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Interactions between organizations and networks in common-pool resource governance

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ABSTRACT

Research on common property and renewable resources has come to be one of the more successful research programs on social–ecological systems. Much of this research has focused on how different kinds of institutions shape the incentives of users who rely on a common-pool resource system for a variety of their needs. In the process, this body of work has greatly advanced knowledge about how organizations and their rules for managing resources can be designed to improve sustainable resource governance. A significant puzzle that has occupied the scholarship on the commons concerns (1) the differences between formally designed and introduced institutions vs. self-organized informal network norms, and 2) the effects of these differences on resources and governance outcomes. This paper analyzes the different effects of informal norms and formal organizations and their rules through an agent-based model. We examine a model of villagers who choose levels of forest consumption based on the information they derive from social interactions with their neighbors (an informal network with two-way flow of information) and an organization that announces prescribed limits on forest product extraction. The paper investigates how changes in the relative dependence of users on information from formal rules vs. informal norms, and the structure of their social networks affect user behavior, harvesting levels, and forest-related outcomes.

1. Introduction

Institutions of different kinds play a particularly important role in influencing local resource use and outcomes for renewable resources such as forests, pastures, irrigation and drinking water and coastal fisheries (Dietz et al., 2003; Ostrom, 1990). The literature on common-pool resources – one of the more successful research programs at the intersection of the social and ecological sciences – has focused on understanding how institutions can be designed to improve sustainable resource governance, the relationship of resource users to each other, and institutional processes themselves (Berkes, 1989; Chhatre and Agrawal, 2008). However, this

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literature rarely examines interactions of formal governance arrangements that often have a material manifestation in the form of written rules, organizational form, and hierarchical decision making with less formal social networks.

The importance of social networks, defined as groups of actors linked by repeated interactions allowing information and resource sharing, competition, and cooperation over time (Rausch, 2001; Newman et al., 2002; Granovetter, 1973), has been broadly recognized in the work on development and natural resource governance. Research efforts in this area have shown that consolidation of social networks can build social as well as ecosystem resilience in the face of environmental change (Tompkins and Adger 2004); that a combination of strong local ties and weak long-range ties are necessary to both exploit and explore ideas and innovations associated with resource use (Newman and Dale, 2004); and that different network measures can provisionally be associated with a number of desired social outcomes related to the adaptive governance of renewable natural resources (Bodin et al., 2006; Janssen et al., 2006).

The understanding of the effects of social networks on resource use, management, and governance can be improved by placing resource users and their behaviors within the context of social networks and their interactions with formal organizations. Such an understanding is certainly theoretically important (Guha-Khasnobus et al., 2006; Lewins, 2007). It is also practically relevant because national governments in much of the developing world recognize formal community-level use and governance rights over forests, fish stocks, and other natural resources. In many resource-dependent communities existing informal networks and related social interactions around resource use are now often supplemented with new organizations created by governments as they decentralize resource-use policies, and resource management must be in compliance with the new rules created by these organizations.

Interactions between formal organizational rules and informal norms for resource use based on social interactions, as indicated by variations in signaling, enforcement mechanisms, network structures, the flow of information, and user preferences, raise an important question for theories and practices of natural resource governance: How are user behaviors and resource outcomes affected by governance rules imposed by formal resource governance organizations (referred to henceforth as ‘‘organizations’’) and resource use norms as generated through informal social interactions (referred to as ‘‘social networks’’)? We address this question by examining four related puzzles in an agent-based computational modeling environment – two related to the characteristics of the agents that depend on the resource, and two focused on the nature of network relationships in the group. Specifically, the paper uses a computational model to examine: (a) How do differences in household-level propensity to follow organizational rules vs. norms emerging from informal network interactions affect resource consumption and stocks? (b) How do changes in ratios of users with different characteristics – high vs. low consumers – in a community affect resource outcomes, (c) How do different social network structures affect resource outcomes? and (d) How do changes in the proportion of rule followers in a given population affect outcomes?

A conceptual representation of the interactions among resource users, organizations, social networks, and resource outcomes illustrates that information flows along different pathways and in different directions for organizations vs. networks in our model (Fig. 1). Organizations monitor the state of the resource and results of prior aggregate behavior for the community, and make decisions about levels of resource extraction based on monitoring information. These decisions are made more infrequently than the resource-use decisions by individual actors. These differences in time-scale represent hypothesized differences in changes in user behaviors in response to changes in organizational rules, and can produce lags in the system that can increase the risk that individuals will exhaust common pool resources through their collective actions. In contrast to aggregate level assessments by formal organizations, information flow through social networks is more localized, and utilizes higher frequency individual interactions that consist of observations of behaviors and actions carried out by socially and spatially contiguous constituents.

We use an agent-based modeling approach to represent the actors who make resource-use and consumption choices as virtual agents (Rounsevell et al., 2012). These choices are based on different individual preferences and the information individuals derive from (a) *rules* enforced by a formal organization to limit firewood extraction and (b) *norms* of resource use that are based on observations of other households' extraction behavior. Household extraction behavior is determined by rules and social interactions among networks of neighbors. We then focus on the relationships between organizations and social networks in a series of resource use and management computational experiments to observe how agent choices shape resource-use behavior and contribute to improvements or degradations in collectively owned common-pool resources. We nominally situate the actions of

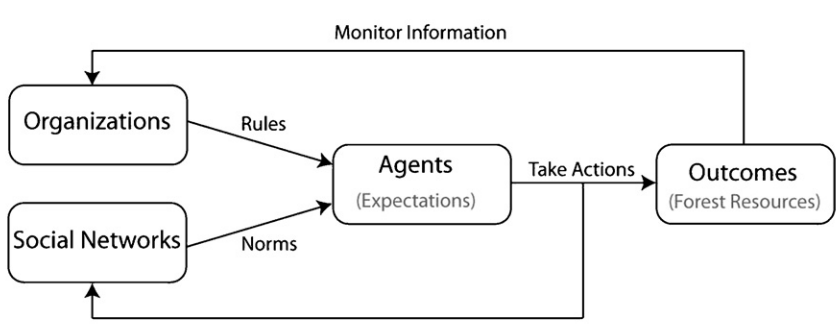

Fig. 1 – Conceptual model of the flow of information between organizations, individual agents, and social networks.

agents in the context of forest use behavior in rural areas because such situations are well-known important examples of a common-pool resource (e.g. Pretty, 2003). We draw upon the existing empirical literature and use our field research based knowledge of communally used forests in the mountainous areas of northern India to identify the parameters and ranges of parameters for variables used in the model and to motivate the model (SI text, Agrawal and Chhatre, 2006). Where there is little empirical evidence, as for example about the relative weights placed by agents on consumption vs. leisure, we explore their effects in the model by varying the weight placed on rule adherence for different agents. However, the selection of forests or northern India as the context is not critical to our results.

2. Methods

Our model has three components: two types of agents that represent the key actors (households and formal organizations) and the resource being utilized (the forest). We model agent behaviors and resource changes over time using discrete monthly time steps. Our focus is on the decisions households make: in particular, at each step, households must decide how much resource to extract. The resource being extracted is firewood, which is obtained from local forests and constitutes the primary energy used for cooking in India (ABE, 1985; Bhatt and Sachan, 2004).

2.1. *Household agent decisions*

Households act as unitary agents, and their decision making is represented using a bounded rationality approach (Simon, 1982). Household agents decide how much wood to extract from the forest at each time step. A household's preferences over how much to extract, x, are represented by the following utility function:

$$U(x) = C(x)^{\alpha_C} \times L(x)^{\alpha_L} \times A(x)^{\alpha_A} \quad (1)$$

where $C(x)$ is utility from consumption of the extracted firewood, $L(x)$ is the utility from "leisure" (i.e., from time not spent gathering firewood) and $A(x)$ is utility from adhering to institutional rules or community norms regarding firewood extraction (which affect the sustainability of the common forest shared by the community). The α's (each in [0,1] and summing to 1) represent the household's relative preferences for the three components, and thus can vary across households. Details on the form of C, L, A, and the parameter values we used are given in the supplemental text. In short: utility from consuming firewood, $C(x)$, increases with x, but with diminishing returns as x approaches a value that depends on household size. $L(x)$ varies inversely with x, since more time gathering amount x means less time for leisure; $L(x)$ also depends on the state of the forest – less wood in the forest means more time required to collect firewood (see supplementary material). $A(x)$ is a weighted function of two factors that represent the relative importance the agent places on adhering to organizational rules or network norms:

$$A(x) = r \times R(x) + (1 - r) \times N(x), \quad 0 \le r \le 1 \quad (2)$$

where $R(x)$ is 0 at or above the level of consumption prescribed for that household by the formal organization's rules (aimed at maintaining a sustainable forest) and $R(x)$ increases to the extent the household's extraction level x is less than that level. $N(x)$ is maximal (1) when the household's extraction level x matches the level of extraction suggested by network norms, as indicated by the average extraction level of the household's neighbors (spatial or social—see below) during the previous time step; $N(x)$ decreases as x deviates (higher or lower) from that norm. The weighting factor r, which can vary across households, determines the degree to which a particular household places more importance on adhering to organizational rules (larger r) or on network norms (smaller r).

To initialize household agent extraction levels a burn-in period is performed, whereby each household agent selects 10 candidate levels of extraction,[1] from a uniform distribution, and chooses the level x^* that maximizes the household's utility. After the burn-in period, which lasts 20 time steps, candidate extraction levels at each subsequent time step are drawn from a normal distribution centered on the extraction level the household chose in the prior time step and a variance provided by the model user (our reported results use the value 0.02).[2] The household then extracts the amount x^* from the forest.

2.2. *Norms, household interactions, and social networks*

Household agents assess (and create) norms around resource use and extraction by interacting with agents in their social networks. In rural areas, a household's social network often reflects interactions with spatially proximate households. In our model households are embedded in a 2D grid, one household per cell, such that a household's social network includes its Moore-neighbor households. Depending on their position in the middle, edge, or corner of the bounded 2D grid, agents have 8, 5, or 3 adjacent neighbors. Households also may interact with more distant households, as a result of various social relationships (e.g., family ties, friendships, etc.). In order to study the effects of different social network structures resulting from varying combinations of adjacent and distant "neighbors," our model includes a parameter, p, which controls the fraction of non-adjacent neighbors in each household's social interaction network. Thus, p represents the level of social mixing: after a household h is placed in the 2D grid and its social network is set to be the list of its Moore neighbors, each neighbor i on that list has probability p of being replaced with a household j randomly selected from the community at large (other than the agent itself). Once created, the social networks remain fixed for the model run.

[1] We evaluated the effects of selection frequency on model outcomes by varying the number of candidate extraction levels sampled from 5 to 20. Agents selected the extraction level that provided the highest utility. Varying the number of sampled levels from 5 to 20 did not make a qualitative different in the reported result. Selecting from substantially higher number of sampled extraction levels (e.g. 100 or 200) is akin to representing fully rational, optimizing agents.

[2] In other experiments, the candidate extraction levels were chosen from a uniform distribution over the allowed range for x; results were qualitatively similar and are therefore not reported.

In our model each household agent uses its social network, one way of representing the social capital of agents and their neighbors, to assess the community norm regarding extraction levels. In particular, each step the agent computes the average extraction level (from the previous step) of the other agents in its network. That average is taken as the extraction level the agent prefers to match when calculating utility $N(x)$ as described for Eq. (2), above. Thus the dissemination of information among household agents provides an indication to each agent of how much resource other agents are using (in Eqs. (1) and (2)).

Note that when $p = 0$ the interaction network of each agent is its adjacent neighbors, so that clustering is high (many of the neighbors of h are also each other's neighbors) and the average path length (following the agents' links to their neighbors) through the community is long. At the other extreme, when $p = 1$, each agent has a social network based on neighbors drawn randomly from the community, so that there are very few or no clusters but path lengths between any two agents are typically short. At moderately low p values, the social network has ''small world'' properties (Watts and Strogatz, 1998), i.e., there are clusters and the average path lengths are short. By varying p across experiments, we alter agent interaction patterns and information flows, and explore how social network structures and information dynamics affect the spread and stability of norms and agent behavior.

2.3. *The organization agent*

The organization agent manages the forest resources. It determines the sustainable per-capita harvest for a given time period by dividing the total new growth of the wood in the forest during the previous time period by the population size and weighting it for each household based on household size and estimated fuelwood requirements. To ensure a match between primary productivity and available biomass for use, it informs each household of its allowable extraction level for that time step. The household uses the information to calculate utilities for the extraction levels it is considering, as described above. The organization agent acts at the end of the burn-in period and then after every 12 time steps (i.e. 1 year).

Interactions between household and organization agents are unidirectional in that the organization agent sends each household a signal indicating the sustainable level of resource extraction based on its assessment of the forest. In contrast, the inter-household interactions can be bi-directional, and the signals sent reflect the level of resource extracted by the interacting households.

2.4. *Forest resource*

The forest resource is assumed to be a closed-canopy maturing mixed pine and oak forest. The model represents the resource aspatially as a total amount of biomass for the entire forest. We set the mean growth rate at 0.22% per month, which approximates the 2.7% average annual live-tree growth rate defined by the USFS (Birdsey, 1992). We introduce some variability around the mean (0.1% per month) to incorporate stochastic climatic conditions. Household agents use forest fodder and lop off branches for fuelwood. In a given time step, they can extract fuelwood until a specified minimum amount of forest biomass remains. Observations of above-ground biomass allocated to different tree components (e.g. stem, bark, branches, and foliage) vary widely (Jenkins et al., 2003). In our model, we divided the above-ground biomass value in half to estimate the amount found in branches.

In our simplified representation of forest growth, the average rate of forest renewal is based on rates of increase in tropical-mountain forests available in literature. The fraction of the initial forest resource remaining after some period of resource extraction is the primary outcome of interest in our analyses. We define sustainable extraction as the balance between annual forest production and the aggregate of all household-agent extraction levels. This metric provides the best indicator of forest sustainability generated through the interactions of household preferences and network structures, and the influences of rules, norms, and their interactions on household actions. Complexities and uncertainties around the average rate of renewal are represented as stochastic variation.

2.5. *Computational experiments*

We conducted four sets of computational experiments, each using the presented model with alternative parameter settings, to acquire insight on how user behaviors and resource outcomes are affected by governance rules imposed by formal resource governance organizations and network-based resource extraction norms. The experiments were designed to explore how resource outcomes in the model varied with (a) the relative weight agents place on adhering to rules and norms, (b) the proportion of the population with a high preference for consumption, (c) social network structure and (d) the proportion of the population with a high preference for adherence to rules. To account for stochastic processes within the model (e.g. network formation) within each experiment, the model was run thirty times and the average and variance of resource remaining were computed. Each individual model run lasted 600 time steps (i.e. 50 years) and comprised 625 household agents. Households varied in size, with an average size of 4.75. Households established social networks at the beginning of a model run and their structure remained stable throughout a given model run.

Social network literature focused on natural resource governance use a set of predefined terms to describe the network structure (e.g. density, centrality, reachability, and bonding and bridging; Bodin et al., 2006; Janssen et al., 2006). The networks we create have a constant density among all computational experiments. The centrality of any one network is dependent on random processes that may reassign network connections from spatially adjacent neighbors to spatially distant contacts. However, the average centrality among our experiments remains the same. We vary other structural aspects of the social networks represented in our model, which are described within each computational experiment below.

In each time step, the resource increases as a function of existing forest biomass, as described in Section 2.4. Then each household acquires information about previous extraction behavior from its social network to determine the current norm for extraction and combines this information with the prescribed sustainable extraction level, provided by the organization agent, to calculate utilities for candidate levels of extraction (as described in Eq. (1)). Each household then selects the extraction level that maximizes its utility. Note that household agents act asynchronously and in a different order each time step of the model. The forest remaining and other measures are recorded after all households had a chance to extract resource. Following every 12 time steps (1 year), the organization agent recalculates the sustainable extraction level and informs the household agents.

In Experiment 1 we showed how altering the weight agents placed on adherence to rules vs. norms affected the amount of forest remaining. Increasing the importance of rules in our model can be interpreted as an increasingly positive reputation of the organization among the population of agents, or increasingly strict enforcement or sanctions that make non-compliance more costly to agents. We set up a series of cases where the weight on rules (r in Eq. (2)) was varied from 0.0 (no attention to rules, complete attention to norms) to 1.0 (complete attention to rules, no attention to norms). For this experiment, agents were each given preference weights of $\alpha C = \alpha L = \alpha A = 0.33$ (Eq. (1)) and social networks consisted of their spatially adjacent neighbors ($p = 0$).

In the second experiment, we evaluated how households with a higher preference for consumption affected resource outcomes for a range of r (weight on adhering to institutional rules vs. weight on adhering to social norms $(1 - r)$). Households were divided into two groups: (1) households with equal preferences for consumption, leisure and adherence (equal α values) as in Experiment 1, and (2) a group of "high consumer" agents that weighted consumption twice as much as leisure and adherence to rules or norms ($\alpha C = 0.5$; $\alpha L = \alpha A = 0.25$). We varied the proportion of the population comprising high consumers from 0% to 100%, for the values of r used in Experiment 1. The 25×25 grid was divided into two sections with one sub-population on each side of a single shared boundary.

In Experiments 1 and 2, interaction among agents was constrained to the spatially adjacent neighbors of each household ($p = 0$). For this our third experiment, we replaced network connections to adjacent households with connections that extended beyond immediate neighbors as described earlier (i.e. increased p value). The objective was to examine how different social network structures affected the dissemination of information that formed informal norms that, along with institutional rules, influence aggregate firewood extraction behavior. We implemented this experiment by varying the parameter p from 0 (only adjacent neighbors) to 1 (only randomly selected neighbors). This experiment allowed us to examine the effects of changes in "reachability" in a spatially explicit environment – reachability is one measure of the ease with which one node in a network connects to another (Bodin et al., 2006).

In Experiments 1, 2 and 3 all households within a model run were given the same value for r, the weight placed on adhering to institutional rules (vs. the weight on norms, $1 - r$). In Experiment 4, we evaluated the degree to which a small number of agents with a high r were able to influence norms sufficiently to yield desirable resource outcomes. We created two groups of agents that each had a different value of r: (1) 'rule adherents' weight rules much higher than norms ($r = 0.9$); and (2) 'norm adherents' have the opposite weights ($r = 0.1$). We then varied the relative proportion of rule adherents (0–100%) and the network structure parameter (p, from 0 to 1). Allowing r and p to vary together enables us to examine the effect of varying levels of modularity in a network – With a low p, the effects of a given level of r in a subgroup do not get transmitted easily between subgroups; higher levels of p allow greater exchange of information between subgroups (Bodin et al., 2006). Like Experiment 1, household agents' preference weights were $\alpha C = \alpha L = \alpha A = 0.33$.

3. Results

3.1. Experiment 1

Altering the level of rule adherence (r) among agents in the different model runs resulted in a non-linear response of the amount of forest remaining (the 0% line in Fig. 2). At very low values of r much of the forest was consumed. However, at low to medium levels (i.e. 0.2–0.4) households dramatically altered their extraction behavior, leading to much higher levels of forest resource remaining.

3.2. Experiment 2

When we repeated Experiment 1 with a population of high-consumer agents (the 100% line in Fig. 2), we found that it took a much higher weight on rule adherence (r) over norms $(1 - r)$ to achieve nearly the same level of remaining forest. In addition, for this high consumer population the nonlinear response to r was damped both in the rate at which it altered system behavior and the amount of forest remaining. Including a mix of agents from the two subpopulations (i.e. agents with high vs. moderate preference for consumption)

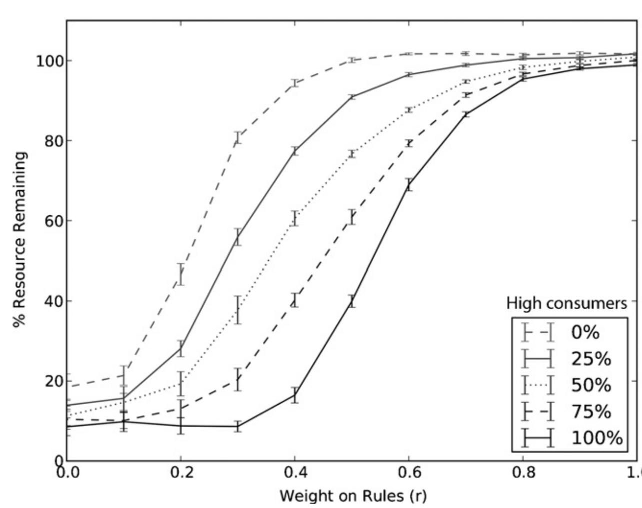

Fig. 2 – Results from Experiments 1 and 2 show the effect on forest remaining of changing the weight placed on rules and the relative number of agents with a high preference for consumption. Error bars represent 95% C.I.

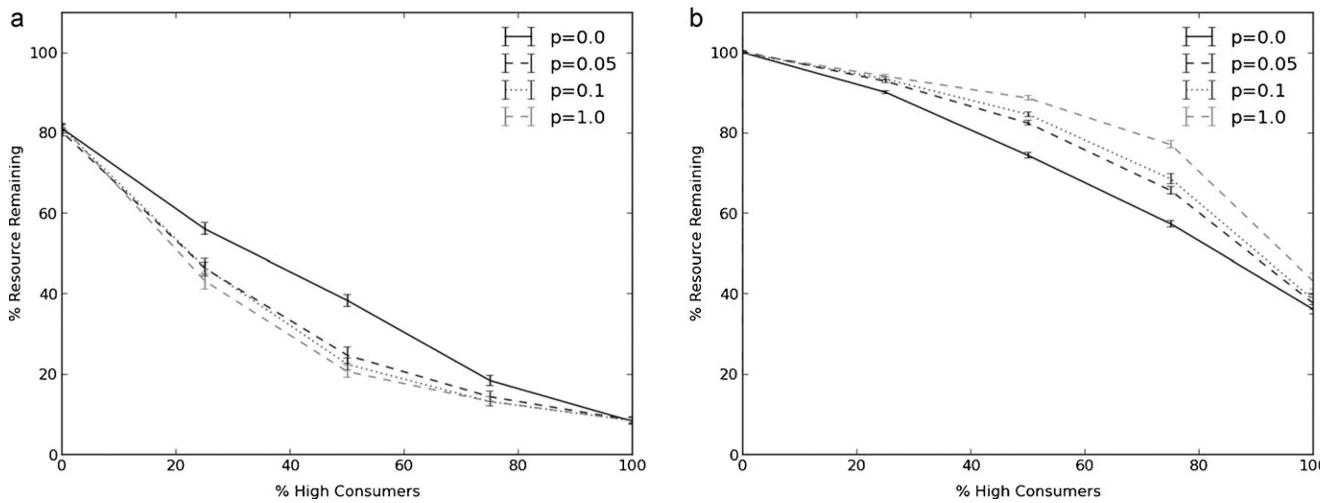

Fig. 3 – The effect of the relative number of high-consumer agents, different network structures (*p* value) and different weights on rules (a) *r* = 0.3 and (b) *r* = 0.5, on forest remaining. Error bars represent 95% confidence intervals.

produced similar, intermediate responses of forest remaining to varying levels of *r* (Fig. 2). For all proportions of agents preferring higher levels of consumption, low values of *r* resulted in the lowest levels of forest remaining. Increasing proportions of high-consumer agents decreased the amount of forest remaining at all levels of *r* and flattened the effect of *r* at lower values. As the proportion of agents with higher weight on consumption increased, agents must place more weight on rules (higher *r*) to realize improvements in forest resources.

3.3. *Experiment 3*

When $p \geq 0.05$, i.e., for social networks with even a few long range ties, and $r = 0.3$ forest resource remaining is reduced (relative to $p = 0$, no long-range mixing) for populations with intermediate (25–75%) proportions of high consumers (Fig. 3a). This suggests that even a small level of social mixing reduces the proportion of high-consumer agents required to create a high-consumption norm for the group. When $p \geq 0.05$ and $r = 0.5$, forest resource remaining is increased (relative to $p = 0$, no mixing) for populations with intermediate (25–75%) proportions of high consumers (Fig. 3b). This suggests that for agents that place more weight on adhering to institutional rules, a small amount of social mixing increases the proportion of high-consumer agents required to establish higher-consumption norms. Note that when the proportion of high-consumer agents was very low (≈0%) or very high (≈100%), the network structure had no effect on forest remaining. Similarly, when values of *r* were less than or equal to 0.2 or greater than 0.5 (not shown), the network structure had little effect.

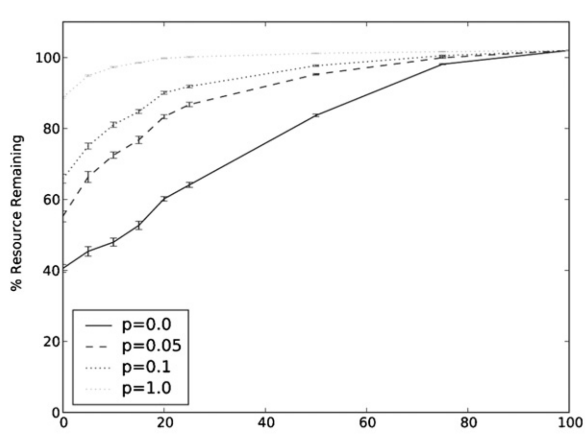

Fig. 4 – Results from Experiment 4 illustrate the effect on forest remaining of relative number of rule adherents (*r*) and network structure (*p*). Error bars represent 95% C.I.

3.4. *Experiment 4*

When we increased the proportion of rule adherents (high *r* in the population) the model produced a near-linear increase in forest remaining outcomes when agents social networks consisted only of adjacent households (Fig. 4, $p = 0$). As we altered the network parameter *p* from a highly clustered network ($p = 0$) to a randomly connected network ($p = 1$), the amount of forest remaining increased, for all proportions of rule adherents less than 100%. At non-zero levels of social mixing ($p > 0$), strong non-linearity in relative outcomes of forest remaining were evident. In particular, small numbers of rule adherents made large differences in forest outcomes when household networks had a small number of distant non-adjacent connections. The effect of additional rule adherents tapered off strikingly once their numbers got above 20% of households. These results were achieved despite rule adherents not having a special place in the network (such as a higher degree of connections). This is consistent with the explanation for the effect of social mixing advanced above, i.e., a small number of long range connections enables information to propagate rapidly across a population.

4. Discussion

Formal resource-management organizations have a number of mechanisms at their disposal through which they affect collective resource-use patterns, resource outcomes, and thereby, sustainability. These include communication of rules and their rationales and rule enforcement, sanctions, and adjudication. Because these management activities are carried out in the context of social interactions through social networks that generate norms for behavior, understanding the effects on resource outcomes of the choices an organization makes can be challenging. Although we cannot make claims about the magnitude of these effects in specific cases, our model reveals, qualitatively, the effects of household preferences, social interactions, and network norms on the effectiveness of an organization's management efforts.

The results of Experiment 1 suggest that when households in a community have homogenous preferences for adhering to the rules of an organization that seeks to maintain sustainable harvesting levels, the level of resource use decreases and remaining resource amount increases non-linearly with greater weight on adherence to organizational rules. This non-linearity is governed by the process of norm formation in the community. We modeled norm formation through households seeking to match the level of extraction of their neighbors. Low levels of preference for adhering to rules in our model can be interpreted as representing low levels of (a) confidence in the organization, (b) confidence in communications from the organization, (c) enforcement of organizational rules, or (d) sanctions for rule violations. In such cases, household decision making is influenced more by the behavior of neighbors and the utility households derive by balancing consumption and leisure.

Our results provide theoretical support for and refine the Tompkins and Adger (2004) finding that small modifications in behavioral norms can be instigated through group processes. We find that to be true, but only until a tipping point is reached – beyond this tipping point, extraction norms based on the behavior of neighbors are strongly influenced by the rules created by the organization, with a substantial influence on outcomes. One implication of this result is that common-pool resource-managers may wish to seek levels of investment in communication, enforcement, sanctions, and/or adjudication that are just sufficient to influence community norms and tip behavior. The "good news" is that, once there is sufficient interest in rule adherence to affect the process of norm formation, little additional effort may be required to achieve levels of resource use consistent with goals of improved management. A possible confounding factor is the degree to which agents' preferences may change in response to actions by organizations. For example, the imposition of rules and associated sanctions to reduce extraction levels can have the side-effect that agents increase the weight they put on self-interest (Cardenas et al., 2000; Bowles, 2008).

Our initial experiment was predicated on two key assumptions. The first was a homogeneous population, in terms of the importance households place on various contributors to their utility (i.e., consumption, leisure, and adherence to rules or norms) and the relative importance of adherence to norms vs. rules. The second was that there were no long-range ties within the agents' social networks. In Experiment 2, we relaxed the first assumption to form two groups. The first group had equally balanced preferences for consumption, leisure, and adherence to sustainability rules and the second group had a greater preference for consumption. We found that as the number of agents with high consumption preferences increased, the effectiveness of organizational rules decreased (Fig. 2). The decreased effectiveness was evidenced by a decline in the amount of the resource remaining – for all but the highest levels of preference for adhering to rules vs. norms. Additionally, as preference for adherence to rules (r) was increased, a tipping point was crossed such that the amount of forest remaining as a function of r increased rapidly, reflecting a shift in extraction norms towards more sustainable behavior (Fig. 2). These results suggest that an understanding of the diversity and types of preferences in a community are necessary to effectively prescribe levels of sustainable resource extraction.

The results of Experiment 3 (on the importance of long-range ties in social networks) indicate that at moderate levels of rule adherence ($0.3 \leq r \leq 0.5$), the presence of long-range ties results in a non-linear relationship between the number of high-consumer households and the amount of forest remaining. At moderate levels of rule adherence, a small number of households with greater preference for consumption can produce a large decline (for $r = 0.3$ or 0.4) or improvement (for $r = 0.5$) in the forest outcome. These preferences likely have a greater influence on extraction norms based on observed behavior of neighbors because the structure of the social networks results in short path lengths between all agents. This effect of network structure enhances the sensitivity of the response of resource outcomes.

The results of Experiment 2 indicate that a small group of households with a preference for high consumption can strongly influence norms and thereby reduce the effectiveness of efforts to reduce resource consumption. The results of Experiment 4 show how a small group of households, with a strong interest in adhering to the organizational rules can have a strong positive influence on community members' behavior. Our results indicate that (a) as the number of rule adherents increases the amount of resource remaining also increases and (b) as the social network includes more long-range ties, a smaller number of rule adherents are needed to reduce extraction levels and achieve a high-level of resource remaining. Although a formal institution may have little influence on the structure of the social network itself, these results suggest that resource-management organizations may be able to use norm formation processes to enhance rule effectiveness. The most obvious way to do so would be to focus on rule adherence by a fraction of the community rather than all community members. Such commitments might be secured through greater participation in the organization within the community. In any case, these results suggest that knowing the structure of the social networks in a community is crucial to design effective resource governance institutions, and in consequence, for sustainable resource management.

5. Conclusion

In contrast to many studies of institutions and resource management that focus on specific organizational forms, this paper initiates an analysis of interactions between two major institutional forms that affect communal resource governance

– those related to organizations and social networks. The paper finds considerable evidence for important interaction effects between networks and organizations. The nature of these effects depends on the strength of agent preferences to sustain resources and the structure of the network as reflected in the length over which agents can form ties. As the proportion of non-local social ties increases, there is stronger evidence for non-linear effects and tipping points with small changes in the proportion of agents who have strong preferences for high levels of consumption, or conversely agents with a strong preference for following organizational rules.

The relationships shown in Fig. 1 and described by our results illustrate that organizations shape outcomes by structuring formal rules. The prescriptions encoded in these rules can sometimes be in conflict with community level extraction norms that affect behavior. Faced with the choice of adhering to either rules or to norms, individuals choose among various combinations of the two by selecting a combination that yields high individual "utility," given their preferences for higher incomes or consumption, leisure, lower risks of sanctions imposed by organizations or social networks, and desire to contribute to sustainable use of the community's shared resources. Thus effective organizations achieve desirable outcomes by recognizing the existing preferences and social networks in a community, and using available mechanisms (e.g., prescriptive rules) to shape incentives such that desired aggregate behavior – sustainable resource use – can be achieved by influencing the actions of a subset of the overall user group. Over time, resource extraction norms among users may shift towards behaviors that contribute to more sustainable outcomes.

Our paper focuses on how resource outcomes change when we vary agent preferences, network structure, ratio of high to low consumers, and ratio of users with a propensity to follow rules. These changes produce substantial differences in outcomes. Our model results are based on the behaviors of virtual agents: as such, they are useful to the extent they allow investigators to test the effects of specific variables and their interactions in a precise and systematic manner. They are analogous to results of laboratory or field experiments, with the difference that computational simulations do not incorporate the human element inherent even in laboratory experiments with human subjects.

Our results are likely to be of interest to other researchers and scholars interested in using and operationalizing agent-based models to understand the behavior of resource dependent households, and to policy makers interested in understanding how formal rules are likely to interact with and structure the norms that shape resource use related behaviors.

Future research needs to explore and highlight how and under what conditions these factors change dynamically – both as a function of changes in resource availability and characteristics, but also as a result of social processes and interactions. For example, propensity for rule adherence among household agents (*r*) can be determined endogenously by modeling it as a function of available resources, expectations about future resource availability, organizational legitimacy, and efficiency of monitoring and sanctions. Although field-based evidence on these factors continues to be limited, such modeling refinements will allow analysts to explore more fully how agent behavior affects organizational level rule changes and within-group norm changes. Our paper thus identifies future directions for both empirical and modeling work.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2012.08.004.

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