Executive Summary

A fundamental challenge in natural resource management is how to address the natural complexity of resource problems, which typically involve complex interactions along both ecological and social dimensions. Work within a single discipline is already complex, but integration across disciplines is even more so, because many more factors have to be taken into account, and disciplinary approaches are not necessarily compatible. The importance of capturing space-time dimensions adds to the computational complexity of the analysis. The dynamic interaction of human and animal system elements may be contingent on past experience, especially when agents learn or adapt from those experiences. Furthermore, the interaction of agents with each other and their environment is dependent on local conditions, which vary across space. Capturing and analyzing the resulting non-equilibrial and non-linear system dynamics often presents an intractable challenge for analytic mathematical models.

Agent-based computational simulation models offer potential for studying complex systems involving human-environment interactions. Key features of agent-based models include: heterogeneity of agents, decentralized specification of agent behaviors, explicit representation of space, localized agent interactions in space and time, bounded agent information, and non-equilibrial system dynamics which manifest as tipping points and large-scale patterns which emerge from decentralized local agent interactions (Epstein 2005). Furthermore, agents can be of any type and at any scale, allowing for models integrated across disciplines.

In this agent-based simulation, the ecological dynamics of a simple coral reef ecosystem are linked to the social dynamics of a recreational fisher community. Simulations capture the interaction and dynamic feedback between the two systems and how these affect fish stocks and fisher compliance under centralized and decentralized management approaches. The dynamics
are structured from the bottom up; simple individual rules of behavior based on available empirical data drive changes to the system in space and time.

The agent-based simulation models a simple coral reef recreational fishery in which human and animal agents interact with each other and their complex environment over stable ecological time. The simulation environment is scaled to a 1 km² study area consisting of an oceanic island and fringing reef with complex coral reef structure characterized by depth, rugosity and substrate type (coral, algae, sand/rubble) and inhabited by fish. The energetics and ecology of three trophic levels are modeled: photosynthetic turf algae grows; grazing herbivorous fish forage on algal patches while schooling and avoiding predation; and roaming piscivores hunt herbivores and patrol the reef edge. Fishers arrive at the reef daily ready to set gear and fish under various personal, environmental, regulatory and social constraints. The functional reef community serves as the environment in which to test questions of fisher behavior under centralized and decentralized management regimes.

The model serves to demonstrate how the microdynamics of individual behaviors can generate macrolevel patterns in model behavior. Specifically, simple individual behaviors give rise to the more complex ecological phenomena of fish schooling, carrying capacity, and population cycles, and the sociological phenomena of resource depletion, diffusion of knowledge and cooperation. All of these patterns emerge at the group level without any top-down command or control. Simple sets of individual-based rules alone generate the observed patterns of system behavior. Through exploration of alternative sets of individual behaviors, insight is gained into the range of expected system dynamics and unexpected emergent behavior.

A. Modeling fish populations from the bottom up

1. Herbivores

Herbivores interact with each other and the reef through size-class specific schooling and grazing behaviors that drive fish movement through the reefscape and govern growth and survival. The
goal is to determine what simple individual behavioral rules generate fish schooling, fish grazing and habitat preferences, while population densities are governed by reef carrying capacity.

The simple behaviors to align, cohere and separate result in age segregated groups of fish that move in aggregate across the reef, with schools coalescing and disintegrating, growing and shrinking. Herbivores opportunistically forage by grazing on algae in their path. The macrolevel pattern of schooling is generated by microlevel interactions – there is no leader among the fish or top-down commands determining the location of the school or its membership. Opportunistic foraging leads to individual fish growth following the von Bertalanffy growth model and using empirically determined growth parameters. Each fish is endowed with the same foraging ability, but encounters a unique set of habitat characteristics during its foraging experiences. The patchy food availability and the resulting differential foraging success result in differential growth and survival rates. The skewed and multi-modal population structures are emergent, since each population started from zero and each cohort of recruits displayed an approximately normal distribution of sizes upon arrival at the reef.

The stable population dynamic of algal-herbivore trophic interactions also emerges due to a collective of unique experiences. The heterogeneous distribution of herbivores across the landscape allows the algae to survive on some patches, while being grazed down on others. On average, this keeps algae standing crop well above 50% cover on algal cells, allowing the herbivore population to persist at carrying capacity. Populations under all recruitment scenarios arrive at approximately the same level of total daily consumption, suggesting that carrying capacity is governed by the availability of algal biomass for consumption. In contrast, when fish and algae are uniformly distributed in space, herbivore populations grow and graze down algae to unsustainable levels resulting in a population crash. Thus system level patterns in population persistence, growth and size-class structure are generated by the microscale spatial dynamics between the schooling fish and their habitat.
2. *Piscivores*

Piscivores interact with the reef and the herbivores as they patrol the reef edge and hunt their prey through size-class-specific hunting behaviors that drive fish movement through the reefscape and govern growth and reef residence time. Exploration of sets of alternative behaviors yielded insight into model conditions giving rise to dynamic equilibria versus boom/bust cycles among herbivore and piscivore populations. Not surprisingly, piscivore populations are unsustainable if hunting behaviors do not provide adequate opportunity to capture the daily ration of prey. However, increasing hunting opportunity in terms of daily hunt time and herbivore attack rate does not lead to commensurate increases in piscivore populations. In this model, piscivore abundance is limited through intraspecific competition for herbivores on the reef.

Piscivore density is important in structuring herbivore populations. At high arrival frequencies (high densities), piscivores quickly consumed most of the herbivore standing stock, leading to a dramatic predator-prey boom/bust cycle between herbivore recruitment events. With longer intervals between piscivore arrivals, the number of herbivores in mid-range size classes is larger. Apparently, reducing the intensity of piscivore introductions over time helps alleviate the bottleneck for juveniles, allowing many more to grow to adult sizes. The impact of predation is revealed in the altered herbivore population structure. The expected sigmoidal population growth curve is flattened in the early adult stages due to a dramatic reduction in the targeted size classes. Herbivore populations are not generally limited by algal resources in the presence of predation. However, occasionally predator-prey cycles become unlinked, allowing herbivore populations to grow to carrying capacity.

The analysis also reveals the complex nature of how individual-level localized behaviors drive the dynamics, especially among interdependent model parameters. With herbivores, emergent spatial variation in the local availability of algal resources to individual herbivores ultimately serves to mitigate herbivore over-consumption and population collapse. Similarly, success for predators and their prey varies by individual. Emergent spatial variation in predator-prey densities creates localized differences in piscivore hunting success that stabilize herbivore-
piscivore dynamics. A dynamic equilibrium occurs when piscivores meet their daily ration so as to maintain reef fidelity for weeks or months, while herbivores find refuge from predation through their juvenile stages in order to grow to adult size. For the individual, survival on the reef is a matter of being in the right place at the right time.

**B. Fisher compliance**

Expanded to include fishers and enforcement agents, the model further demonstrates how the microdynamics of individual behaviors can generate macrolevel patterns in model behavior. Specifically three new system patterns emerge: 1) the familiar resource depletion of an open fishery where there is no management, 2) the deterrent effect of enforcement agents arresting fishers who fish in a no-take area when there is fisher communication about arrests, and 3) the persistence of fisher coalitions for cooperative resource conservation even when they have the option to cheat. In each scenario, 50 recreational fishers in a community interact with each other and the physical and biological components of the reef by deciding when to go fishing, finding appropriate locations on the reef to set gear, and attempting to catch fish. Under various scenarios, the recreational fishers assess their level of enthusiasm, the sea conditions, risk and pay-off to decide when to fish. They arrive at the reef by boat and choose their fishing locations by identifying bottom characteristics and depth, and change locations as required to maximize catch based upon trial-and-error or peer-to-peer learning and memory of previous catch.

**1. Open Access**

In the open access fishery, fishing effort results in an immediate and dramatic decline in biomass of the targeted herbivore population. However, numerical abundance of herbivores is not obviously affected, oscillating around pre-fishing levels. Thus, patterns of growth-overfishing emerge over time, where larger fish are depleted and replaced with smaller fish. Increases in algal abundance show further evidence of the effect of “fishing down” herbivores. Although total daily catch in biomass declines rapidly over time, it does not manifest as a constant drop in catch-per-unit-effort (CPUE) across all fishers and all fishing days. Rather, the decline in catch is due to an increase in the number of zero-catch days – days during which all fishing trips yield
nothing. As was observed with piscivore success in capturing prey, fisher success is extremely variable, with orders of magnitude differences in total catch from day to day and among fishers. Because of the patchy nature of the schools of herbivores, once populations are depleted it becomes more difficult for the fishers to locate their catch, resulting in more frequent zero-catch days. But once a good location is found, their gear is still effective in capturing any targeted fish within range. The decline in target populations creates negative feedback on fishing effort by damping enthusiasm and the number of fishing trips to the reef, thereby regulating fishing effort. Notably, although the effect of declining enthusiasm with declining catch moderates the rate of fishing effort, the resulting fishing mortality still leads to ecological decline.

2. Centralized management

A management regime is introduced to protect the reef and control fishing with enforcement agents patrolling the reef making arrests for illegal fishing. The goal is to model the dynamics of fisher compliance under a top-down, centralized management regime and explore the conditions that lead to optimal and efficient enforcement of the rules (i.e., the greatest compliance with the least enforcement effort).

A fisher’s decision to fish illegally is determined by weighing his individual level of grievance against the centralized authority versus his individual evaluation of the net risk of being caught. Three system variables are explored for their effect on compliance: numbers of enforcement agents patrolling the reef, number of days jail time imposed as penalty for non-compliance, and size of a fisher’s group of acquaintances in the fisher community. At the spatial scale of this model, increasing the number of enforcement agents beyond two is not as effective in promoting compliance as increasing jail time, although any additional deterrent effect of increasing jail time beyond ten days is negligible. Considering system behavior generally, jail time appears to regulate the temporal cycle of recidivism among fishers prone to cheating (those with high grievance and/or low risk aversion), who cycle in and out of jail. The ratio of enforcement agents to fishers determines how quickly cheaters are caught, removed from the reef and penalized. Where fishers maintain larger groups of acquaintances with whom they communicate their experiences, greater numbers of fishers comply with regulations and fewer are jailed, with a
modest decrease in the number of cheaters. This emergent pattern results from variation in the accuracy of information on which fishers base their assessment of net risk: the larger the communication network, the better informed fishers are of the actual risk. With strict and consistent enforcement and effective penalties for non-compliance, centralized top-down management can help protect resources. More importantly, the cost burden of enforcement can be leveraged by enhancing communication (and in turn compliance) among fishers, especially if news of enforcement actions is made public. With enhanced communication among fishers, the shift in dominance from jailed fishers to abiding fishers shifts the burden of the management system and the strain on the resource. Having fewer fishers in jail conserves human resources and more fishers abiding conserves fishery resources.

3. Decentralized management

Under what conditions would fishers exercise restraint in harvesting common-pool resources even in the absence of top-down control by a governmental authority? To explore how fisher incentives to exploit the resource (i.e. to cheat) can be altered so that restraint (i.e. cooperation) is the fisher’s preferred choice, the model of the recreational fishery is adapted to an evolutionary Common Pool Resource (CPR) game where a fixed number of individuals have rights of access and removal of a natural resource from a common-resource pool. The payoff structure that fishers use to decide their behavior is linked to resource-stock dynamics, intensity of sanctions against cheaters and cost of sanctioning for cooperators (both proportional to the composition of the fisher community), and intangible incentives for belonging to the cooperator’s coalition. Cheaters fish to maximize their catch at all times and do not communicate, although their identity and actions are common knowledge in the community. The cooperators form a coalition, and collectively agree to limit catch, impose sanctions on cheaters, and share information about their best fishing spots only among themselves. Cooperators participate in the fishery only on a catch-and-release basis and thus their catch is discounted in the payoff calculation.

A series of theoretical diagrams showing the pay-offs for cheating or for cooperating at various levels of cooperation suggest that under the assumptions of this simulation, cheaters and
cooperators are not likely to co-exist. Two mutually exclusive equilibrial states seem possible, with the outcome predicted by the location of the tipping point along the horizontal axis, which measures the fraction of cooperators in the population (Figure 8.7). Thus, the starting ratio of cheaters and cooperators is critical, and incentives (material or non-material) that enhance the payoff for cooperating move the tipping point in favor of the optimal cooperator equilibrium. With starting ratio of 1) the cheat/cooperate strategies and 2) the catch discount rate (the cost of limiting catch) each varied across five levels, twenty-five unique simulation scenarios generate the payoff structures of the two fishing strategies.

Average daily catch per fisher is greater for the cooperator strategy with any ratio of cooperators-to-cheaters, and daily catch for everyone is higher when there are more cooperators. Cooperators enjoy a particular advantage in locating fish, because they can draw on the experiences of other coalition members, and because they release fish back to the reef to be caught another day. Although cheaters remember and return to their own favorite fishing locations, they quickly fish out that spot and then must rely on trial and error to find the next good location. Although catch is always greater among cooperators, payoff is not. Payoff is lower for cooperators than for cheaters when the catch discount rate is high and under low ratios of cooperation due to the high cost of sanctioning many cheaters. For cheaters, payoff drops with the sanctions imposed by a large coalition of cooperators, but cheaters also experience low payoffs with a small coalition of cooperators due to the corresponding effect of a large number of cheaters depleting the resource.

In the evolutionary dynamics of the game simulation, it is not the average experience that matters; rather, it is the success of the individual as compared to the average. In a dynamic world with heterogeneous players, strategic decisions made by individuals do not strictly follow pathways predicted by average expected payoffs. Individuals make decisions based on their own actual payoffs. The eventual outcome can be predicted by the starting ratios of cooperators to cheaters. So long as the payoff structure remains the same, the transition to equilibrium is inevitable and irreversible. Furthermore, the evolutionary dynamic is robust against small groups of contrarians who switch strategies together, so long as the ratio of cooperators to cheaters does not cross the tipping point. However, a strong coalition of cooperators can be overpowered by an influx of outsiders whose numbers tip the ratio in favor of cheating. A
decline in the intensity of sanctions or a rise in CPUE can change the payoff structure and break down a norm of restraint. If the fisher community identity is lost, cheaters can escape the cost of sanctions through increased anonymity, both by avoidance of physical sanctions and minimization of the psychological impact of peer disapproval. If technology aids in increasing CPUE, the increased payoff can outweigh the cost of any sanctioning.