions”

   AS  AE  AC  LS  LE  LC  FS  ME  MC  NE  NC  MI  NI  JO
AS +   -   0*  0*  ?+  0*  +   ?-  +   -   +   ?+  +   0*
AE -   +   +   0*  ?-  ?-  ?-  ?-  -   ?+  0*  0*  ?-  0*
AC 0*  -   +   0*  ?-  ?-  +   ?-  0*  -   0*  +   +   +
LS -   +   0*  +   -   0*  0*  ?-  ?-  0*  0*  ?-  0*  ?-
LE +   -   ?-  -   +   +   ?+  0*  ?+  ?-  0*  +   +   ?+
LC 0*  -   -   0*  ?-  +   +   ?-  0*  -   0*  +   +   +
FS 0*  0*  0*  -   +   ?-  +   ?-  +   -   +   0*  ?+  ?-
ME 0*  ?-  ?-  +   -   0*  ?-  +   +   0*  -   ?+  0*  +
MC 0*  ?-  ?-  -   ?+  ?-  +   -   +   -   ?+  ?+  +   0*
NE 0*  0*  0*  +   -   ?+  -   ?+  -   +   +   0*  +   -
NC 0*  0*  0*  -   +   ?-  +   ?-  +   -   +   0*  +   -
MI 0*  -   -   0*  ?-  ?-  +   ?-  0*  -   0*  +   +   +
NI 0*  0*  0*  -   +   ?-  +   ?-  +   -   -   0*  +   -
JO 0*  0*  0*  -   +   ?-  +   ?-  +   -   -   0*  +   +
```

Model 3

```
"Community matrix"

   AS AE AC LS LE LC FS ME MC NE NC MI NI JO
AS -1 -1  1  1  0  0  1  0  0  0  0  0  0  0
AE -1 -1  1  0  0  0  0 -1  0  0  0  0  0  0
AC  0  0 -1  0  0  0  0  0  0  0  0  1  0  0
LS -1  0  0 -1 -1  1  1  0  0  0  0  0  0  0
LE  0  0  0 -1 -1  1  0 -1  0  0  0  0  0  0
LC  0  0  0  0  0 -1  0  0  0  0  0  1  0  0
FS -1  0  0 -1  0  0 -1  0  1  0  1  0  0  0
ME  0  0  0  0  0  0 -1 -1  1  0  0  0  0  0
MC  0  0  0  0  0  0  0 -1 -1  0  0  1  0  0
NE  0  0  0  0  0  0 -1  0  0 -1  1  0  0  0
NC  0  0  0  0  0  0  0  0  0 -1 -1  0  1  0
MI  0 -1  0  0 -1  0  0 -1  0  0  0 -1  0  1
```

```
NI  0  0  0  0  0  0  0  0  0 -1  0  0 -1 -1
JO  0  0  0  0  0  0  0  0  0  0  0  0  1 -1


Percentage of  " + "

         AS       AE       AC       LS       LE       LC       FS       ME
AS 83.35221 15.85504 44.69611 50.77388 38.69385 33.03133 90.48698 43.18611
AE 22.31031 93.01623 85.69271 35.03209 54.51114 41.63835 37.63684 27.89732
AC 42.61986 22.95206 87.31597 62.77841 15.66629 18.27105 72.78218 50.32088
LS  6.34202 83.88071 41.33635 79.01095 30.46433 62.24991 48.24462 42.24236
LE 86.74972 18.27105 45.86636 14.60929 92.63873 73.68818 73.27293 26.50057
LC 42.61986 22.95206 14.94904 62.77841 15.66629 88.48622 72.78218 50.32088
FS 56.02114 47.94262 53.86938  4.75651 85.99471 34.76784 87.91997 17.74254
ME 41.71385 38.12760 28.31257 89.99622  8.19177 43.79011 31.67233 91.92148
MC 49.94337 33.63533 31.33258 22.65006 54.13364 21.70630 87.46697 11.74028
NE 43.97886 52.05738 46.13062 95.24349 14.00529 65.23216 12.08003 82.25746
NC 56.02114 47.94262 53.86938  4.75651 85.99471 34.76784 87.91997 17.74254
MI 42.61986 22.95206 14.94904 62.77841 15.66629 18.27105 72.78218 50.32088
NI 56.02114 47.90487 53.83163  4.75651 85.95696 34.76784 87.88222 17.74254
JO 56.02114 47.90487 53.83163  4.75651 85.99471 34.76784 87.91997 17.74254
         MC       NE       NC       MI       NI       JO
AS 87.31597 11.58928 76.67044 67.64817 81.23820 44.84711
AE 16.53454 57.07814 35.18309 58.36165 51.03813 62.70291
AC 68.10117 19.47905 41.37410 91.88373 87.35372 82.25746
LS 42.77086 50.28313 49.30162 49.75462 50.13213 49.11287
LE 43.22386 27.67082 61.57040 64.85466 68.89392 53.11438
LC 68.10117 19.47905 41.37410 91.88373 87.35372 82.25746
FS 58.73915 20.27180 84.59796 46.28162 65.87391 30.57758
ME 81.27595 54.92639 20.00755 76.06644 59.00340 81.46470
MC 89.31672 13.74103 66.81767 74.44319 82.29521 58.02190
NE 41.26085 97.31974 82.97471 53.71838 79.35070 25.36806
NC 58.73915  2.68026 96.97999 46.28162 85.57946 13.70328
MI 68.10117 19.47905 41.37410 91.88373 87.35372 82.25746
NI 58.70140  2.68026 17.02529 46.24387 97.99924  3.66176
JO 58.70140  2.68026 17.02529 46.28162 97.99924 95.92299


Percentage of " - "

         AS       AE       AC       LS       LE       LC       FS       ME
AS 16.64779 84.14496 55.30389 49.22612 61.30615 66.96867  9.51302 56.81389
AE 77.68969  6.98377 14.30729 64.96791 45.48886 58.36165 62.36316 72.10268
AC 57.38014 77.04794 12.68403 37.22159 84.33371 81.72895 27.21782 49.67912
LS 93.65798 16.11929 58.66365 20.98905 69.53567 37.75009 51.75538 57.75764
LE 13.25028 81.72895 54.13364 85.39071  7.36127 26.31182 26.72707 73.49943
LC 57.38014 77.04794 85.05096 37.22159 84.33371 11.51378 27.21782 49.67912
FS 43.97886 52.05738 46.13062 95.24349 14.00529 65.23216 12.08003 82.25746
ME 58.28615 61.87240 71.68743 10.00378 91.80823 56.20989 68.32767  8.07852
MC 50.05663 66.36467 68.66742 77.34994 45.86636 78.29370 12.53303 88.25972
NE 56.02114 47.94262 53.86938  4.75651 85.99471 34.76784 87.91997 17.74254
NC 43.97886 52.05738 46.13062 95.24349 14.00529 65.23216 12.08003 82.25746
MI 57.38014 77.04794 85.05096 37.22159 84.33371 81.72895 27.21782 49.67912
NI 43.94111 52.05738 46.09287 95.20574 13.96753 65.19441 12.08003 82.21971
JO 43.97886 52.05738 46.09287 95.24349 14.00529 65.19441 12.08003 82.21971
         MC       NE       NC       MI       NI       JO
AS 12.68403 88.41072 23.32956 32.35183 18.76180 55.15289
AE 83.46546 42.92186 64.81691 41.63835 48.96187 37.29709
AC 31.89883 80.52095 58.62590  8.11627 12.64628 17.74254
LS 57.22914 49.71687 50.69838 50.24538 49.86787 50.88713
LE 56.77614 72.32918 38.42960 35.14534 31.10608 46.88562
LC 31.89883 80.52095 58.62590  8.11627 12.64628 17.74254
FS 41.26085 79.72820 15.40204 53.71838 34.12609 69.42242
ME 18.72405 45.07361 79.99245 23.93356 40.99660 18.53530
MC 10.68328 86.25897 33.18233 25.55681 17.70479 41.97810
NE 58.70140  2.68026 17.02529 46.28162 20.64930 74.63194
NC 41.26085 97.31974  3.02001 53.71838 14.42054 86.29672
MI 31.89883 80.52095 58.62590  8.11627 12.64628 17.74254
NI 41.22310 97.31974 82.97471 53.71838  2.00076 96.33824
JO 41.26085 97.31974 82.97471 53.71838  2.00076  4.07701
```

```
Percentage of " 0 "
        AS      AE     AC      LS     LE      LC      FS      ME      MC NE NC
AS 0.00000 0.00000 0.0000 0.00000 0.0000 0.00000 0.00000 0.00000 0.00000  0  0
AE 0.00000 0.00000 0.0000 0.00000 0.0000 0.00000 0.00000 0.00000 0.00000  0  0
AC 0.00000 0.00000 0.0000 0.00000 0.0000 0.00000 0.00000 0.00000 0.00000  0  0
LS 0.00000 0.00000 0.0000 0.00000 0.0000 0.00000 0.00000 0.00000 0.00000  0  0
LE 0.00000 0.00000 0.0000 0.00000 0.0000 0.00000 0.00000 0.00000 0.00000  0  0
LC 0.00000 0.00000 0.0000 0.00000 0.0000 0.00000 0.00000 0.00000 0.00000  0  0
FS 0.00000 0.00000 0.0000 0.00000 0.0000 0.00000 0.00000 0.00000 0.00000  0  0
ME 0.00000 0.00000 0.0000 0.00000 0.0000 0.00000 0.00000 0.00000 0.00000  0  0
MC 0.00000 0.00000 0.0000 0.00000 0.0000 0.00000 0.00000 0.00000 0.00000  0  0
NE 0.00000 0.00000 0.0000 0.00000 0.0000 0.00000 0.00000 0.00000 0.03775  0  0
NC 0.00000 0.00000 0.0000 0.00000 0.0000 0.00000 0.00000 0.00000 0.00000  0  0
MI 0.00000 0.00000 0.0000 0.00000 0.0000 0.00000 0.00000 0.00000 0.00000  0  0
NI 0.03775 0.03775 0.0755 0.03775 0.0755 0.03775 0.03775 0.03775 0.07550  0  0
JO 0.00000 0.03775 0.0755 0.00000 0.0000 0.03775 0.00000 0.03775 0.03775  0  0
        MI NI JO
AS 0.00000  0  0
AE 0.00000  0  0
AC 0.00000  0  0
LS 0.00000  0  0
LE 0.00000  0  0
LC 0.00000  0  0
FS 0.00000  0  0
ME 0.00000  0  0
MC 0.00000  0  0
NE 0.00000  0  0
NC 0.00000  0  0
MI 0.00000  0  0
NI 0.03775  0  0
JO 0.00000  0  0
```

```
"Table of predictions”
   AS AE AC LS LE LC FS ME MC NE NC MI NI JO
AS +  -  0* 0* ?- ?- +  0* +  -  +  ?+ +  0*
AE -  +  +  ?- 0* 0* ?- ?- -  0* ?- 0* 0* ?+
AC 0* -  +  ?+ -  -  ?+ 0* ?+ -  0* +  +  +
LS -  +  0* +  ?- ?+ 0* 0* 0* 0* 0* 0* 0* 0*
LE +  -  0* -  +  ?+ ?+ ?- 0* ?- ?+ ?+ ?+ 0*
LC 0* -  -  ?+ -  +  ?+ 0* ?+ -  0* +  +  +
FS 0* 0* 0* -  +  ?- +  -  0* -  +  0* ?+ ?-
ME 0* ?- ?- +  -  0* ?- +  +  0* -  +  0* +
MC 0* ?- ?- -  0* -  +  -  +  -  ?+ ?+ +  0*
NE 0* 0* 0* +  -  ?+ -  +  0* +  +  0* +  ?-
NC 0* 0* 0* -  +  ?- +  -  0* -  +  0* +  -
MI 0* -  -  ?+ -  -  ?+ 0* ?+ -  0* +  +  +
NI 0* 0* 0* -  +  ?- +  -  0* -  -  0* +  -
JO 0* 0* 0* -  +  ?- +  -  0* -  -  0* +  +
```

Model 4

```
"Community matrix"

   AS AE AC LS LE LC FS ME MC NE NC MI NI JO
AS -1 -1  1  1  0  0  1  0  0  0  0  0  0  0
AE -1 -1  1  0  0  0  0 -1  0  0  0  0  0  0
AC  0  0 -1  0  0  0  0  0  0  0  0  1  0  0
LS -1  0  0 -1 -1  1  1  0  0  0  0  0  0  0
LE  0  0  0 -1 -1  1  0  0  0  0  0  0  0  0
LC  0  0  0  0  0 -1  0  0  0  0  0  1  0  0
FS -1  0  0 -1  0  0 -1  0  1  0  1  0  0  0
ME  0  0  0  0  0  0 -1 -1  1  0  0  0  0  0
MC  0  0  0  0  0  0  0 -1 -1  0  0  1  0  0
NE  0  0  0  0  0  0 -1  0  0 -1  1  0  0  0
NC  0  0  0  0  0  0  0  0  0 -1 -1  0  1  0
MI  0 -1  0  0 -1  0  0 -1  0  0  0 -1  0  1
NI  0  0  0  0  0  0  0  0  0 -1  0  0 -1 -1
```

```
JO  0  0  0  0  0  0  0  0  0  0  0  0  1 -1


Percentage of " + "
         AS       AE       AC       LS       LE       LC       FS       ME
AS 87.14910 10.85465 44.38553 48.28447 38.67748 33.15658 94.91578 37.89769
AE 22.83219 93.32502 85.21522 32.03369 58.82720 42.63880 37.61697 22.70742
AC 43.38740 22.08359 88.55271 53.33749 17.52963 15.62695 83.37492 27.97879
LS  5.36494 87.52339 42.45165 76.07611 33.00062 63.03805 49.25140 28.38428
LE 92.70119  5.80162 36.11978 25.04679 89.83157 77.23019 68.27823 54.99064
LC 43.38740 22.08359 16.03244 53.33749 17.52963 91.70306 83.37492 27.97879
FS 58.67124 40.04991 47.50468  5.05303 84.74735 31.87773 88.67748 31.72177
ME 38.39676 41.89021 29.94386 89.55084  8.35933 42.23331 33.21896 89.23893
MC 52.74485 29.66313 28.13475 19.96257 54.49158 20.24329 91.26638  8.04741
NE 41.32876 59.95009 52.49532 94.94697 15.25265 68.12227 11.32252 68.27823
NC 58.67124 40.04991 47.50468  5.05303 84.74735 31.87773 88.67748 31.72177
MI 43.38740 22.08359 16.03244 53.33749 17.52963 15.62695 83.37492 27.97879
NI 58.67124 40.04991 47.50468  5.05303 84.74735 31.84654 88.67748 31.72177
JO 58.64005 40.04991 47.50468  5.05303 84.74735 31.81535 88.67748 31.72177
         MC       NE       NC       MI       NI       JO
AS 92.91953  8.14099 82.84467 71.36619 84.31067 43.73051
AE 12.60137 57.42358 35.52714 56.70618 50.56145 61.10418
AC 56.76856 12.50780 52.24579 92.85714 91.11042 79.75671
LS 29.94386 52.46413 51.99626 42.57642 45.72676 42.88833
LE 70.61759 25.67062 47.84779 82.09607 78.54024 73.08172
LC 56.76856 12.50780 52.24579 92.85714 91.11042 79.75671
FS 78.85215 16.99938 81.09794 56.92452 72.36432 36.36931
ME 78.32190 55.36494 23.83032 73.58079 59.07673 79.91266
MC 94.72863 10.66750 70.96070 78.97692 86.18216 59.01435
NE 21.14785 98.44042 84.77854 43.07548 76.88709 19.83780
NC 78.85215  1.55958 96.10106 56.92452 89.70680 17.40487
MI 56.76856 12.50780 52.24579 92.85714 91.11042 79.75671
NI 78.85215  1.55958 15.22146 56.89333 99.25140  4.83468
JO 78.85215  1.55958 15.22146 56.86213 99.25140 97.31753



Percentage of " - "

         AS       AE       AC       LS       LE       LC       FS       ME
AS 12.85090 89.14535 55.61447 51.71553 61.32252 66.84342  5.08422 62.10231
AE 77.16781  6.67498 14.78478 67.96631 41.17280 57.36120 62.38303 77.29258
AC 56.61260 77.91641 11.44729 46.66251 82.47037 84.37305 16.62508 72.02121
LS 94.63506 12.47661 57.54835 23.92389 66.99938 36.96195 50.74860 71.61572
LE  7.29881 94.19838 63.88022 74.95321 10.16843 22.76981 31.72177 45.00936
LC 56.61260 77.91641 83.96756 46.66251 82.47037  8.29694 16.62508 72.02121
FS 41.32876 59.95009 52.49532 94.94697 15.25265 68.12227 11.32252 68.27823
ME 61.60324 58.10979 70.05614 10.44916 91.64067 57.76669 66.78104 10.76107
MC 47.25515 70.33687 71.86525 80.03743 45.50842 79.75671  8.73362 91.95259
NE 58.67124 40.04991 47.50468  5.05303 84.74735 31.87773 88.67748 31.72177
NC 41.32876 59.95009 52.49532 94.94697 15.25265 68.12227 11.32252 68.27823
MI 56.61260 77.91641 83.96756 46.66251 82.47037 84.37305 16.62508 72.02121
NI 41.32876 59.95009 52.46413 94.94697 15.25265 68.12227 11.32252 68.24704
JO 41.29757 59.91890 52.49532 94.94697 15.25265 68.12227 11.32252 68.24704
         MC       NE       NC       MI       NI       JO
AS  7.08047 91.85901 17.15533 28.63381 15.68933 56.26949
AE 87.39863 42.57642 64.44167 43.29382 49.43855 38.89582
AC 43.23144 87.49220 47.75421  7.14286  8.88958 20.24329
LS 70.05614 47.53587 48.00374 57.42358 54.27324 57.11167
LE 29.38241 74.32938 52.15221 17.90393 21.45976 26.91828
LC 43.23144 87.49220 47.75421  7.14286  8.88958 20.24329
FS 21.14785 83.00062 18.90206 43.07548 27.63568 63.63069
ME 21.67810 44.63506 76.16968 26.41921 40.92327 20.08734
MC  5.27137 89.33250 29.03930 21.02308 13.81784 40.98565
NE 78.85215  1.55958 15.22146 56.92452 23.11291 80.16220
NC 21.14785 98.44042  3.89894 43.07548 10.29320 82.59513
MI 43.23144 87.49220 47.75421  7.14286  8.88958 20.24329
NI 21.14785 98.44042 84.77854 43.07548  0.74860 95.16532
JO 21.14785 98.44042 84.77854 43.07548  0.74860  2.68247
```

```
Percentage of " 0 "
        AS       AE       AC LS LE       LC FS       ME MC NE       NC       MI NI JO
AS 0.00000 0.00000 0.00000  0  0 0.00000  0 0.00000  0  0 0.00000 0.00000  0  0
AE 0.00000 0.00000 0.00000  0  0 0.00000  0 0.00000  0  0 0.03119 0.00000  0  0
AC 0.00000 0.00000 0.00000  0  0 0.00000  0 0.00000  0  0 0.00000 0.00000  0  0
LS 0.00000 0.00000 0.00000  0  0 0.00000  0 0.00000  0  0 0.00000 0.00000  0  0
LE 0.00000 0.00000 0.00000  0  0 0.00000  0 0.00000  0  0 0.00000 0.00000  0  0
LC 0.00000 0.00000 0.00000  0  0 0.00000  0 0.00000  0  0 0.00000 0.00000  0  0
FS 0.00000 0.00000 0.00000  0  0 0.00000  0 0.00000  0  0 0.00000 0.00000  0  0
ME 0.00000 0.00000 0.00000  0  0 0.00000  0 0.00000  0  0 0.00000 0.00000  0  0
MC 0.00000 0.00000 0.00000  0  0 0.00000  0 0.00000  0  0 0.00000 0.00000  0  0
NE 0.00000 0.00000 0.00000  0  0 0.00000  0 0.00000  0  0 0.00000 0.00000  0  0
NC 0.00000 0.00000 0.00000  0  0 0.00000  0 0.00000  0  0 0.00000 0.00000  0  0
MI 0.00000 0.00000 0.00000  0  0 0.00000  0 0.00000  0  0 0.00000 0.00000  0  0
NI 0.00000 0.00000 0.03119  0  0 0.03119  0 0.03119  0  0 0.00000 0.03119  0  0
JO 0.06238 0.03119 0.00000  0  0 0.06238  0 0.03119  0  0 0.00000 0.06238  0  0

"Table of predictions"
   AS AE AC LS LE LC FS ME MC NE NC MI NI JO
AS +  -  0* 0* ?- ?- +  ?- +  -  +  ?+ +  0*
AE -  +  +  ?- 0* 0* ?- -  -  0* ?- 0* 0* ?+
AC 0* -  +  0* -  -  +  ?- 0* -  0* +  +  +
LS -  +  0* +  ?- ?+ 0* ?- ?- 0* 0* 0* 0* 0*
LE +  -  ?- ?- +  +  ?+ 0* ?+ ?- 0* +  +  ?+
LC 0* -  -  0* -  +  +  ?- 0* -  0* +  +  +
FS 0* 0* 0* -  +  ?- +  ?- +  -  +  0* ?+ ?-
ME ?- 0* ?- +  -  0* ?- +  +  0* -  ?+ 0* +
MC 0* ?- ?- -  0* -  +  -  +  -  ?+ +  +  0*
NE 0* 0* 0* +  -  ?+ -  ?+ -  +  +  0* +  -
NC 0* 0* 0* -  +  ?- +  ?- +  -  +  0* +  -
MI 0* -  -  0* -  -  +  ?- 0* -  0* +  +  +
NI 0* 0* 0* -  +  ?- +  ?- +  -  -  0* +  -
JO 0* 0* 0* -  +  ?- +  ?- +  -  -  0* +  +
```

Model 5

```
"Community matrix"
   AS AE AC LS LE LC FS ME MC NE NC MI NI JO
AS -1 -1  1  1  0  0  1  0  0  0  0  0  0  0
AE -1 -1  1  0  0  0  0  0  0  0  0  0  0  0
AC  0  0 -1  0  0  0  0  0  0  0  0  1  0  0
LS -1  0  0 -1 -1  1  1  0  0  0  0  0  0  0
LE  0  0  0 -1 -1  1  0 -1  0  0  0  0  0  0
LC  0  0  0  0  0 -1  0  0  0  0  0  1  0  0
FS -1  0  0 -1  0  0 -1  0  1  0  1  0  0  0
ME  0  0  0  0  0  0 -1 -1  1  0  0  0  0  0
MC  0  0  0  0  0  0  0 -1 -1  0  0  1  0  0
NE  0  0  0  0  0  0 -1  0  0 -1  1  0  0  0
NC  0  0  0  0  0  0  0  0  0 -1 -1  0  1  0
MI  0 -1  0  0 -1  0  0 -1  0  0  0 -1  0  1
NI  0  0  0  0  0  0  0  0  0 -1  0  0 -1 -1
JO  0  0  0  0  0  0  0  0  0  0  0  0  1 -1

Percentage of " + "

         AS       AE       AC       LS       LE       LC       FS       ME
AS 83.62847 16.43836 48.94754 41.79753 48.17908 34.38022 93.55162 20.84865
AE 12.22853 94.82125 82.15837 59.17140 30.83862 38.42299 20.11360 65.08520
AC 45.53959 23.15403 89.54227 51.55363 22.45239 15.60307 79.88640 30.80521
LS  7.51754 81.22285 35.51620 86.83595 21.11594 60.37421 43.76879 66.32142
LE 81.25626 23.98931 52.75643  8.72035 95.75677 72.26863 74.07284  9.48881
LC 45.53959 23.15403 16.70565 51.55363 22.45239 88.00535 79.88640 30.80521
FS 51.62045 52.32208 55.89709  4.64417 86.46843 35.21550 85.16539 14.46709
ME 47.21016 33.37788 24.15636 88.60675  9.55563 41.59706 36.98630 91.91447
MC 46.87604 36.25125 33.41129 20.14701 56.99967 21.48346 87.37053  6.88273
NE 48.37955 47.67792 44.10291 95.35583 13.53157 64.78450 14.83461 85.53291
NC 51.62045 52.32208 55.89709  4.64417 86.46843 35.21550 85.16539 14.46709
MI 45.53959 23.15403 16.70565 51.55363 22.45239 15.60307 79.88640 30.80521
```

```
NI 51.62045 52.28867 55.89709  4.64417 86.46843 35.21550 85.16539 14.46709
JO 51.58704 52.28867 55.89709  4.64417 86.43502 35.21550 85.16539 14.40027
         MC       NE       NC       MI       NI       JO
AS 79.31841 10.12362 84.29669 62.11159 79.45205 37.72135
AE 27.46408 66.72235 15.03508 72.33545 51.58704 81.72402
AC 58.46976 15.20214 49.44871 89.97661 88.74039 77.88172
LS 61.37655 52.72302 41.76412 57.50084 51.98797 58.43635
LE 24.65753 29.00100 67.15670 56.53191 65.18543 45.94053
LC 58.46976 15.20214 49.44871 89.97661 88.74039 77.88172
FS 53.62513 21.65052 83.02706 44.97160 63.84898 28.76712
ME 88.43969 52.15503 23.35449 77.74808 63.14734 82.05814
MC 87.43735 13.83228 70.49783 73.13732 81.52355 54.66088
NE 46.37487 97.19345 82.75977 55.02840 79.38523 25.42599
NC 53.62513  2.80655 96.55864 44.97160 85.16539 12.49582
MI 58.46976 15.20214 49.44871 89.97661 88.74039 77.88172
NI 53.62513  2.80655 17.24023 44.93819 98.26261  3.64183
JO 53.62513  2.80655 17.24023 44.90478 98.26261 95.95723


Percentage of " - "

         AS       AE       AC       LS       LE       LC       FS       ME
AS 16.37153 83.56164 51.05246 58.20247 51.82092 65.61978  6.44838 79.15135
AE 87.77147  5.17875 17.84163 40.82860 69.16138 61.57701 79.88640 34.91480
AC 54.46041 76.84597 10.45773 48.44637 77.54761 84.39693 20.11360 69.19479
LS 92.48246 18.77715 64.48380 13.16405 78.88406 39.62579 56.23121 33.67858
LE 18.74374 76.01069 47.24357 91.27965  4.24323 27.73137 25.92716 90.51119
LC 54.46041 76.84597 83.29435 48.44637 77.54761 11.99465 20.11360 69.19479
FS 48.37955 47.67792 44.10291 95.35583 13.53157 64.78450 14.83461 85.53291
ME 52.78984 66.62212 75.84364 11.39325 90.44437 58.40294 63.01370  8.08553
MC 53.12396 63.74875 66.58871 79.85299 43.00033 78.51654 12.62947 93.11727
NE 51.62045 52.32208 55.89709  4.64417 86.46843 35.21550 85.16539 14.46709
NC 48.37955 47.67792 44.10291 95.35583 13.53157 64.78450 14.83461 85.53291
MI 54.46041 76.84597 83.29435 48.44637 77.54761 84.39693 20.11360 69.19479
NI 48.37955 47.67792 44.03608 95.35583 13.53157 64.78450 14.83461 85.53291
JO 48.37955 47.64450 44.03608 95.28901 13.53157 64.75109 14.83461 85.53291
         MC       NE       NC       MI       NI       JO
AS 20.68159 89.87638 15.70331 37.88841 20.54795 62.27865
AE 72.53592 33.27765 84.96492 27.66455 48.41296 18.27598
AC 41.53024 84.79786 50.55129  9.98998 11.25961 22.11828
LS 38.62345 47.27698 58.23588 42.49916 48.01203 41.56365
LE 75.34247 70.99900 32.84330 43.46809 34.81457 54.05947
LC 41.53024 84.79786 50.55129  9.98998 11.25961 22.11828
FS 46.37487 78.34948 16.97294 55.02840 36.15102 71.23288
ME 11.56031 47.84497 76.64551 22.25192 36.85266 17.94186
MC 12.56265 86.16772 29.50217 26.86268 18.47645 45.33912
NE 53.62513  2.80655 17.24023 44.97160 20.61477 74.57401
NC 46.37487 97.19345  3.44136 55.02840 14.83461 87.50418
MI 41.53024 84.79786 50.55129  9.98998 11.25961 22.11828
NI 46.37487 97.19345 82.75977 55.02840  1.73739 96.35817
JO 46.34146 97.19345 82.75977 54.99499  1.73739  4.04277

Percentage of " 0 "

        AS      AE      AC      LS      LE      LC FS      ME      MC NE NC
AS 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000  0 0.00000 0.00000  0  0
AE 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000  0 0.00000 0.00000  0  0
AC 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000  0 0.00000 0.00000  0  0
LS 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000  0 0.00000 0.00000  0  0
LE 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000  0 0.00000 0.00000  0  0
LC 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000  0 0.00000 0.00000  0  0
FS 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000  0 0.00000 0.00000  0  0
ME 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000  0 0.00000 0.00000  0  0
MC 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000  0 0.00000 0.00000  0  0
NE 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000  0 0.00000 0.00000  0  0
NC 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000  0 0.00000 0.00000  0  0
MI 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000  0 0.00000 0.00000  0  0
NI 0.00000 0.03341 0.06682 0.00000 0.00000 0.00000  0 0.00000 0.00000  0  0
JO 0.03341 0.06682 0.06682 0.06682 0.03341 0.03341  0 0.06682 0.03341  0  0
        MI NI JO
AS 0.00000  0  0
```

```
AE 0.00000  0  0
AC 0.03341  0  0
LS 0.00000  0  0
LE 0.00000  0  0
LC 0.03341  0  0
FS 0.00000  0  0
ME 0.00000  0  0
MC 0.00000  0  0
NE 0.00000  0  0
NC 0.00000  0  0
MI 0.03341  0  0
NI 0.03341  0  0
JO 0.10023  0  0

"Table of predictions"

   AS AE AC LS LE LC FS ME MC NE NC MI NI JO
AS +  -  0* 0* 0* ?- +  -  +  -  +  ?+ +  ?-
AE -  +  +  0* ?- ?- -  ?+ ?- ?+ -  ?+ 0* +
AC 0* -  +  0* -  -  +  ?- 0* -  0* +  +  +
LS -  +  ?- +  -  ?+ 0* ?+ ?+ 0* 0* 0* 0* 0*
LE +  -  0* -  +  ?+ ?+ -  -  ?- ?+ 0* ?+ 0*
LC 0* -  -  0* -  +  +  ?- 0* -  0* +  +  +
FS 0* 0* 0* -  +  ?- +  -  0* -  +  0* ?+ ?-
ME 0* ?- -  +  -  0* ?- +  +  0* -  +  ?+ +
MC 0* ?- ?- -  0* -  +  -  +  -  ?+ ?+ +  0*
NE 0* 0* 0* +  -  ?+ -  +  0* +  +  0* +  ?-
NC 0* 0* 0* -  +  ?- +  -  0* -  +  0* +  -
MI 0* -  -  0* -  -  +  ?- 0* -  0* +  +  +
NI 0* 0* 0* -  +  ?- +  -  0* -  -  0* +  -
JO 0* 0* 0* -  +  ?- +  -  0* -  -  0* +  +
```

Table S3. Sensitivity Analyses. Number of cases in which each prediction matrix differs from all other matrices in a series of pairwise comparisons.

a. Numbers based on tendencies of changes (i.e. including ?+ and ?). The greatest difference is between models 2 (M2) and 3 (M3) (55 cases, corresponding to 28% of the total number of comparisons). The average difference computed considering all comparisons is 20%.

	M1	M2	M3	M4	M5
M1	0	39	42	50	29
M2	0	0	55	25	46
M3	0	0	0	40	34
M4	0	0	0	0	43
M5	0	0	0	0	0

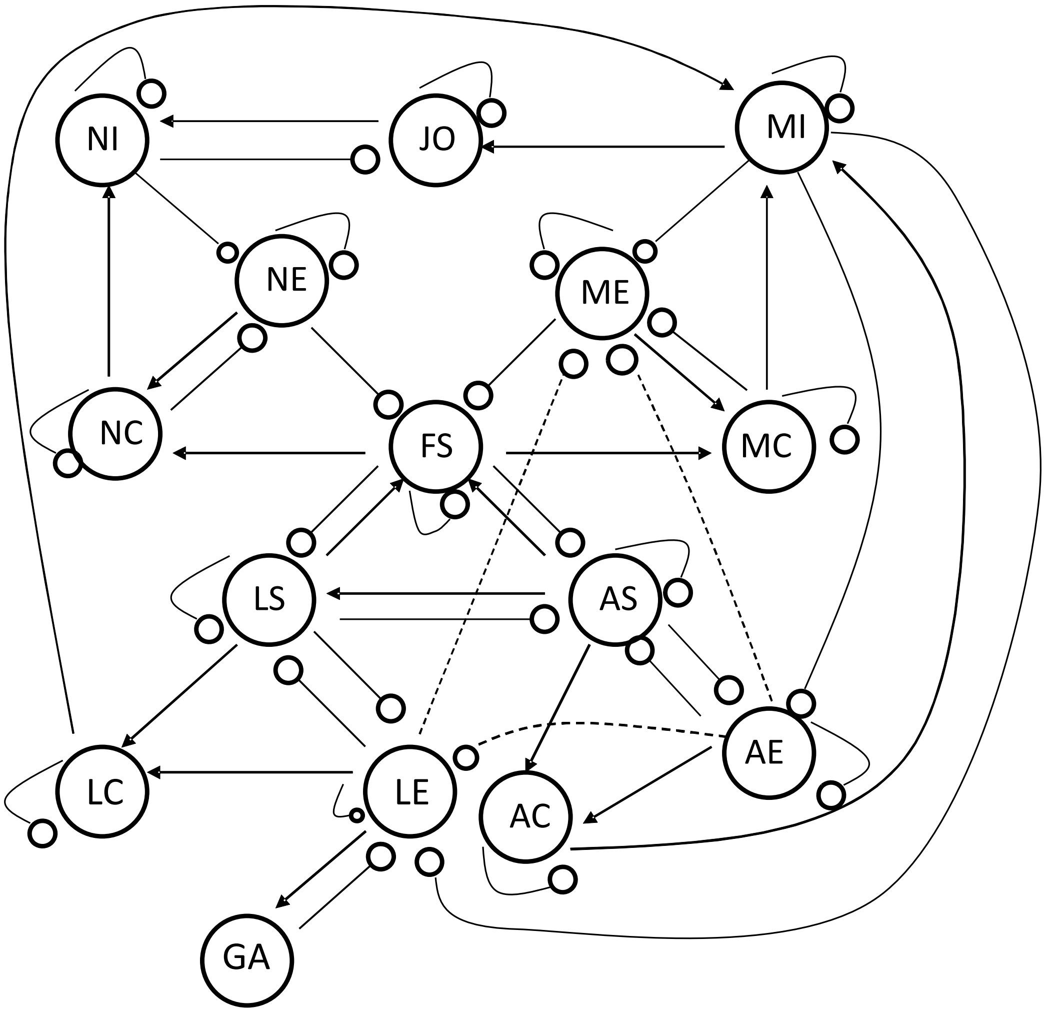
b. Numbers re-calculated (from Table S3a) when tendencies are transformed in signs (i.e. ?+ becomes + and ?- becomes -). The largest difference is between models 2 and 3 (35 cases): their predictions differ in 17% of the comparisons. The average difference is 12%.

	M1	M2	M3	M4	M5
M1	0	25	28	31	15
M2	0	0	35	15	27
M3	0	0	0	24	24
M4	0	0	0	0	25
M5	0	0	0	0	0

Table S4. Control over lobster effort through regulation. In this model, control is exerted by a governmental agency (GA) that is represented in the graph as a “predator” on LE (lobster fishing effort). This represents the situation where a controlling factor (GA, in this case) reacts promptly to any variation in the level of effort, bringing it back to its original level. This controll is possible because of the negative feedback between GA and LE and because GA is not self-damped. Without self-damping, GA responds only to LE. Its response is typical of a negative feedback that exerts a buffering effect. Moreover, LE remains unaffected by any input entering the system because GA, being non self-damped, makes the complementary feedback of all pathways to LE null. Therefore, GA protects LE against the effect of variations in the system. The table of predictions is reported below. The table shows that LE changes only for variations in the rate of change of the governmental agency which controls it.

	AS	AE	AC	LS	LE	LC	FS	ME	MC	NE	NC	MI	NI	JO	GA
AS	+	?−	?−	0*	0	0*	+	0*	+	−	?+	−	0*	?−	?+
AE	−	+	+	−	0	−	0*	−	−	0*	?−	+	+	+	−
AC	+	−	−	?+	0	?+	?+	+	+	?−	0*	−	0*	?−	+
LS	−	+	?+	0*	0	0*	0*	−	?−	0*	0*	+	?+	?+	−
LE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	+
LC	+	−	−	?+	0	+	?+	+	+	?−	0*	−	0*	?−	+
FS	?−	?+	?+	−	0	−	?+	?−	0*	?−	0*	?+	?+	0*	0*
ME	?+	−	−	+	0	+	0*	+	+	0*	0*	?−	0*	?−	?+
MC	+	−	−	?+	0	?+	?+	+	+	?−	0*	−	0*	?−	+
NE	?+	?−	?−	+	0	+	?−	?+	0*	+	+	?−	+	−	0*
NC	?−	?+	?+	−	0	−	?+	?−	0*	−	+	?+	+	−	0*
MI	+	−	−	?+	0	?+	?+	+	+	?−	0*	−	0*	?−	+
NI	?−	?+	?+	−	0	−	?+	?−	0*	−	−	?+	+	−	0*
JO	?−	?+	?+	−	0	−	?+	?−	0*	−	−	?+	+	+	0*
GA	?−	?+	?+	?+	−	−	0*	?+	0*	0*	0*	?+	0*	?+	?+

Figure S1. Control over lobster effort through regulation (see Table S4).


NI
JO
MI
NE
ME
NC
FS
MC
LS
AS
AE
LC
LE
AC
GA

Appendix S-B

R code for simulations

The procedure for simulations and the code are illustrated in what follows.

Input needed:

1- tab.txt (the community matrix with values -1, 0, +1 has to be created in .txt format and called tab.txt).
2- names2.txt (this is a row vector that contains labels for the variables. They have to be the same used in the community matrix, namely the column heads, and in the same order as they appear along the rows or columns of the community matrix)

Functions:

Once in R space launch:

```
> source ("com_mat2.R")
```

Script: com_mat2.R

```
#marcus<-matrix(c(-1,1,-1,0),nrow=2,byrow=TRUE)
#marcus<-matrix(c(-1,0,-1,0,0,-1,-1,-1,1,1,0,-1,0,1,0,0),nrow=4,byrow=TRUE)
#marcus<-matrix(c(-1,1,0,0,0,0,-1,1,0,-1,0,0,-1,1,0,1,0,0,-1,0,0,0,0,1,-1), nrow=5, byrow=T)

names<-scan("names2.txt", what=character(), sep="," )

marcus<-read.table("tab.txt", col.names=names, row.names=names, sep="," )

#colnames(marcus)<-names
#rownames(marcus)<-names

print("community matrix")
print(marcus)

ll<-length(marcus)
print("ll")
print(ll)

#library("Rgraphviz")
#rEG<-new("graphNEL", nodes=c(names), edgemode="directed")
# plot(rEG)

#for (i in 1:ll)
#  for (j in 1:ll)
#  { if (i==j) (rEG<-addEdge(names(marcus)[i], names(marcus)[i], rEG, 1))
#  else if ((i!=j) & (marcus[i,j]==1)) (rEG<-addEdge(names(marcus)[i], names(marcus)[j], rEG, 1))
#  else if ((i!=j) & (marcus[i,j]==-1)) (rEG<-addEdge(names(marcus)[i], names(marcus)[j], rEG, 1))
#  }
#  plot(rEG, recipEdges = "distinct")

library("LoopAnalyst")
mat<-scan("tab.txt", what=character(), sep=",")
mat_v<-as.vector(mat)
mat_c<-matrix(c(mat_v), nrow=ll, byrow=T)
```

```
mat_tc<-t(mat_c)
colnames(mat_tc)<-names
rownames(mat_tc)<-names
graph.cm(mat_tc, file="mat_tc.dot")


#library("network")
#g<-network(marcus, direct=T, hyper=F, loops=T)
#plot(g, usearrow=T, arrowhead.cex=2, loop.cex=3, vertex.cex=1, edge.col=4,
#plot.network(g, usearrow=T, arrowhead.cex=2, loop.cex=3, vertex.cex=1, edge.col=4,
#   vertex.col=1, label=network.vertex.names(g), displaylabels=T, boxed.labels=F, label.lwd=3, label.pos=0)
```

Output is the community matrix

Launch:

```
>source ("func_LOOP_sugg2.R")
```

Script: func_LOOP_sugg2.R

```
## Community matrix in Levins' notation###

library("MASS")
Loop <- function(marcus) {

            ### initializing count###
#           print ("WARNING!!! MASS PACKAGE NEEDED")

            print("community matrix")
            print(marcus)

            names<-scan("names2.txt", what=character(), sep="," )

            k<-1
            m<-0
       h<-0
            ########################################
            #community matrix as sign matrix: lev #
            ########################################
            ####MATRIX IS: a11, a21, a31,...ect. where
            # aij=dfi/dxj change in the growth function of i due to j!############
            #1°es. Predator-Prey

                        lev<-t(marcus)
                        Det_m<-det(lev)

              print("Determinant")
              print(Det_m)

             dl<-sqrt(length(lev))
             dl2<-dl^2
              print("dl")
               print(dl)
```

```
        #  print(dl^2)

        nacc<-as.vector(k, mode="integer")
        nacc[1]=0

        n_p<-as.vector(m, mode="integer")
        n_m<-as.vector(m, mode="integer")
        n_oo<-as.vector(m, mode="integer")

        for (m in 1:dl2) {(n_p[m]=0) & (n_m[m]=0) & (n_oo[m]=0)}

        n_plus<-as.vector(n_p, mode="integer")
        n_min<-as.vector(n_m, mode="integer")
        n_o<-as.vector(n_oo, mode="integer")

######### NUMBER OF RUNS
        # ntent<-(length(lev)*100)
        # ntent<-(length(lev)*500)
        ntent<-(length(lev)*1000)
        # ntent<-(length(lev)*5000)
        # ntent<-(length(lev)*10000)

    print(ntent)
#########

        for (k in 1:ntent){

        #########################
        #random matrix: casuale #
        #########################

        casuale<-matrix(rep(0,dl2),nrow=dl)

###### RANDOM MATRIX GENERATION  (NAME IS: casuale) in [1e-6,1]
        for (i in 1:dl)
            for(j in 1:dl) casuale[i,j]<-runif(n=1,min=1e-6,max=1)

        #  print(casuale)

        ###################################################
        #weighted matrix (on degree tot for each variable) #
        ###################################################

        num=0

        ww<-matrix(rep(NA,dl2),nrow=dl)

          for(i in 1:dl)
            for(j in 1:dl){ww[i,j]<-(lev[i,j]*casuale[i,j])
                      }

        det_ww<-round(det(ww), digits=6)


        eig_vre<-round(Re(eigen(ww)$values), digits=6)
        eig_vim<-round(Im(eigen(ww)$values), digits=6)
```

```
          for (y in 1:dl) {if (eig_vre[y]<0) (num=num+1)}

          ##########A MINUS SIGN IS INSERTED DURING MATRIX INVERSION TO TAKE INTO
          ACCOUNT THE SIGN OF COEFF b=-dfi/dc  #########

          if ((num-dl)==0) {(nacc[k]=nacc[k]+1) & (inv_ww<-(-round(ginv(ww), digits=6))) & (vector<-
          as.vector(inv_ww))
                          for (m in 1:dl2)
                            {if (vector[m]>0) (n_plus[m]=n_plus[m]+1)
                                     else if (vector[m]<0) (n_min[m]=n_min[m]+1)
                                           else if (vector[m]==0) (n_o[m]=n_o[m]+1)}
                          }

          round(ginv(ww), digits=6)

          per_p<-round(matrix(c((n_plus*100)/nacc[k]), nrow=dl, byrow=T), digits=5)
          per_m<-round(matrix(c((n_min*100)/nacc[k]), nrow=dl, byrow=T), digits=5)
          per_o<-round(matrix(c((n_o*100)/nacc[k]), nrow=dl, byrow=T), digits=5)

          v_p<-as.vector(per_p)
          v_m<-as.vector(per_m)
          v_o<-as.vector(per_o)

          nacc[k+1]=nacc[k]


          ############################################

            }


          ntot=nacc[k]

OUT <- as.list(rep(NA,5))


OUT[[1]]<-ntot
OUT[[2]]<-k
OUT[[3]]<-per_p
OUT[[4]]<-per_m
OUT[[5]]<-per_o

print("n° ACCEPTED MOVES")
print(OUT[[1]])
print("n° loops")
print(OUT[[2]])
print(" (%) + ")
colnames(OUT[[3]])<-names
rownames(OUT[[3]])<-names
print(OUT[[3]])
print(" (%) - ")
colnames(OUT[[4]])<-names
rownames(OUT[[4]])<-names
print(OUT[[4]])
print(" (%) 0 ")
```

```
   colnames(OUT[[5]])<-names
   rownames(OUT[[5]])<-names
   print(OUT[[5]])

tab<-as.vector(h, mode="any")

   for (h in 1:dl2) {
      if (v_o[h]==100) (tab[h]<-0)
       else if (v_p[h]>=75) (tab[h]<-"+")
         else if (v_p[h]<=25 & v_p[h]>=0) (tab[h]<-"-")
                else if (abs(v_p[h]-v_m[h])<=20) (tab[h]<-"0*")
                 else if (25<v_p[h] & v_p[h]<40) (tab[h]<-"?-")
            else if (60<v_p[h] & v_p[h]<75) (tab[h]<-"?+")
                   }


tab_m<-matrix(c(tab), nrow=dl, byrow=T)
tabella_predizioni<-t(tab_m)

### insert as external#########
colnames(tabella_predizioni)<-names
rownames(tabella_predizioni)<-names

  print("tabella_predizioni")
  print.noquote(tabella_predizioni)


   }
```

Launch: >Loop(marcus)

Output is: community matrix, determinant, accepted moves (i.e. stable matrices), matrices of +, - and 0 sign and percentages for each predictions, table of predictions.