

ANALYSIS

Human–ecosystem interactions: a dynamic integrated model

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Abstract

We develop an interactive simulation model that links ecological and economic systems, and explore the dynamics of harvest patterns as they simultaneously affect natural and human capital. Our models represent both single and multiple systems. The level of natural capital is influenced by interactions of (1) natural capital growth and (non-human influenced) depletion, (2) ecological fluctuations, (3) harvest rules, and (4) biological transfers from one ecological system to another. We focus first on isolated systems in which there are no biological transfers between units and humans rely for subsistence on the resource; thus both the economic and ecological portions of the system are relatively independent of other systems. In this case, the maximum sustainable harvest rate depends on the local carrying capacity, the stock growth rate, and fluctuations in such ecological variables as rainfall and temperature, which are ‘extrinsic’ to the stock–human harvest, but nonetheless affect stock levels. Next, we address spatially complex situations in which biological resources move from one spatial unit to others. In these models, the greater the potential movement of stocks across ecosystems, the more any particular human sub-system can increase its harvesting rate without danger of its own collapse — although at a cost to neighboring subsystems. © 1999 Elsevier Science B.V. All rights reserved.

1. Introduction

Managing human use of important ecosystem resources to be sustainable can clearly be problematic (McCay and Acheson, 1987; Ludwig et

al., 1993; Jansson et al., 1994). We mine ocean and coastal ecosystems to provide important biological resources — fish, whales, and lobsters, for example — yet these ecosystems remain particularly intractable for sustainable resource management. Both resource stocks and harvesters may cross boundaries; it is difficult-to-impossible to

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Framework for Ecosystem and Human System Linkages

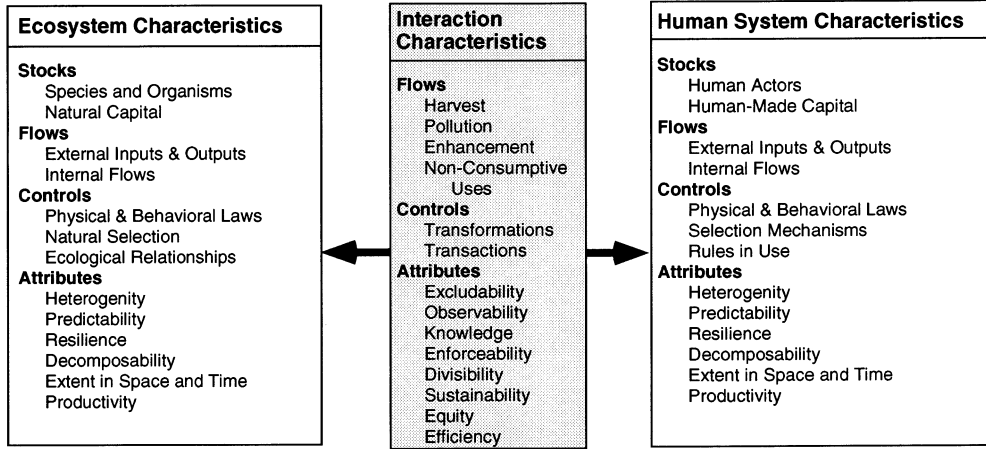


Fig. 1. Ecosystems and human social systems may be structured in parallel ways to facilitate analysis of interactions. Both systems have ‘stocks’ (resource stocks, human-made capital) that result from ‘flows’ (births, deaths, harvests of resource stocks; interests, taxes, and expenditures of human-made capital). ‘Controls’ (physical, behavioral, and legal laws) influence these flows. ‘Attributes’ of stocks and flows include predictability, resilience, efficiency, and extent in time and space.

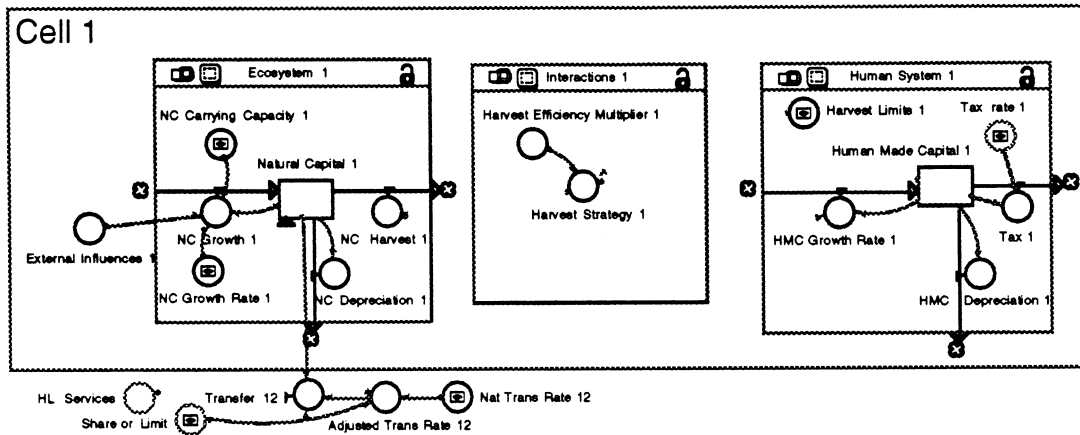


Fig. 2. A simplified model of an isolated ecosystem in which some resource stock is harvested by humans.

census many resource stocks accurately; numerous and varied actors have conflicts over resource use, and may find it difficult to agree on rules. Even when formal agreement exists, if actors exceed quotas, it can be extremely difficult both to monitor (because of physical scope) and to sanction (because agreements are frequently international and interests differ greatly). Many fisheries resources are common-pool resources, with all the

attendant difficulties in resource management (Ostrom et al., 1994).

Almost all scholars agree that sustainability is enhanced when human-designed rules are ‘well-tailored’ to the realities of the exploited resource. But what does that mean? Many factors contribute to the problem: carrying capacity, growth rate of populations over time, the extent to which an ecosystem is isolated or connected to adjacent

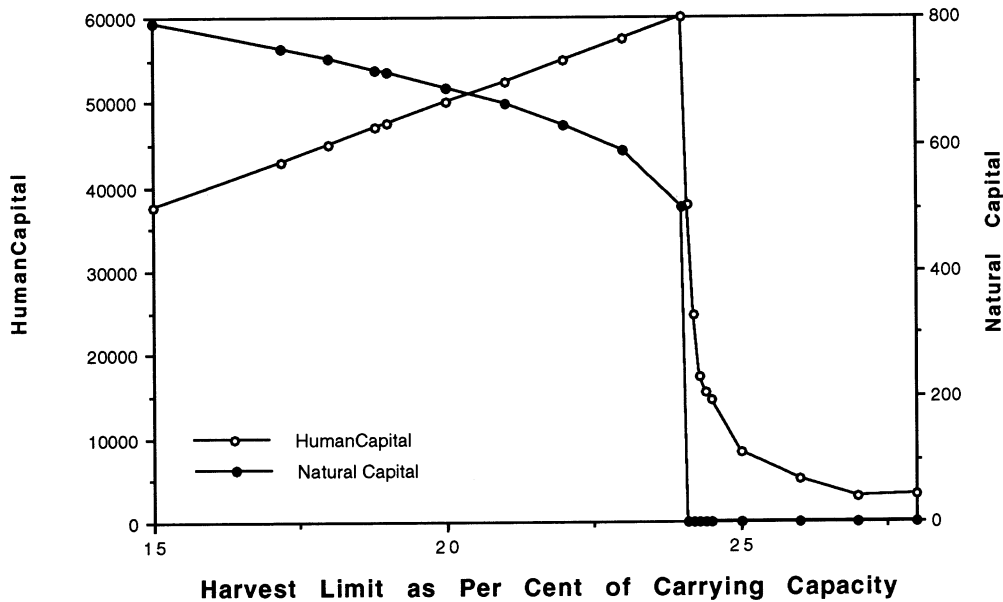


Fig. 3. Up to the sustainable harvest limit (here, 24% of carrying capacity), profit (human capital at the end of the 200-year simulation) increases as the harvest limit increases; the effect on natural capital is less dramatic. When sustainable limits are exceeded, the collapse in this model is relatively dramatic; there is little 'early warning' that sustainable limits are being approached.

ecosystems, and the impacts of ecological influences such as rainfall or temperature, to name only a few. The relationships among these variables are frequently non-linear. Interactions between human systems and ecosystems also vary along many dimensions — the wealth and power of users, their harvesting strategies, whether any rules exist to limit use of an ecosystem, and the impact of population growth on resource demand, among others.

Such complex, non-linear, interactive systems present challenges. Empirical tests are difficult because field data may not include all variables (particularly those considered external to the system). Thus, field studies of ecosystems may of necessity ignore important economic, social, and political variables; and studies of human institutions and decision-making systems frequently ignore important ecological variables. Yet if ecological and economic realities interact, both approaches will miss patterns, and make unreliable predictions.

Because ecosystems are complex, dynamic, and non-linear, no single model is appropriate to all

systems. Here we apply a flexible framework, within which we can construct diverse worlds by specifying five variables:

1. The carrying capacity of the resource system;
2. The regeneration rate at which the stock of a system can grow;
3. The natural mortality rate of the resource units;
4. The predictability of external influences on stock growth and mortality; and
5. The natural transfer rate from one spatial unit to another.

The resulting compartmental dynamic model of fisheries structures ecological and economic components in precisely parallel ways (Cleveland et al. 1996). It links human decision systems and ecosystems, measuring outcomes directly in each. Initially, the model is extremely simple; we establish its basic behavior as an isolated system, and analyze the interactions of harvest rates (maximum sustained yield rule), resource growth rate, and external stochastic fluctuations as they affect natural capital and fishermen's profit. We then model a three-unit system — like a series of

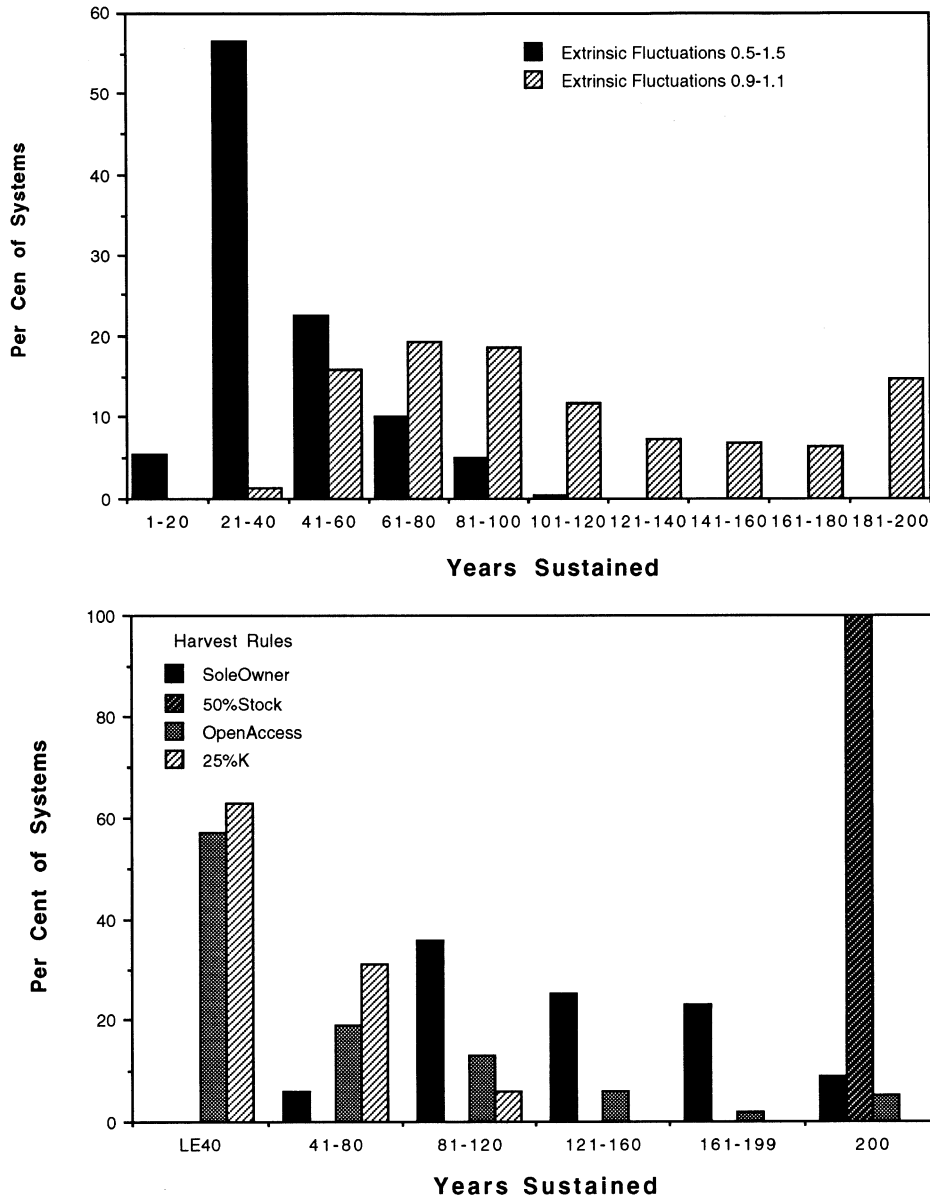


Fig. 4. (a) The sustainable harvest limit in any system will be influenced not only by the growth rate of the resource stock, but by fluctuations in the extrinsic ecological factors that influence the stock level (e.g. any fluctuation causing deaths or heightened recruitment of the stock). With a harvest limit of 24% of carrying capacity, sustainable if there are no extrinsic fluctuations, some systems fail. Failure is more frequent when extrinsic fluctuations are of greater magnitude (here, extrinsic factors affect the population causing fluctuations from 50 to 150%, average effect, 100%) than when fluctuations are more limited (90%–110%, average, 100%). (b) The four harvest rules tested are differentially vulnerable to extrinsic fluctuations in stock populations of $\pm 50\%$: ‘per cent stock’ and ‘sole owner’ systems proved more robust than ‘% carrying capacity’ and open access. Note, however, that complications such as mis-counts of stock populations and lags in effect of fluctuations are not included, so all systems here perform better than is likely in real-world systems.

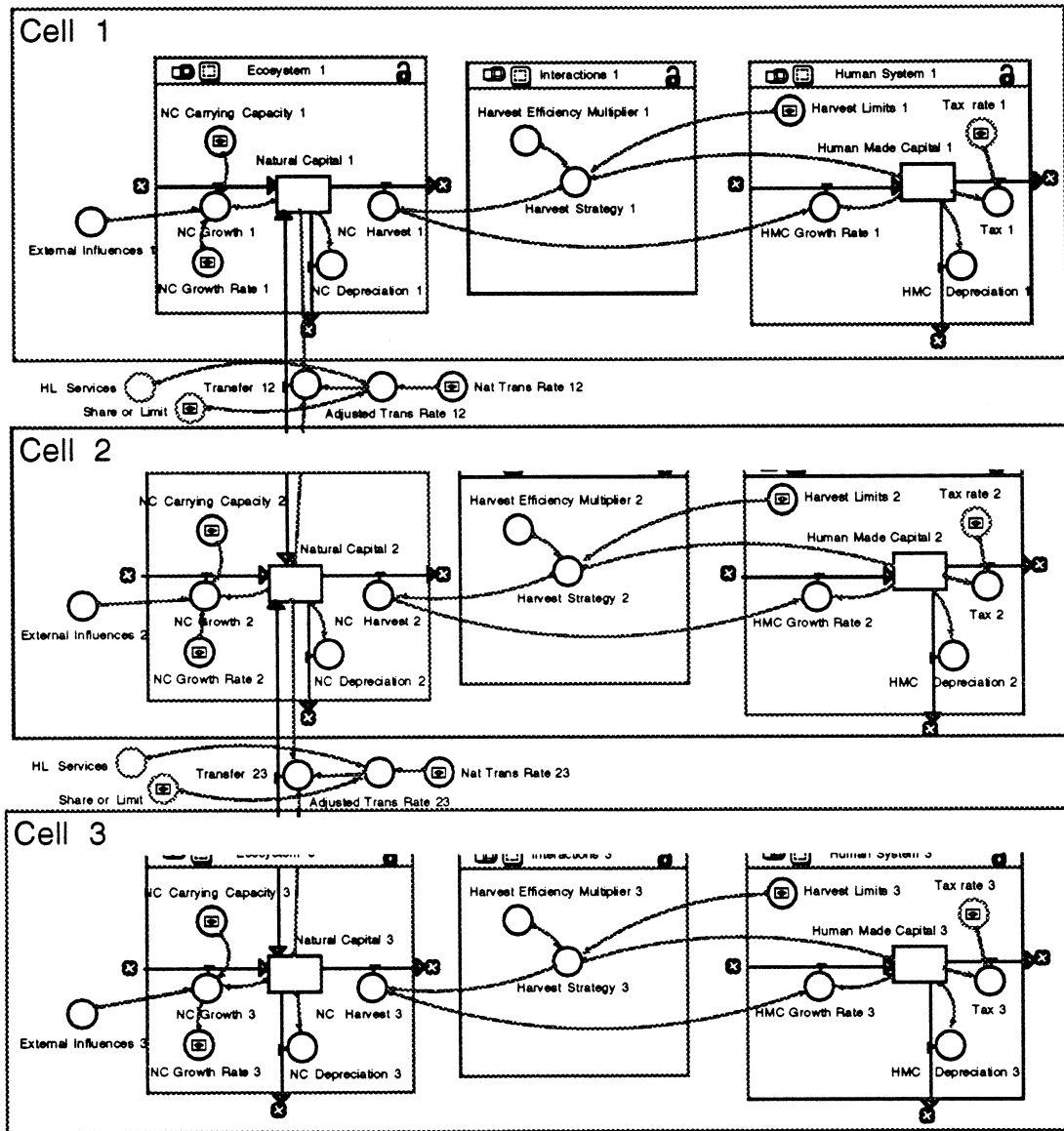


Fig. 5. When resource systems are not isolated, both resource stocks and resource users may move among systems. Here, movement of natural capital is shown.

coastal fisheries — in which the independent actions of fishers in any subsystem can affect the harvests of fishers in other units, and fish can move from one harvesting region to another. In this three-unit system we compare the robustness of additional harvest rules. Wilson et al. (1999) add reality to test effects in structured metapopulations versus large single populations.

We focus on how natural capital and human profit are affected by: carrying capacity; stock growth rate; range of variation in ‘extrinsic’ ecological variables such as rainfall and temperature (‘extrinsic’ to the stock-human harvest, but nonetheless affecting stock levels); harvest rules; and rates of movement of stocks such as fish across both ecosystem and political system

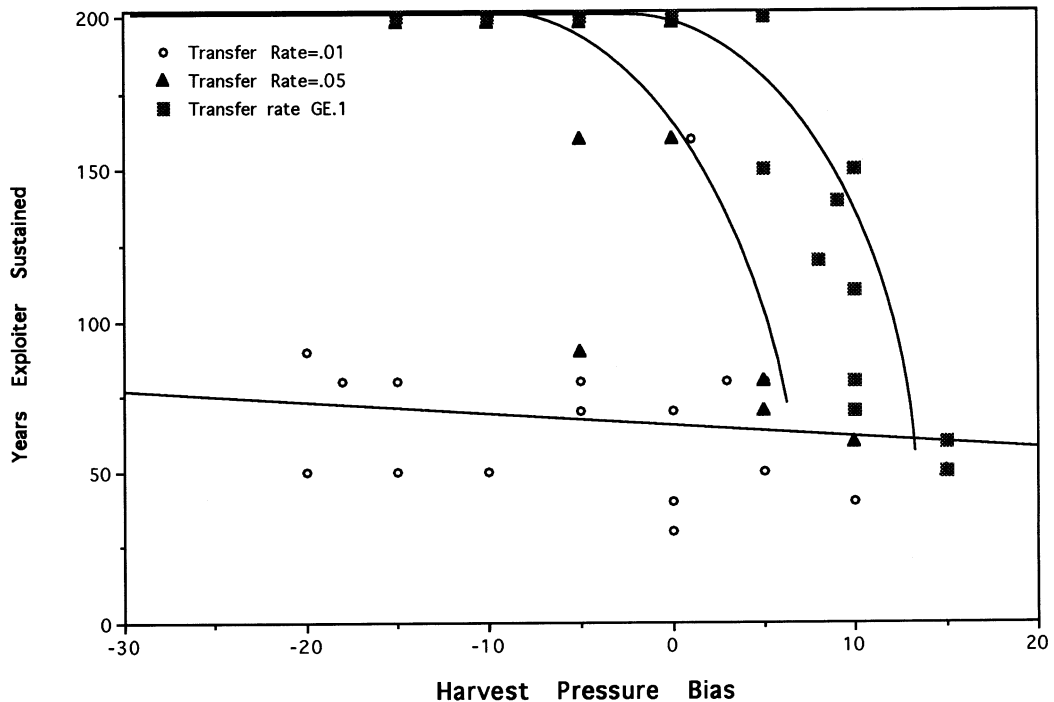


Fig. 6. Transfer rates of natural capital and harvesting rates of all units interact. Here, combined harvest rates are reflected by the 'harvest pressure bias' ($[\text{exploiter rate} - \text{MSY}_c] - [\text{MSY}_c - \text{conserver rate}]$). This number increases as all harvest rates increase in any system. When natural capital transfer rates are low, the failure of the highest-harvesting unit is relatively independent of the total harvesting bias, and 'exploiters' fail at approximately the same harvest levels as for isolated systems. At higher transfer rates, units that harvest heavily can be protected and persist throughout the run (200 years), up to some harvest bias (e.g. when other units harvest near the MSY, or the exploiter takes $\geq 26\%$ of the carrying capacity). This is shown by the flat portion of the high transfer rate curves.

boundaries. We examine the interactions of these as they affect the robustness of a system.

2. Structure of an ecosystem–human system model

Fig. 1 represents a general scheme of parallels between human and ecological systems, and the nature of their interactions (Cleveland et al., 1996). Both ecological and social systems have 'stocks,' 'flows,' and 'controls' of those flows. All stocks, flows, and controls have attributes (e.g. richness, predictability). The interaction sector, where human decisions affect resources in ecosystems, lacks stocks; it has flows, controls, and attributes.

'Stocks,' in both human and ecological sub-systems, are materials whose basic unit of measure does not involve time; they can accumulate or decline. In the ecosystem sector, stocks are natural capital of one of two broad types: (1) renewable (biotic) natural capital, and (2) non-renewable (abiotic) natural capital. Here we focus entirely on one renewable stock: the biomass of one species of fish. Additional complexities will arise when more than one species is modeled (Clark 1990; Hilborn and Walters 1992). In the human system, human-made capital (typically renewable), is the monetary stock upon which actors can draw. Human capital assets, including boats and fishing equipment as well as the knowledge and skills of the fishers, comprise additional stocks.

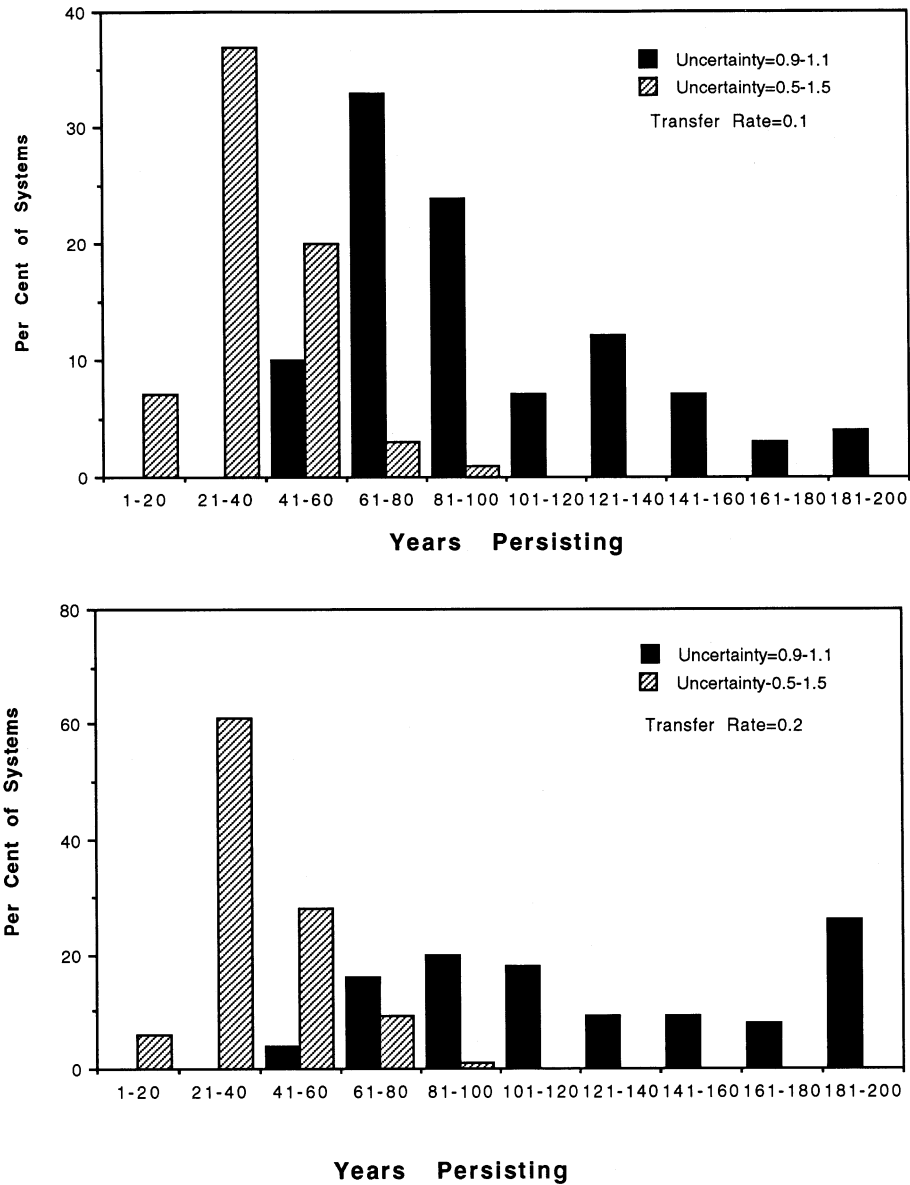


Fig. 7. The interactions of transfer rates, total harvest pressure bias, and extrinsic ecological uncertainties mean that high transfer rates alone cannot protect exploiters. In all cases here, the total harvest pressure is 720 (= 3 × 240, or the sustainable harvest as per cent of carrying capacity if all units acted identically); the exploiting unit takes 250, and the two conservative units each take 235. At both transfer rates (0.1 and 0.2), higher extrinsic fluctuations cause more failures of the exploiter. (a) When the transfer rate is 0.1 (10% of stock differential can move between units in a time period), > 30% of exploiters fail by year 40 (extrinsic fluctuations 0.5–1.5), or by year 80 (fluctuations 0.9–1.1), as opposed to persisting 150 years, the case if there were no extrinsic fluctuations. (b) The pattern is different for higher transfer rates (0.2): moderate (0.9–1.1) fluctuations and high transfer rates allow > 20% of exploiters to persist for the full 200-year run (as would be the case with no extrinsic fluctuations). However, in the face of both high fluctuations and high transfer rates, > 60% of exploiters fail by year 40 — and in contrast to low transfer rate conditions, these failures have also destroyed the neighboring conservative units.

All systems involve controls that regulate flows (Fig. 1). In ecosystems, physical and behavioral laws control many processes (e.g. temperature controls the speed at which many reactions can occur). Natural selection, the rules governing the existence and reproduction of all living things, interacts with physical laws to constrain the life histories and behavior of living components of ecosystems. Ecological relationships (competition, predator–prey, mutualism) result from the interaction of physical laws and natural selection, and further constrain the type of interactions possible in ecosystems. In human systems, controls include not only the same physical and behavioral laws that influence other species but also cultural rules (mores, laws). In the first model, the principal control in the human sector is simply the harvest rule; later, higher-order political controls will be added.

In interactions between humans and ecosystems, two controls, production and consumption, represent major transformations (physical changes of inputs into outputs). In addition, there are transactions: the transfers from one party to another, in exchange relationships, of rights to inputs, outputs, and assets. Harvesting rules affect both transformations (how much of the stock is removed) and transactions (who receives the distributions of benefits from productive activities). Here we focus on the effects of rules on transformations.

Attributes are the characteristics of stocks, flows, controls, and the relationships among these (Fig. 1). The number of attributes that potentially affect the capacity of human actors to manage resources sustainably is very large, including at least: heterogeneity, predictability, resilience, decomposability, range of variation, extremeness, extent in space and time, and productivity (Cleveland et al., 1996). All of these attributes can be measured in ecosystems as well. Here we concentrate on a limited number of attributes: range of variation (e.g. in ecological fluctuations affecting resources), and extremeness (of growth rates of stock), for example. Because this model includes human and ecosystems interactions, an additional set of attributes can be modeled in this framework: excludability, observability, enforceability,

divisibility, and sustainability (Ostrom et al., 1994). Here, we focus on sustainability.

3. A single-unit model

Using this framework, we construct as simple an initial model as possible while retaining the crucial aspects of these complex systems (Fig. 2). We use STELLA, a dynamic programming software (Hannon and Ruth, 1994). This first model represents an isolated fishery, and (like our general framework) has three sectors: ecosystem, human system, and interactions.

3.1. Ecosystem

The ecosystem sector contains one state variable, labeled natural capital, that here represents the biomass of fish. Natural capital (NC) grows over time at a rate determined by the carrying capacity of the area, some intrinsic growth or recruitment rate (births, immigration of animal stocks), and a set of external influences. The growth of natural capital is represented by:

$$NC_{\text{growth}} = NC \times \text{ExtInfl} \times NC_{\text{growth rate}} [1 - NC/K] \quad (1)$$

This formulation reflects logistic stock growth (including ‘*r*,’ the intrinsic growth rate) as it is influenced by ‘*K*,’ the carrying capacity, and external influences (e.g. weather, rainfall, and natural disasters) that can influence this growth rate. We reflect the fact that stocks are reduced by harvesting, death, emigration, etc., by the natural capital depreciation rate. We represent human harvest separately from other natural capital depreciation, as harvest strategy, defined in the interactions sector (below), rather than the ecosystem sector.

The overall equation for natural capital is:

$$\begin{aligned} d(\text{NC})/dt \\ = NC_{\text{growth}} - NC_{\text{depreciation}} - \text{Transfer} - NC_{\text{harvest}} \end{aligned} \quad (2)$$

where $NC_{\text{depreciation}} = (NC_{\text{depreciation rate}}) * NC$. We set the initial value of natural capital at the start of the simulation to equal the long-term carrying capacity. The transfer value is only operative when multiple socio-ecosystems are connected. In

our initial analyses of a single system, transfer is zero.

The logistic growth curve for dynamic Eq. (2), with NC harvest and Transfer set to 0, produces the standard parabolic recruitment curve of most bioeconomic models (Hilborn and Walters 1992). Under these assumptions the actual carrying capacity is $x^* = K(1 - (D/Er))$, and the maximum sustained yield — the maximum value of the growth curve — is:

$$x_{msy} = (KrE/4)(1 - (D/Er))^2 \quad (3)$$

where K is the carrying capacity, r is the growth rate, D is the depreciation rate, and E is the external stochastic influences.

3.2. Human system

In the simplest model, the human system sector also has a single state variable, human made capital (HMC), representing the assets that humans are able to amass to carry out the harvest. Human-made capital fluctuates as a result of its growth rate (e.g. interest), depreciation, and in some cases, taxes (we do not model taxation in this set of models). Depreciation and taxes are set at a value by the researcher to represent particular environments of interest. Here, the growth rate of human capital is simply revenues minus costs, where revenue is (price per unit of NC) \times (amount of NC harvested) and cost is (cost per unit of HMC) \times (HMC used for harvesting). In these simulations, we set the (price/unit NC) = 10 and the (cost/unit HMC) = 500. As is true for biological stocks Eq. (2), the stock of human-made capital is a function of prior human-made capital, and the growth and depreciation rates for human-made capital:

$$dHMC/dt = HMC_{\text{growth}} - HMC_{\text{depreciation}} - \text{Tax} \quad (4)$$

3.3. Human–ecosystem interaction sector

The interaction sector has no state variables, but two-way flows between ecosystems and human systems. In this initial application we focus on two relationships: harvest efficiency and har-

vest strategy. We assume in these first models that the amount harvested is proportional to both the harvest factors (i.e. HMC) and the size of the resource population (NC). We call this proportionality factor the total efficiency (TE) and set it equal to 0.007 in these simulations. In later explorations, we will explore the effects of increased efficiency.

Thus the amount harvested in the absence of any externally imposed limits is $HMC \times NC \times TE$. We call the multiplier ($NC \times TE$) of HMC the Harvest Efficiency, HE. For resources for which there is no search problem (i.e. when harvest success is unrelated to resource abundance), we would use a constant HE, independent of NC.

Harvest rules can now be chosen. In these initial models we do not allow for harvests above harvest limits (there is no cheating). Four harvest rules are compared: ‘per cent carrying capacity’ (maximum sustained yield), per cent population, open access, and sole owner profit maximizer.

The ‘per cent carrying capacity’ harvest strategy rule sets the harvest limit, HL, at a constant percentage of the carrying capacity K . The harvest is then given by:

$$HS_1 = \min\{HMC \times HE, HL\} \quad (5)$$

Thus if the potential harvest, $HMC \times HE$, is less than the harvest limit, then the potential harvest is taken; otherwise, the harvest limit HL is taken.

In the ‘per cent population’ rule, harvest (HL) is simply a specified per cent of the current population of fish. This rule requires absolutely accurate censoring of the stock at the appropriate times to predict sustainable harvest (including effects of ‘lag’ related to seasonality of stock reproduction and growth, for example). In these simulations, harvesting 28.5% of the existing population maximized HMC under this rule.

In the ‘open access’ regime, each actor responds to his/her current revenues minus costs, and keeps harvesting so long as profit is non-negative; entry continues in this regime until total profits are zero. Actors do not behave as if they could predict a trend; they are short-term profit maximizers with no incentives for restraint.

Under the ‘sole owner profit maximizer’ rule, the sole owner controls access to natural capital

and harvests it at a rate that maximizes long-term profit. In these simulations, the sole owner's decisions are based on the 5-year trend (slope) of profits instead of the most recent profits, because delays in feedback from the biological sector can cause the most recent profit level to produce a false signal. A 5-year trend generates a slower response but tends to find the sustainable profit-maximizing harvest level more reliably. The time horizon for sole owner's decisions is thus longer than for fishers under the open access rule.

4. Rules and sustainability in a single-unit model

For convenience in the STELLA runs that follow, K is set to 1000; the initial value of natural capital is set to 10. We allow the system to run to a maximum of 200 periods (e.g. years), and unless otherwise specified, do 100 runs (equivalent to gathering empirical data on 100 fisheries for 200 years each). For such systems, we explore how:

1. Harvest limits influence the stock levels of natural and human-made capital. When the system is not sustained (where 'sustained' is defined as having natural capital in excess of 20 units at the end of a 200-year run), we track the number of years until collapse of the system.
2. The growth rate of natural capital influences the sustainability of different harvest limits.
3. (1) and (2) interact, and finally,
4. Stochastic fluctuations in extrinsic ecological influences affect the resource stock (and thus sustainability). In all runs, fluctuations are randomly generated, so we explore the effects of range of variation, rather than temporal predictability.

In the first three analyses, we focus on deterministic relationships to explore the underlying curvilinear structure affecting long-term survival of the natural capital. We then model stochastic environmental fluctuations that affect growth of natural capital, mimicking the complexities of empirical data.

4.1. Harvest rules and stock growth rate in a single-unit deterministic model

Local, regional, or national authorities frequently impose an upper bound on the quantity of ecosystem flow, such as fish, that can legally be harvested during a defined time period. One type of harvesting rule assigns an upper limit on the quantity harvested based on a judgment made of the carrying capacity K of the ecosystem. We can see in Eq. (3) that if one assumes a constant harvest rate, the maximum sustainable yield (MSY) is the maximum reasonable harvest (as we note below, in actual practice, MSY is problematic). One computes easily that $x_{\text{msy}} = 0.2401K$ under our initial conditions of growth rate $r = 1$, death rate = 0.2, and no external perturbations ($E = 1$). For a series of growth rates (0.9–1.1), we varied the authorized harvesting rate from 15 to 30% of K . One can see in Eq. (3) that the maximum sustained yield is an increasing function of growth rate r : $\partial x_{\text{msy}} / \partial r = E \times K / 4(1 - (D/Er)^2) > 0$. That is, rapidly growing stocks can sustain heavier exploitation. In all systems, exceeding MSY caused the collapse of a system; the greater the excess, the more rapid was the collapse of the system.

4.2. Growth and harvest rates with ecological perturbations

The intrinsic growth rate of an exploited stock can have a great impact on the sustainability and effectiveness of management strategies. Extrinsic fluctuations (mimicked here by stochastic shifts affecting stock levels by $\pm 10\%$) also affect sustainability. In a series of runs tracking natural capital and human made capital in a single-unit system with stochastic perturbation, the strongest predictor of the amount of natural capital at the end of a run (200 years, or whenever natural capital was exhausted) was harvest limits (d.f. = 2.98, $r^2 = 0.63$, $P < 0.00001$), although the growth rate of natural capital was also highly significant ($P < 0.0001$). When human-made capital was the dependent variable (d.f. = 2.98, $r^2 = 0.27$), harvest limits were again most significant ($P < 0.00001$); the growth rate of natural capital, while signifi-

cant, contributed less to the model ($P < 0.032$). The strongest predictor of years until collapse of the system (d.f. = 2,98, $r^2 = 0.49$) was harvest limits ($P < 0.00001$), though growth rate of natural capital is more influential in this case than it was in predicting human capital ($P < 0.009$).

This analysis highlights some of the difficulties in using the concepts of K (carrying capacity) and MSY (Conrad and Clark 1987; Clark 1990). In real-world situations, using carrying capacity estimates to set harvest limits ignores information. Fig. 3 reflects an additional management problem. Up to the sustainable harvest limit, human capital increases in a linear fashion as the harvest limit is increased; the decline in natural capital (biomass of the resource) is less dramatic. Up to the point of collapse, there is a relatively great increase in human capital for a relatively small decrease in natural capital. This concern is further heightened by the fact that most resource users are able to measure the change in human capital (the accumulation of assets such as buildings, boats, harvesting equipment) more reliably than the change in natural capital.

When sustainable limits are exceeded even slightly, the collapse of both forms of capital is relatively dramatic. Thus, in this model, there is little 'early warning' that sustainable limits are being approached (Gulland, 1977). Nor is there any feedback that allows regulators to react to changes in stock size or growth. The pattern we uncover here may be related to the empirical observation that many resource-use systems fail relatively abruptly.

Unless we have chosen wildly inappropriate numbers, these results, combined with the information in Fig. 3, suggest precisely the sorts of difficulties actually encountered in the field. That is, high harvest limits, even when no cheaters exist, can build human capital at the expense of natural capital. Further, the level of human capital gives little prior warning of impending system collapse. In fact, since all human capital is plowed back into harvesting capacity in this set of runs, the growth of human capital accelerates the rate at which the system approaches collapse. If other opportunities existed for the use of human capital or if the investment in harvesting capacity were

sensitive to the state of natural capital, the probable collapse of the system might vary. We will explore these possibilities in future papers.

4.3. Harvest rules and stochastic extrinsic factors

In the real world, extrinsic ecological events affect the level of natural capital, and thus the outcomes of harvest rules, even in isolated systems. Consider Eq. (3): with our values of r and D , if no extrinsic fluctuations exist and the regeneration rate is held constant at 1, a harvest rate of 24% of carrying capacity generates the maximum sustained yield. This rule is not responsive to ecological fluctuations: stochastic extrinsic factors influence resource stock levels, and the probability of an ecosystem remaining active to year 200 is reduced in the face of environmental fluctuations (Fig. 4). When the rule was '24% of carrying capacity' and stochastic fluctuations occurred at $\pm 10\%$, approximately 15% of systems retained some natural capital by year 200; most survived up to 100 years (Fig. 4a). At $\pm 10\%$ stochastic fluctuations in stock, systems using more conservative rules uniformly persisted to 200 years. Wealth accumulation under stochastic fluctuations differed with harvest rule (maximum about \$500,000 per actor for sole owner and per cent stock rules; about \$22,000 for open access).

When extrinsic fluctuations were more severe, harvest rules were still differentially sensitive (Fig. 4b). With extrinsic fluctuations causing stock to fluctuate $\pm 50\%$, 57% of '24% carrying capacity' systems failed by 40 years; only eight systems (of 100) persisted beyond 120 years. No sole owner system failed within 40 years; 57% of sole-owner systems lasted more than 120 years, and nine of these were functioning at 200 years when the experimental runs were terminated. The rule '50% of stock' lasted to 200 years in all tests, reflecting the buffering effect of harvesting according to existing stock population levels. Note, however, that this rule still retains unrealistic assumptions. Among the principle assumptions are: that we fully understand and have captured in the model the essence of the population dynamics, that stock populations can be sampled and the data analyzed with absolute accuracy, that there are no

delays due to measurement, analysis or any other reason. These and other complications are introduced in later versions of the models.

5. Spatial heterogeneity

These results appear to be reasonably consistent with the expected behavior of a single exploited population. However, the ‘reasonable’ behavior explicitly assumes no significant interactions with other populations.

But populations are rarely isolated in this way. We now explore a series of coastal fisheries, in which the fish can move (‘transfer’) from one system to another along the coast (Fig. 5). Allowing harvesters to move across the limits of a system generates a similar transfer (Wilson et al., 1999). Maine lobster fisheries represent such complex conditions, and both political and biological difficulties arise from this fact. Although only older, mature (marketable) lobsters migrate, migration can create significant biological transfers when mature lobsters move across human boundaries, as from inshore waters where one set of local rules obtains, to offshore waters where different rules exist. Inshore Maine fishermen may only retain lobsters above a minimum, and below a maximum, size. They are required to return to the sea lobsters outside this range. The (local) conservation idea behind the rule is to maintain a size/age distribution in the wild population, to minimize the risk of recruitment failure. However, because animals at and above the maximum permissible size tend to migrate outside the area where the rule applies, boats from other areas (New Hampshire and Massachusetts) line up each fall at the Maine boundary to catch the migrating lobsters (Carl Wilson, personal communication).

This creates a variety of problems. It does not simply mean a more compressed size/age distribution in all areas (and thus greater risk of recruitment failure), but Maine fishermen see outside lobstermen as free riders and question the collective wisdom of their restraint — why should we restrain ourselves, for others to reap the benefits? At a larger scale, eliminating restraint for Maine fishermen would simply mean higher takes in all

areas — and likely overexploitation typical of open-access resources. Yet to ask Maine fishermen to restrain themselves so that outsiders can profit seems illogical. In this example, there is high biological transfer across governance units, local harvest rules, low or no higher-level control; that is, human rules and ecological realities do not appear to match.¹

5.1. Spatial representation of multiple ecosystems

Here we explore how, and at what levels, biological transfers between non-isolated systems affect situations such as the Maine lobster fishery; we reserve exploration of the governance rules for a later paper. Each of the spatially identifiable systems in Fig. 5 has three compartments: ecosystem, human system, and interactions (Sancho and Wilen, 1999, who have developed a remarkably parallel system independently). To represent three spatial areas, all equations for a unit model are appended with a suffix to indicate the appropriate unit. In the ecosystem portion of each spatial unit, initial values of variables such as natural capital, natural capital growth rate, and carrying capacity can be set independently, mimicking spatial ecological variation. Local ecological areas, then, can differ from one another in terms of the stock-carrying capacity and the incidence of ecological fluctuations. In the human systems of each model unit, decision rules (e.g. harvest limits, effort) can also vary.

The natural transfer of natural capital between units (T) is here assumed to be proportional to the biomass differential in the two units. If the natural transfer rate is 0, the three spatial units are ecologically isolated from each other, as in the single-unit analyses above. A transfer rate of 50% between adjacent units will equalize the stock population in the two units. The higher the natural transfer rate, the more biological transfer exists between adjacent units.

¹ As the reader might imagine, this situation has created political conflict between Maine fishermen and those from Massachusetts and New Hampshire. At the present time, it appears that the conflict will be resolved by applying the Maine inshore rules to offshore areas.

5.2. Questions explored

In this series of experimental runs, we ask the following questions:

1. In the absence of extrinsic ecological fluctuations, by how much can people in one unit exceed the ‘normal’ maximum sustained yield (here 24% of carrying capacity) if there is a small (e.g. 1%) level of biological transfer and other units have conservative harvesting rules?
2. When a moderate (here $\pm 10\%$) level of extrinsic fluctuations exists, how are these parameters shifted?

When no external ecological fluctuations exist, the amount that can be sustainably taken in any unit depends on the carrying capacity, the natural capital growth rate, and the transfer rate. If the transfer rate equalized all differences, then the sustainable total harvest pressure for a three-unit set of ecosystems, with the settings we have explored here, would be 24% of the initial carrying capacity for all three units (here, 24×3000). In such a case, the three systems would be totally interdependent with regard to harvest limits. Most systems, while not completely isolated, do not have full movement of stocks throughout all sub-systems. When this incomplete flow of stocks occurs, what any unit can take sustainably is a complex function of its own harvest, the harvests of other units, and the transfer rate.

What happens when the central unit of the three-unit system receives flows from the first and third units, and adopts a harvesting rate above 24% of the initial carrying capacity of the linked systems? In other words, what happens when the two outer units are conservative (take less than the amount determined to be locally sustainable) in their harvesting practices, while fishers in the central unit exploit their conservative strategies by harvesting at a rate that would not be independently sustainable? When the transfer rate is very low (e.g. 1%), any single unit will be unsustainable if its harvest rules exceed 24% by even a small percentage.

When transfer rates are higher and the harvest rules in neighboring ‘conserving’ units are low, a highly exploitative harvesting unit, one that harvests more than would be sustainable, receives

some protection from the combination of high transfer rates and low exploitation by its neighbors. But how conserving must other units be to sustain an over-exploiting unit? For very low transfer rates, an exploiting unit’s persistence was not related to harvest pressure bias (Fig. 6), but behaved as an isolated system. However, even at quite low rates of natural capital movement across systems, a complex interaction occurred among the transfer rate, the harvest rates of the exploiter and the conservators. To reflect this complexity, we constructed a ‘harvest pressure bias’ index:

$$\text{HPB} = ([\text{exploiter rate} - \text{MSY}_c] - [\text{MSY}_c - \text{conserver rate}]) \quad (6)$$

to represent the range of conservator-versus-exploiter harvest limits that will leave the entire system’s natural capital sustainable. In our runs, this measure ranged from -20 to $+15$, depending on the natural capital transfer rate. The effects of any level of harvest pressure bias differ, depending on the transfer rate of natural capital. For natural capital transfer rates as low as 5%, when the harvest pressure bias was low (-5 for 5% transfer rate; 5 for transfers rates ≥ 1), even quite high harvest rates could be sustained in a single unit — if the other units were sufficiently conservative. When the limits are exceeded, the time an exploiting unit can be sustained declines precipitously (Fig. 6).

Although a combination of high transfer rates and conservative neighbors could theoretically shield an exploitative unit, it is likely in most circumstances that people in conserving units will learn of the situation (as in the Maine lobster example above). If ‘conserving’ units respond by raising their harvests, the entire system collapses. Thus, a real problem exists in matching local and supra-local rules to the ecological realities of transfer rates, as well as to more obvious phenomena such as carrying capacity and intrinsic growth rate (not varied in this set of runs).

The combination of high transfer rates and conservative neighbors affords protection for exploiters in the absence of extrinsic unpredictable fluctuations — but almost all ecological systems are subject to extrinsic fluctuations, which have

the potential, at least, to interact with harvest limits and transfer rates. To explore these problems (Fig. 7), we modeled four conditions:

1. Transfer rate, 0.1; range of stochastic fluctuations, 0.9–1.1. (Stochastic extrinsic fluctuations *on average* have no effect on natural capital level, but in any one year randomly influence population numbers from 90 to 110%.) An ‘exploiter’ in such systems with no extrinsic fluctuations would persist 150 years.
2. Transfer rate, 0.1; range of stochastic fluctuations, 0.5–1.5. An exploiter in such systems with no extrinsic fluctuations would persist 150 years.
3. Transfer rate, 0.2, range of stochastic fluctuations, 0.9–1.1. An exploiter in such systems with no extrinsic fluctuations would persist 200 years.
4. Transfer rate, 0.2; range of stochastic fluctuations, 0.5–1.5. An exploiter in such systems with no extrinsic fluctuations would persist 200 years.

Fig. 7 shows that the presence of *any* fluctuations reduces the probable persistence of the exploiter — even when protected by conservative neighbors and a 10% natural capital transfer rate. The greater the range of unpredictable fluctuation, the more persistence is lowered (Fig. 7a). When fluctuations are moderate (0.9–1.1), a higher transfer rate affords greater protection to an exploiter with conservative neighbors. When transfer rates are higher, the non-linear interaction changes the response. With a 20% transfer rate, 28% of exploiters survive more than 180 years (Fig. 7b), versus only 4% (Fig. 7a) when the transfer rate is 0.1. At the low transfer rate, 33% of exploiters fail before year 80. Thus, in the face of moderate extrinsic fluctuations, high transfer rates and conservative neighbors can protect exploiters. In contrast, when both extrinsic fluctuations and transfer rates are high (Fig. 7b), the exploiter is likely to cause the entire system to crash relatively earlier; this is reflected in Fig. 7b by the fact that more than 60% of exploiters fail by year 40 under these conditions. Short-term gains by exploiters from exceeding ‘baseline’ sustainable harvest rates are reduced by external fluctuations as well as by (above) any response managers in nearby units might make.

6. Discussion and conclusions

These dynamic models are extremely simple, compared to many fisheries models. Nonetheless, their linking of human and ecosystems demonstrates that human resource–use systems interact non-linearly with ecosystem parameters.

The growth rate of natural capital interacts strongly with the harvest limits to affect the sustainability of systems. These variables are difficult to measure and frequently are only loosely incorporated in current efforts to manage resources sustainably. Further, some variables that are *rarely* measured and analyzed by natural resource managers have a major impact on the sustainability of ecosystems. Many models of sustainable yield are based on averages over a long time period, and information about the quantity of a stock removed is recorded. The degree of exogenous variation — here a strong influence on long-term sustainability — is rarely measured or taken into account in textbooks, yet its effect argues that variance, not simply the long-term mean, in resources should be considered.

The sustainable management of complex ecological economic systems can be a tricky thing indeed, especially when incentives to maximize short-term economic gain are strong, as is typical. Even the relatively simple models we show here demonstrate complex behaviors and subtle thresholds that are difficult to foresee. The real world is much less tractable; perhaps it is not surprising that many resource systems, even relatively isolated ones, have collapsed in recent years.

In isolated ecosystem models, the sustainability of stock depended on the harvesting rule as this interacted with the stock regeneration rate and extrinsic ecological fluctuations. In the second set of simulations, spatially discrete ecosystems were linked, and the possibility of free-rider behavior by some sub-unit managers was possible (as in the Maine fisheries example above). Even if outsiders can be excluded, if one fishery limits harvest in a conservative way, while another sets limits at or above sustainability, and fish can move between the fisheries, we have a spatially dispersed free-rider system, in which one fishery’s restraint simply subsidizes another fishery’s harvest.

With others, we have argued that many resource-management failures arise from problems of ‘scale mismatch’ between human rules and ecological realities (Cleveland et al., 1996). Modeling additional forms of spatial heterogeneity will allow us to explore the effects of match or mismatch between the scale of interrelationships in an ecosystem and the scale of decision making about the governance and management of that system (Wilson et al., 1999). Large-scale ecosystems are not simply small-scale systems writ large, nor are small ecosystems mere microcosms of large-scale systems. Thus, we suggest that management systems that produce perfectly acceptable outcomes in ecosystems at one level can produce disruptive or destructive results when applied to higher-level or lower-level systems. The importance of scale depends greatly upon the structure of both human systems and ecosystems, and the geographical range over which ecological interactions occur in that system. No wonder sustainable management of ocean fisheries is problematic!

When the scale of ecological interactions and human rules for their governance are appropriately matched, we suggest that governance systems can be responsive and appropriate; whether a local or larger-scale rule is appropriate depends on the scale at which the relevant interactions take place. For example, if small coastal villages, spatially isolated from each other, take fish from independent populations of fish, to what extent are higher-level rules helpful in creating sustainable use? In contrast, if, as in the lobster fisheries (above), certain age classes of lobster move across political boundaries, other problems arise. In future work we need to explore further what that means.

If one management goal is sustainability, then managers might consider some notion of invoking ‘safe minimum standards’ (Bishop, 1993) or the ‘precautionary principle’ (Low and Berlin, 1984; Costanza and Cornwell, 1992; Costanza et al., 1998) to ensure that harvest limits and other environmental thresholds are not exceeded. These are difficult to impose or get agreement on in most systems, because ‘safe’ levels may be difficult to determine, particularly when significant exogenous fluctuations exist. They are particularly

difficult in systems in which significant conflicts of interest exist among actors — most resource systems. Dynamic modeling may help us resolve some conflicts, in part by helping actors with opposing views appreciate the sensitivity and complexity of the system about which they are making decisions.

Acknowledgements

This is a report of the Social and Ecological System Linkages Project of the Property Rights and the Performance of Natural Resource Systems Workshop, The Beijer International Institute of Ecological Economics, The Royal Swedish Academy of Sciences <29–30 August 1994, and 28 May–3 June 1995, Stockholm, Sweden). We appreciate the support provided our project by the Beijer Institute and by the Workshop in Political Theory and Policy Analysis at Indiana University.

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