

Chapter 6

Complex Ecological-Economic Systems and Their Governance Issues



6.1 Introduction: Ostrom, Complexity, and Governance

The late Elinor Ostrom was the person who most clearly saw through the supposed dilemma called the “tragedy of the commons” (Hardin 1968; Ostrom 1990). It was widely argued that managing common property resources was an impossible proposition, that either common property is privatized in some way or else there will be an inevitable tendency for the resource to be overharvested, possibly to complete destruction or exhaustion. Such outcomes were seen as inevitable outcomes of prisoner dilemma games where agents using common property resources will fail to cooperate with one another and instead seek to get as much of the resource for themselves as soon as possible. However, she understood from early in her work (Ostrom 1976) that people seek to work out arrangements for managing common property resources. As she studied this phenomenon over time she came to realize that different groups pursue different solutions. This led her to pose the concept of polycentricity and the importance of institutional diversity around the world, based on local circumstances and cultures (Ostrom 2005, 2012).

Also over time she came to understand that the challenge of managing common property resources becomes more difficult when the governance system inevitably becomes part of a complex ecologic-economic system (Ostrom 2010a, b). Indeed, it is often the human intervention into a natural system that introduces the complexity in the system, the ecologic-economic system. This induced complexity makes those managing it that more responsible for what they do.

6.2 Complex Fishery Dynamics

The classic tragedy of the commons for fisheries was first posed by Gordon (1954), who incorrectly identified it as a problem of common property, while nevertheless identifying the inefficient overharvesting that can occur in an open access fishery. However, even when efficiently managed, fisheries may exhibit complex dynamics, particularly when discount rates are sufficiently high. Just as species can become extinct under optimal management when agents do not value future stocks of the species sufficiently, likewise in fisheries, as future stocks of fish are valued less and less, the management of the fishery can become to resemble an open access fishery. Indeed, in the limit, as the discount rate goes to infinity at which point the future is valued at zero, the management of the fishery converges on that of the open access case. But well before that limit is reached, complex dynamics of various sorts besides catastrophic collapses may emerge with greater than zero discount rates, such as chaotic dynamics.

We shall now lay out a general model based on intertemporal optimization to see how these outcomes can arise as discount rates vary, following Hommes and Barkley Rosser Jr (2001).¹ We shall start considering optimal steady states where the amount of fish harvesting equals the natural growth rate of the fish as given by the Schaeffer (1957) yield function.

$$h(x) = f(x) = rx(1 - x/k), \quad (6.1)$$

where the respective variables are the same as in Chap. 2: x is the biomass of the fish, h is harvest, $f(x)$ is the biological yield function, r is the natural rate of growth of the fish population without capacity constraints, and k is the carrying capacity of the fishery, the maximum amount of fish that can live in it in situation of no harvesting, which is also the long-run bionomic equilibrium of the fishery.

We more fully specify the human side of the system by introducing a catchability coefficient, q , along with effort, E , to give that the steady state harvest, Y , also is given by

$$h(x) = qEx = Y. \quad (6.2)$$

We continue to assume constant marginal cost, c , so that total cost, C is given by

$$C(E) = cE. \quad (6.3)$$

With p the price of fish, this leads to a rent, R , that is

¹For further discussion, see Rosser Jr (2001b, 2011a, Chap. 9), and Foroni et al. (2003).

$$R(Y) = pqEx - C(E). \tag{6.4}$$

So far this has been a static exercise, but now let us put this more directly into the intertemporal optimization framework, assuming that the time discount rate is δ . All of the above equations will now be time indexed by t , and also we must allow at least in principle for non-steady state outcomes. Thus

$$dx/dt = f(x) - h(x), \tag{6.5}$$

with $h(x)$ now given by (6.2) and not necessarily equal to $f(x)$. Letting unit harvesting costs at different times be given by $c[x(t)]$, which will equal c/qx , and with a constant $\delta > 0$, the optimal control problem over $h(t)$ while substituting in (6.5) becomes

$$\max \int_0^\infty e^{-\delta t} (p - c[x(t)])(f(x) - dx/dt)dt, \tag{6.6}$$

subject to $x(t) \geq 0$ and $h(t) \geq 0$, noting that $h(t) = f(x) - dx/dt$ in (6.6). Applying Euler conditions' gives

$$f(x)/dt = \delta = [c'(x)f(x)]/[p - c(x)]. \tag{6.7}$$

From this the optimal discounted supply curve of fish will be given by

$$x(p, \delta) = k/4 \left\{ 1 + (c/pqk) - (\delta/r) + \left[(1 + (c/pqk) - (\delta/r))^2 + (8c\delta/pqkr) \right]^{1/2} \right\}. \tag{6.8}$$

This entire system is depicted in Fig. 6.1 (Rosser Jr 2001b, p. 27) as the Gordon-Schaefer-Clark fishery model.

The most dramatic aspect of this model is the backward-bending supply curve that arises, with Copes (1970) being the first to explain this possibility for fisheries, strongly supported by Clark (1990). One can see that a gradual increase in demand in this situation can lead to a sudden increase in price and a catastrophic collapse of output.

We note that when $\delta = 0$, the supply curve in the upper right quadrant of Fig. 6.1 will not bend backwards. Rather it will asymptotically approach the vertical line coming up from the maximum sustained yield point at the farthest point to the right on the yield curve in the lower right quadrant. As δ increases, this supply curve will start to bend backwards and will actually do so well below $\delta = 2\%$. The backward bend will continue to become more extreme until at $\delta = \infty$ the supply curve will converge on the open access supply curve of

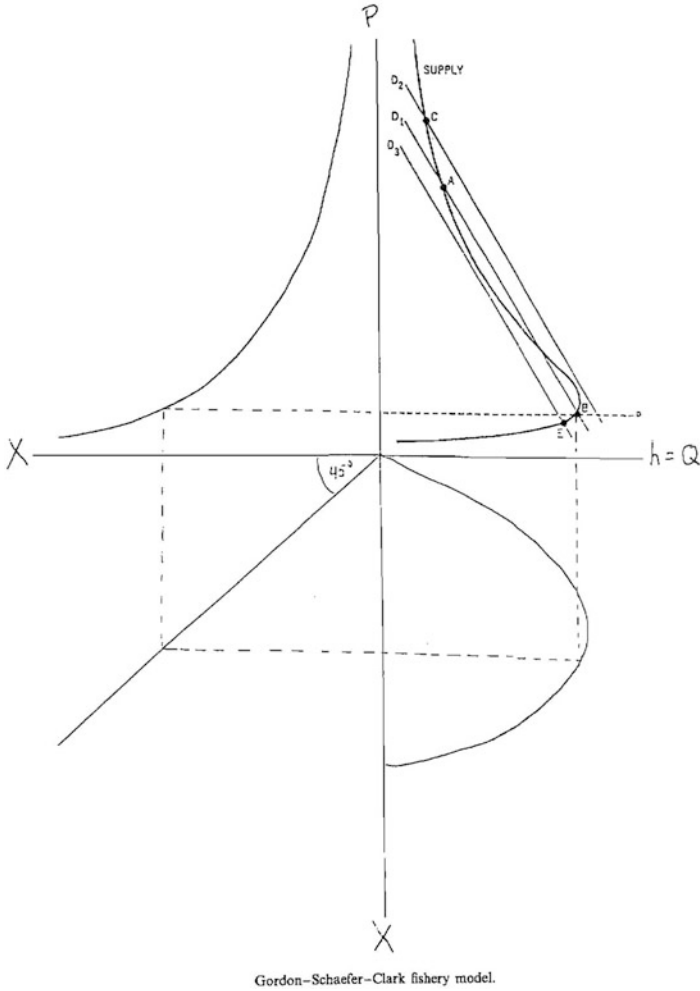


Fig. 6.1 Gordon-Schaefer-Clark fishery model

$$x(p, \infty) = (rc/pq)(1 - c/pqk). \tag{6.9}$$

It should be clear that the chance of catastrophic collapses will increase as this supply curve bends further backwards and the possibility for multiple equilibria increases, so that a smooth increase in demand can lead to a catastrophic increase in price and collapse of quantity. So, even if people are behaving optimally, as they become more myopic, the chances of catastrophic outcomes will increase.

Regarding the nature of the optimal dynamics, Hommes and Rosser Jr (2001) show that for the zones in which there are multiple equilibria in the backward-bending supply curve case, there are roughly three zones in terms of the nature of the

optimal outcomes. At sufficiently low discount rates, the optimal outcome will simply be the lower price/higher quantity of the two stable equilibrium outcomes. At a much higher level the optimal outcome will simply be the higher price/lower quantity of the two stable equilibria. However, for intermediate zones, the optimal outcome may involve a complex pattern of bouncing back and forth between the two equilibria, with the possibility of this pattern being mathematically chaotic arising.²

To study their system, Hommes and Rosser Jr (2001) assume a demand curve of the form

$$D(p(t)) = A - Bp(t), \quad (6.10)$$

with the supply curve being given by (6.8). Market clearing is then given by

$$p(t) = [A - S(p(t), \delta)]/B. \quad (6.11)$$

This can be turned into a model of cobweb adjustment dynamics by indexing the p in the supply function to be one period behind the p being determined, with Chiarella (1988) and Matsumoto (1997) showing chaotic dynamics in generalized cobweb models.

Drawing on data from Clark (1985, pp. 25, 45, 48), Hommes and Barkley Rosser Jr (2001) assumed the following values for parameters: $A = 5241$, $B = 0.28$, $r = 0.05$, $c = 5000$, $k = 400,000$, $q = 0.000014$ (with the number for A coming from $A = kr/(c - c^2/qk)$). For these values they found that as δ rose from zero at first a low price equilibrium was the solution, but starting around $\delta = 2\%$ period-doubling bifurcations began to appear, with full-blown chaotic dynamics appearing at around $\delta = 8\%$. When δ rose above 10% or so, the system went to the high price equilibrium.

6.3 Complexity Problems of Optimal Rotation in Forests

Some complexities of forestry dynamics have long been known in connection with the matter of spruce-budworm dynamics (Ludwig, Jones, and Holling, 1978).³ In order to get at related sorts of dynamics arising from unexpected patterns of forest benefits as well as such management issues as how to deal with forest fires and patch

²This is below the range that chaotic dynamics emerge in Golden Rule growth models (Nishimura and Yano 1996). Chaotic dynamics appear in the non-optimizing model of a halibut fishery with a backward-bending supply curve (Conklin and Kohlberg 1994). Doveri et al. (1993) showed this for more generalized multiple-species aquatic ecosystems. Zimmer (1999) argued that chaotic cycles are more likely to appear in laboratories due to noise in natural environments, while Allen et al. (1993) argue that chaotic dynamics in a noisy environment may help a species to survive.

³See also Holling (1965) for a foreshadowing of this argument. For broader links, Holling (1986) argued that these spruce-budworm systems in the Canadian forests could be affected by "local surprise" or small events in distant locations, such as the draining of crucial swamps in the US Midwest on the migratory paths of birds that feed on the budworms.

size, as well as the basic matter of when forests should be optimally cut, we need to develop a basic model (Rosser Jr 2005). We shall begin with the simplest sort of model in which the only benefit of a forest is the timber to be cut from it and consider the optimal behavior of a profit-maximizing forest owner under such conditions.

Irving Fisher (1907) considered what we now call the “optimal rotation” problem of when to cut a forest as part of his development of capital theory. Positing positive real interest rates he argued that it would be optimal to cut the forest (or a tree, to be more precise) when its growth rate equals the real rate of interest, the growth rate of trees tending to slow down over time. This was straightforward: as long as a tree grows more rapidly than the level of the rate of interest, one can increase one’s wealth more by letting the tree grow. Once its growth rate is set to drop below the real rate of interest, one can make more money by cutting the tree down and putting the proceeds from selling its timber into a bond earning the real rate of interest. This argument dominated thinking in the English language tradition for over half a decade, despite some doubts raised by Alchian (1952) and Gaffney (1957).

However, as eloquently argued by Samuelson (1976), Fisher was wrong. Or to be more precise, he was only correct for a rather odd and uninteresting case, namely that in which the forest owner does not replant a new tree to replace the old one, but in effect simply abandons the forest and does nothing with it (or perhaps sells it off to someone else). This is certainly not the solution to the optimal rotation problem in which the forest owner intends to replant and then cut and replant and cut and so on into the infinite future. Curiously, the solution to this problem had been solved in 1849 by a German forester, Martin Faustmann (1849), although his solution would remain unknown in English until his work was translated over a century later.

Faustmann’s solution involves cutting sooner than in the Fisher case, because one can get more rapidly growing younger trees in and growing if one cuts sooner, which increases the present value of the forest compared to a rotation period based on cutting when Fisher recommended.

Let p be the price of timber, assumed to be constant,⁴ $f(t)$ be the growth function of the biomass of the tree over time, T be the optimal rotation period, r be the real interest rate, and c the cost of cutting the tree, Fisher’s solution is then given by

$$pf'(T) = rpf(T), \quad (6.12)$$

which by removing price from both sides can be reduced to

$$f'(T) = rf(T), \quad (6.13)$$

⁴This is a nontrivial assumption, with a large literature existing on the use of option theory to solve for optimal stopping times when the price is a stochastic process (Reed and Clarke 1990). Arrow and Fisher (1974) first suggested the use of option theory to deal with possibly irreversible loss of uncertain future forest values.

which has the interpretation already given: cut when the growth rate equals real rate of interest.

Faustmann solved this by considering an infinite sum of discounted earnings of the future discounted returns from harvesting and found this to reduce to

$$pf'(T) = rpf(T) + r[(pf(T) - c)/(e^{rT} - 1)]. \quad (6.14)$$

which implies a lower T than in Fisher's case due to the extra term on the right-hand side, which is positive and given the fact that $f(t)$ is concave. Hartman (1976) generalized this to allow for non-timber amenity values of the tree (or forest patch of same aged trees to be cut simultaneously),⁵ assuming those amenity values can be characterized by $g(t)$ to be given by

$$pf'(T) = rpf(T) + r[(pf(T) - c)/(e^{rT} - 1)] - g(T). \quad (6.15)$$

An example of a marketable non-timber amenity value that can be associated with a privately owned forest might be grazing of animals, which tends to reach a maximum early in the life of a forest patch when the trees are still young and rather small. Swallow et al. (1990) estimated cattle grazing amenity values in Western Montana to reach a maximum of 12.5 years, with the function given by

$$g(t) = \beta_0 \exp(-\beta_1 t), \quad (6.16)$$

Rosser Jr (2005) showed that this case reached a global maximum at 76 years, slightly longer than the 73 years of the Faustmann solution, but it indeed exhibits multiple local optima, reflecting nonlinearities in these forestry dynamics (Rosser Jr 2005; 2011a, b, 2013; Vincent and Potts 2005).⁶

More frequently this $g(t)$ function involves matters not so easily appropriated by a private owner, in short, externalities. Some government forest owners try to incorporate these into planning efforts, with this something long done by the United States Forest Service, which uses public hearings to gauge public sentiment regarding alternative land uses in its planning for national forests (Johnson et al. 1980; Bowes and Krutilla 1985). Among those are hunting and fishing, which sometimes

⁵A more general model based on Ramsey's (1928) intertemporal optimization that solves for the optimal profile of a forest was initiated by Mitra and Wan Jr. (1986). This approach took seriously Ramsey's invocation of a zero discount rate in which case management converges on the maximum sustained yield solution, with Khan and Piazza (2011) studying this from the standpoint of classical turnpike theory.

⁶The existence of these multiple equilibria opens the possibility for capital theoretic paradoxes as the real rate of interest varies (Rosser Jr 2011b). Prince and Rosser Jr (1985) studied the implications of this for benefit-cost analysis, with this holding potentially for the George Washington National Forest case discussed in this paper below. See Asheim (2008) for an application to the case of nuclear power.

both private and public owners can get some payments by users, if for public forests more indirectly through hunting and fishing licenses.

Less easily captured are broader biodiversity issues, especially involving endangered species (Perrings et al. 1995). This has been a difficult issue in many developing nations, where systems have been established to try to provide economic benefits for local populations for preserving such species, with in some nations ecotourism a method for this. This becomes more difficult in situations where aboriginal rights have been violated in the past (Kant 2000; Gram 2001).⁷

Carbon sequestration is an externality of forests getting more attention, with less frequent cutting tending to aid this (Alig et al. 1998), especially given that standard timber harvesting often involves burning underbrush and unused limbs, not to mention that timber harvesting also can also increase soil erosion and flooding (Plantinga and Wu, 2003). But younger trees may absorb more CO₂ and replacing one species with others may also improve this (Alavalapati et al. 2002). All of this may also interact with biodiversity efforts in various ways (Caparrós and Jacquemont 2003).

A good example of these complexities has been studied for the George Washington National Forest in Virginia and West Virginia drawing on information in its planning process (FORPLAN, Johnson et al. 1980). There one finds hunting-related multiple maxima tied to deer that reach a peak 8 years after a clearcut, with wild turkeys and grouse reaching a maximum at about 25 years after a clearcut (and this also the maximum for vegetative diversity), and bears reaching a maximum after about 60 years, with this setting up conflicts over cutting more frequently in some parts of the forest to please deer hunters and much less to even no cutting in other parts to favor bear hunters, both of these powerful interest groups pressuring decision makers for that forest (Rosser Jr 2005, 2011a, 2013).

If a forest is not strictly a subsistence one and thus has at least one product sold in a market, then for a fixed land area, a forest may a backward-bending long-run supply curve for that product, particularly if it is timber. Empirical observations support the possible existence of such situations, including a study of smallholder timber sales from the edge of the Amazon rain forest (Amacher et al. 2009). They found strongly negative and statistically significant elasticities of supply for timber in their sample for plots with secure tenure, although for ones with insecure tenure the curve slopes upward. The authors offer little argument for why this result should occur, partly as they are mostly concerned with other issues such as the role of credit and the presence or not of the Transamazonian highway. The little explanation they do provide invokes the model of the backward-bending supply curve of individual labor rather than that of fisheries. "The timber price effect follows from the fact that the smallholder may have predetermined revenue targets that timber sales are intended to help meet" (Amacher et al. 2009, p. 1796).

⁷For more detailed discussions of the special problems of tropical deforestation and rights of indigenous peoples, see Barbier (2001); Kahn and Rivas (2009).

As it is, theoretical models of the possibility of backward-bending supply curves of timber have been developed in the past, inspired in particular by the work of Colin Clark on such curves for fisheries. The first to do so was Hyde (1980). Even more strongly inspired by Clark (1985, 1990), Binkley (1993) developed a formal model based on the Faustmann model,⁸ also presenting tentative evidence in support of it from the long run supply of loblolly pines in the US Southeast. Needless to say, these cases open up the possibility of the sort of complex dynamics already discussed for the fishery case.

Using the variables already defined, we present Binkley's model below, adding $\pi(t)$ for the net present value of the future stream of timber receipts, which the forest owner will seek to maximize. In contrast to our earlier discussion, price will be allowed to change, although we shall eschew using option theory. This forest may contain trees or stands of varying ages. In any given year, some tree or stand will reach the optimal rotation age, T , and will be harvested. Supply will be in per unit land area terms.

The forest owner seeks to maximize

$$\pi(t) = -c + pf(t)e^{-rt} + \pi(t)e^{-rt}. \quad (6.17)$$

The first order condition for solving this is to find $d\pi/dt = 0$, which is given by

$$f'(t)/[f(t) - c/p] = r/(1 - e^{-rt}). \quad (6.18)$$

This implies a long-run supply relationship between price and optimal rotation age, T , as given by

$$S(p) = f(T(p))/T(p). \quad (6.19)$$

From this one gets a non-monotonic supply curve as a function of T that goes from zero to zero as T increases, with a maximum sustained yield (MSY) at an intermediate value of T given by

$$1/T = f'(T)/f(T). \quad (6.20)$$

From this it is possible to derive the relationship between price and optimal rotation age, T , which appears in (6.20) as given by

$$p = c/\{f(T) - f'(t)[(1 - e^{-rt})/r]\}. \quad (6.21)$$

This is summarized in Fig. 6.2.⁹

⁸Yin and Newman (1999) confirmed the basic model, although also showing that aggregate supply curves allowing for variable land will be upward-sloping.

⁹Variables in the figure are those used by Binkley, translating to this paper as $v = f$, $t = T$, and $l = r$.

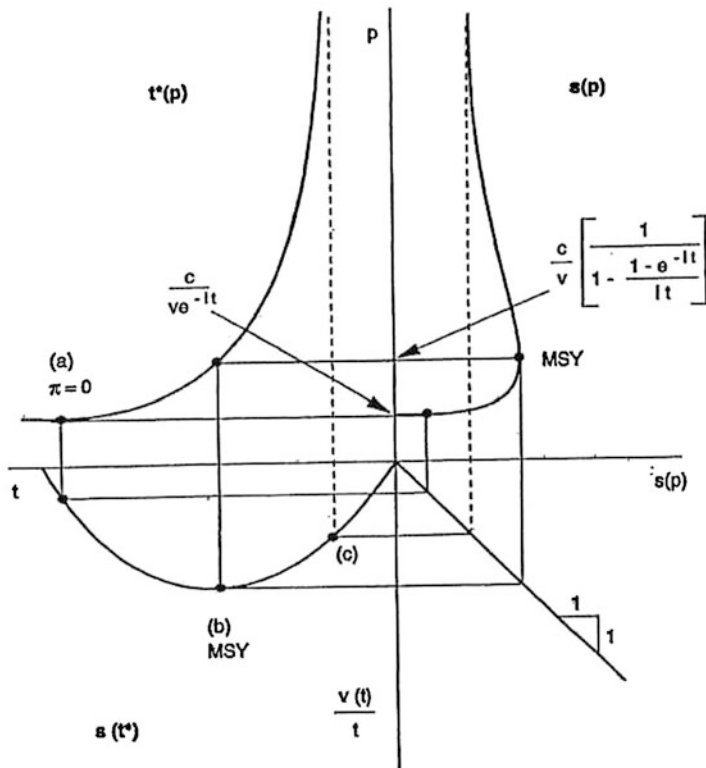


Fig. 6.2 The backward-bending supply curve of timber

There are parallels to the backward-bending supply curve of fish presented above, but also some differences. Crucial to both is the assumption of a maximum carrying capacity. Both effectively have only three figures, with one quadrant just a 45 degree line, between rotation age for the forest and fish biomass for the fishery. Both have a non-monotonic function that lies behind the backward bend of the supply curve, the Schaefer yield function of steady state harvest and fish biomass for the fishery and between rotations age and timber supply for the forest. In both, the maximum supply point is associated with the MSY point.

In both the upward sloping portion of the supply curve is associated with the “outer” portion of the relevant yield function beyond the MSY point. For the fishery there are lots of fish there, easily caught at low prices. For the forest this is the longer rotation periods when the trees are larger. On the other side of MSY is the backward-bending portion of the supply curve. For the fishery there are few fish, thus expensive to catch. For the forest, this is associated with a much shorter rotation period in which the trees are small when cut, thus producing less timber over time.

Binkley summarizes the situation in his conclusion thusly (1993, p. 178):

“High stumpage prices imply not only that the output from the forest has a high value, but also that capital in the form of growing stock has a high opportunity cost. At high prices, it is optimal to conserve on the use of capital and therefore to reduce the growing stock inventory by reducing the rotation age.”

6.4 Complexities of Climate-Economy Systems

It has long been argued that climatic systems just by themselves are chaotic, with Lorenz (1963) posing the butterfly effect initially specifically in connection with modeling climate, and with this being a main reason that it is difficult to do weather forecasting beyond a few days for a specific location. However, even if climate by itself is not chaotic and the economy by itself is not chaotic, a coupled system of the two may well be (Rosser Jr 2002, 2020d).

In particular, Chen (1997) has shown how such a system can arise. He assumes a two-sector economic model with agriculture and manufacturing that is closed by a CES utility function for a homogenous agent and with labor the only economic input. There is a two-way interaction with climate, drawing on a model due to Henderson-Sellers and McGuffie (1987). Hotter climate reduces agricultural production while increased manufacturing heats the climate due to pollution. Under certain parameter values of this model, chaotic dynamics emerge, even though neither system by itself is chaotic.

Rosser Jr (2020d) considers further a model that extends an analysis of *flare attractors* in economic systems, with these initially used to study autocatalytic reactions such as flares in physical chemistry (Rössler and Hartmann 1995). This is arguably part of the not-so-well developed *econochemistry*. The underlying mathematics derive from Milnor attractors (Milnor 1985) that are continuous but nowhere differentiable and exhibit “riddled basins.” Rössler (1976) used this approach to develop his continuous chaotic attractor and then extended this in Rössler et al. (1995). Hartmann and Rössler (1998) applied this model to entrepreneurial activities and Rosser Jr. et al. (2003a) applied it to examining asset price volatility. Rosser Jr (2020d) further applied this to a coupled climate-economic system that can provide the sort of kurtotic climate outcomes studied by Weitzman (2009, 2011, 2012, 2014) and Rosser Jr (2011a).

In this model the economic part derives from a model of Day (1982) that is a modified Solow growth model that faces limits to capital expansion, possibly due to environmental limits. This sets it up for a logistic formulation that resembles the model of May (1976) known to generate chaotic dynamics. This economic model is then posed in a regional setup with interacting inputs to climate that can lead to kurtotic “flares.” The basic economic model has a labor exponent of α , a capital exponent of β , y is per capita output, k is the capital-labor ratio, population growth rate is λ , and m is the “capital-congestion coefficient.” These modified production function is

$$F(k) = \beta k^\beta (m - k)^y. \quad (6.22)$$

Assuming a consistent savings rate, the capital ratio implies the following difference growth equation:

$$K_{t+1} = \alpha \beta k_t^\beta (m - k_t)^y / (1 + \lambda). \quad (6.23)$$

Following May (1976), Rosser Jr. et al. (2003a) assumed values that guarantee a chaotic dynamic assuming a constant capital share, given by

$$A\beta / (1 + \lambda) = 3.99 = k_{t+1} / (1 - k_t). \quad (6.24)$$

In contrast to earlier formulations, the heterogeneous entities are locations rather than agents. They are driven by a reaction function B , with parameters b and a critical value of k that is a , beyond which there will be a substantial increase in temperature, a “flare.” A full outburst depends on a sufficient number of locations passing their critical value, with $1 > a > 0$. With $c > 0$ and location of type l out of n , s is overall demand, the general form of this reaction function is given by:

$$B_{t+1}^l = b_t^i + b_t^l (a^l - k_t^l) - cb^{(i)2}_t + cs_t. \quad (6.25)$$

In this system the first term is an autoregressive component; the second is the switching term; the third provides a stabilizing component, while the fourth is the destabilizing element coming from the buildup of previous trends, with the overall demand given by:

$$S_{t+1} = b^1_t + b^2_t + \dots + b^n_t. \quad (6.26)$$

In Rosser Jr. et al. (2003a) assuming certain values of these parameters allow a simulation that provides a sequence of outcomes exhibiting scattered Kurtotic outbursts consistent with the Weitzman scenario for global warming.

6.5 Stability, Resilience, Complexity of Ecosystems Revisited and Policy

It has been argued that there is a relationship between the diversity of an ecosystem and its stability, although this was later found not to be true in general, with indeed mathematical arguments existing suggesting just the opposite May 1973). It was then suggested by some that the apparent relationship between diversity and stability in nature was the other way around, that stability allowed for diversity. More broadly, it was argued that there is no general relationship, with the details of relationships within an ecosystem providing the key to understanding the nature of

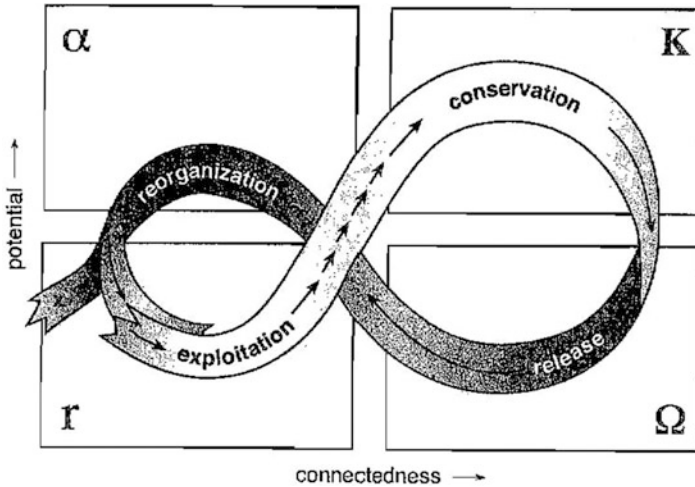


Fig. 6.3 Cycle of the four ecosystem functions

the stability of the system, although certainly declining biodiversity is a broad problem with many aspects (Perrings et al. 1995).

Out of this discussion came the fruitful insight by C.S. Holling (1973) of a deep negative relationship between stability and resilience. This relationship can be posed as a conflict between local and global stability: that greater local stability may be in some sense purchased at the cost of lesser global stability or resilience. The palm tree is not locally stable as it bends in the wind easily in comparison with the oak tree. However, as the wind strengthens, the palm tree's bending allows it to survive, while the oak tree becomes more susceptible to breaking and not surviving. Such a relationship can even be argued to carry over into economics as in the classic comparison of market capitalism and command socialism. Market capitalism suffers from instabilities of prices and the macroeconomy, whereas the planned prices and output levels of command socialism stabilize the price level, output, and employment. However, market capitalism is more resilient and survives the stronger exogenous shocks of technological change or sudden shortages of inputs, whereas command socialism is in greater danger of completely breaking down, which indeed happened with the former Soviet economic system.

This recognition that ecosystems involve dynamic patterns and do not remain fixed over time, led Holling (1992) to extend his idea to more broadly consider the role of such patterns within maintaining the resilience of such systems, and also to consider how the relationships between the patterns would vary over time and space within the hierarchical systems (Holling and Gunderson 2002; Holling et al. 2002; Gunderson et al. 2002a, b). This resulted in what has come to be called the "lazy eight" diagram of Holling, which is depicted in Fig. 6.3 (Holling and Gunderson 2002, p. 34) and shows a stylized picture of the passage of a typical ecosystem through four basic functions over time.

This can be thought of as representing a typical pattern of ecological succession on a particular plot of land.¹⁰ Conventional ecology focuses on the r and K zones, corresponding to r -adapters and K -adapters. So, if an ecosystem has collapsed (as in the case of a forest after a total fire), it begins to have populations within it grow again from scratch, doing so at an r rate through the phase of exploitation. As it fills up, it moves to the K stage, wherein it reaches carrying capacity and enters the phase of conservation, although as noted previously, succession may occur in this stage as the precise set of plants and animals may change at this stage. Then there comes the release as the overconnected system now become low in resilience collapses into a release of biomass and energy in the Ω stage, which Gunderson and Holling identify with the “creative destruction” of Schumpeter (1950). Finally, the system enters into the α stage of reorganization as it prepares to allow for the reaccumulation of energy and biomass. In this stage soil and other fundamental factors are prepared for the return to the r stage, although this is a crucially important stage in that it is possible for the ecosystem to change substantially into a different form, depending on how the soil is changed and what species enter into it, with an example of the shift from buffalo-grass and grama to rattlesnake bush and tumbleweed in the US Southwest a possibility as described by Leopold (1933)

This basic pattern can be seen occurring at multiple time and space scales within a broader landscape as a set of nested cycles (Holling 1986, 1992). An example drawn on the boreal forest and also depicting relevant atmospheric cycles is depicted in Fig. 6.4 (Holling et al. 2002, p. 68). One can think in terms of the forest of each of the levels operating according to its own “lazy eight” pattern as described above. Such a pattern is called a *panarchy*.

Increasingly policymakers come to understand that it is resilience rather than stability per se that is important for longer term sustainability of a system. In the face of exogenous shocks and the threat of extinction of species (Solé and Bascompte 2006), special efforts must be made to approach things adeptly. Costanza et al. (1999) propose seven principles for the case of oceanic management: Responsibility, Scale-Matching, Precautionary, Adaptive Management, Cost Allocation, and Full Participation. Of these, Rosser Jr (2001b) suggests that the most important are the Scale-Matching and Precautionary Principles, with Wilson et al. (1999) especially emphasizing the scale perception and matching problem as deeply crucial.

Scale-matching means that the policymakers operate at the appropriate level of the hierarchy of the ecologic-economic system. Following Ostrom (1990) and Bromley (1991), as well as Rosser Jr (1995) and Rosser Jr. and Rosser (2006), the idea is to align both property and control rights at the appropriate level of the hierarchy. Managing a fishery at too high a level can lead to the destruction of fish species at a lower level (Wilson et al. 1999).

¹⁰We note here the definition often used of an “ecosystem” as being a set of interrelated biogeochemical cycles driven by energy. In terms of scale, these can range from a single cell to the entire biosphere. Thus we have a set of nested ecosystems that may operate at various levels of aggregation.

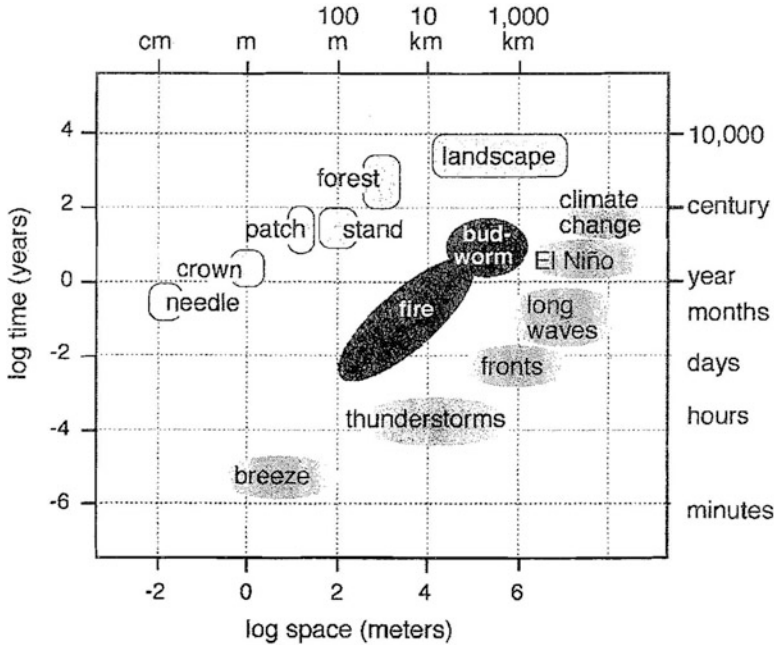


Fig. 6.4 Time and space scales of the boreal forest and the atmosphere

Assuming that appropriate scale-matching has been achieved, and that a functioning system of property rights and control has been established, the goal of managing to maintain resilience may well involve providing sufficient flexibility for the system to be able to have its local fluctuations occur without interference while maintaining the broader boundaries and limits that keep the system from collapsing. In the difficult situation of fisheries, this may involve establishing reserves (Lauck et al. 1998; Grafton et al. 2009) or system of rotational usage (Valderarama and Anderson 2007). Crucial to successfully doing this is having the group that manages the resource able to monitor itself and observe itself (Sethi and Somanathan 1996), with such self-reinforcement being the key to success in the management of fisheries for certain as in the case of the lobster gangs of Maine (Acheson 1988) and the fisheries of Iceland (Durrenberger and Palsson 1987). Needless to say, all of this is easier said than done, especially in the case of fisheries where the relevant local groups are often quite distinct socially and otherwise from those around them and thus tending to be suspicious of outsiders who attempt to get them to organize themselves to do what is needed (Charles 1988).

Property rights and control rights may not coincide (von Ciriacy-Wantrup and Bishop 1975), with control of access being the key to governing the commons. Without control of access, property rights are irrelevant. The work of Ostrom and others makes clear that property rights may take a variety of forms. While these alternative efforts often succeed, sometimes they do not, as the failure of an early

effort to establish property rights in the British Columbia salmon fishery demonstrates (Millerd 2007). Some common property resources have been managed successfully for centuries, as in the case of the Swiss alpine grazing commons (Netting 1976), whose existence has long disproven the simple version of the “tragedy of the commons” as posed by Garrett Hardin (1968).

The policy problems become more difficult when different levels of hierarchy are important in the dynamics of an ecologic-economic system, especially when nonlinear complex dynamics are operative at these important multiple levels. Policies may need to be implemented at different levels, but with these consistent with each other to be effective. This problem becomes probably clearest in returning to considering the global climate issue, which indeed ranges from the almost minutely local to the fully global.

A further complication due to the complexities associated especially with chaotic dynamics is that when a system is decomposed from the global to the regional or local level, it may be subject to severe effects due to sensitive dependence on initial conditions. Thus, Massetti and Lorenzo (2019) have considered in detail the regional level forecasts from simulations of global level climate models using the United Nations IPCC for projecting possible future climate outcomes. In particular they ran simulations slightly varying initial starting values for certain variables and indeed found substantial sensitive dependence for regional level predictions. Thus for the west-central portion of the United States some projections would have substantial warming while others actually found cooling happening, even as the global average temperature showed warming, again for starting values only slightly apart. This replicates the old result for climate models found by Lorenz (1963). Needless to say, this seriously complicated knowing what to do at more local levels for such situations.

These multi-layered complexities involve deep uncertainties about all the matters noted above and more. These include ongoing debates about underlying science issues, as well as the full nature of the interactions between the economic and climatological aspects. The elements of this involve chaotic dynamics subject to sensitive dependence on initial conditions, which makes the whole matter much more difficult to understand. All this leads to the inability of any observer or agent to reliably know how the system operates in full detail reliably. This implies that it would be wise to involve heuristic rules of thumb based on bounded rationality as crucial parts of policy in such highly complex situations (Rosser Jr. and Rosser 2015).