

Theme 4: Managing Human-Environment Systems for Sustainability

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Introduction

There are extreme challenges in working towards a sustainable future for humans. Maintaining food supplies, providing energy, containing diseases, and maintenance of ecosystem services all present challenges. In many cases these challenges take the form of management of systems which couple both human and natural or ecological and environmental components.

The need for management of coupled natural human systems for sustainability is very clear; yet the problems are extraordinarily difficult. As a means of developing this statement, and the mathematical and biological challenges underlying these questions, I will start with three different classes of problems that are in many ways among the simplest ones of this kind, yet still have presented extreme difficulties. These three examples will serve to introduce both the biological and mathematical complexities underlying the problems. It is important to recognize that these three examples are far simpler than many of the challenges we will be facing, so I will then turn to a discussion of the more complex systems that must be considered.

The first class of problems is the management of fisheries. As a problem in management, these have been long studied beginning with early work by Schaeffer (1957), and the book by Colin Clark (1990) presented a very useful summary. Early on, the interplay among several issues became clear which led to the expression of the problem as one in *bioeconomics*, where the management decisions could be reduced to optimization problems as outlined below. However, as is well known, even with long experience, the management of fisheries has not been an unmitigated success, with many fisheries collapsing around the world (Roughgarden and Smith 1996).

A second class of problems has been the management of infectious diseases, both of humans and of animals or plants. This area has had a number of success stories; the reasons for the successes will prove instructive in understanding failures in other areas.

A third class of problems has been considered more recently, namely the control of invasive species. This problem is potentially more complex and difficult, yet is still much simpler than the management of other problems for sustainability. The difficulties inherent in this class of problems will be instructive, as the increased level of complexity in some ways from the fisheries examples provides new insights.

I will then discuss in more general terms some of the issues that arise as the complexity of the underlying problems increase. A truly cautionary tale is provided by the difficulty of dealing with even the simpler settings.

Fisheries

The simplest models for the management of fisheries are deceptively easy to express as simple models of ordinary differential equations. The first step is to write a model describing the (unharvested) population dynamics of the species in question. For example, letting x be the population size of the species, write

$$dx/dt = F(x),$$

where $F(x)$ is the growth rate of the species when its population level is x . Then, with harvesting at a rate $h(t)$ at time t , the species dynamics is simply

$$dx/dt = F(x) - h(t). \tag{1}$$

Then the management decisions are simply to choose the harvesting rate $h(t)$ as a function of time, with the two goals of sustainability and getting a maximum benefit in some sense. I have been purposely vague about assumptions and other issues because it is in making these assumptions concrete and accounting for the complexities in real fisheries and environmental systems that much of the difficulties lie.

First, what is to be maximized? This question has several answers. One possibility is to maximize the sustainable harvest. This would mean, in the simplest model where the species growth rate is independent of time, to choose $h(t)$ to adjust the population level x so $F(x)$, the growth rate is at a maximum F_{\max} , and then to maintain $h(t) = F_{\max}$. Problems with this approach begin with the idea that it does not take into account variability of the growth rate in time. Other problems are that $F(x)$ is not, in general, well known. Another important problem is that how $h(t)$ will actually be implemented is a difficult problem. Recognizing the simple mathematical fact that trying to set $h(t)$ to be the maximum of $F(x)$ is likely to end up, especially with some of the complexities underscored, with $h(t)$ higher than the maximum of $F(x)$ would then mean that the population would be overharvested and would decline. So even this simple problem is not so simple. And, other complexities, like the role of spatial variability, age structure, and temporal variability will only serve to make the problem more difficult.

Another important point to recognize is that the choice to maximize the sustainable harvest does not take into account some economic issues. When economic aspects are included it becomes important to distinguish, at least, between a fishery managed by a 'single owner' and one with

open access. With open access individuals can choose to enter the fishery or leave it, and make their own decisions as to the harvest. With a single owner, decisions about how much to harvest are made by a single entity. (In this latter case, the owner can be a regulator, rather than a true individual owner.) Since aspects of the issues raised by these two kinds of management show up in all problems it is important to provide some detail.

As has been recognized, for a system with open access there is the possibility of the ‘tragedy of the commons’. This means that individuals will choose to enter the system (or harvest) until there are no profits left. This also will typically lead to overharvesting so there are both long term issues of sustainability and short term economic issues. This is an example of a public goods problem; how to avoid the problems inherent in this example are general questions underlying the exploitation of any public good.

With a single owner (or regulator), some of the issues of the tragedy of the commons are avoided, but other important issues arise. Adding an economic perspective to equation (1) means that rather than the goal of maximizing the sustainable yield, the goal is to maximize the net present value of the system. This can be formulated as an optimal control problem. The revenue from the fishery at time t , $R(t)$, can be expressed as the cost of harvesting as a function of the population size $c[x(t)]$, the price, p , and the harvest rate $h(t)$, as

$$R(t) = \{p - c[x(t)]\}h(t).$$

Then the present value of the system is the revenue over all future times *discounted* by the rate δ representing the idea that future profits are worth less than current profits. Then the present value of the fishery, PV , is given by

$$PV = \int_0^{\infty} e^{-\delta t} \{p - c[x(t)]\}h(t) dt.$$

Then the choice of $h(t)$ is a problem in constrained optimal control. This formulation which uses a discount rate can lead to very different conclusions. In particular if the discount rate is high enough relative to the maximal growth rate of the population, then the optimal solution will be to drive the population to zero. This issue of the role that the discount rate plays can be a perplexing one, especially if the prediction is to

Yet, despite the beautiful mathematical models that have very clear solutions, many fisheries have become overfished. There are many potential causes for this, but some of them can relate to inadequacies in the modeling framework. One issue is that some of the simplifying assumptions made to create these models may play an important role. Among the complications are the ones mentioned above of focusing on a single species and not including age or spatial structure.

Perhaps the overarching problems (other than essentially political ones) are the issues of variability and uncertainty. The actual dynamics may not be well known. More importantly, the environment, and the reproduction and survival of the species, can be highly variable over time.

This, coupled with lack of knowledge of population levels and dynamics, makes for a very difficult management problem in what would appear to be one of the simplest settings.

Epidemiology

Here the simplest models have proved quite effective in dealing with at least some particular practical problems. The basic models (see review in (Diekmann and Heesterbeek 2000)) derive from the classic SIR model which, for a single epidemic with complete immunity, is written as

$$dS/dt = -\beta SI$$

$$dI/dt = \beta SI - \gamma I \quad (2)$$

$$dR/dt = \gamma I$$

where S is the number of susceptibles, I the number of infectives, R the number of recovered individuals, the parameter β is called the contact rate, and the parameter γ is the recovery rate. Why has this model and relatively simple modifications proved as effective as it has, from understanding even the spatio-temporal dynamics of childhood diseases (Grenfell et al. 2001) to cases like managing the foot and mouth epidemic (Keeling et al. 2001) in the United Kingdom?

There are a number of features of epidemic modeling that have helped to make the models so useful. The approximations necessary to obtain equation (2) are well justified, namely that the time scale of the epidemic is short relative to the population dynamics of the infected species. More important are the observations, which hold even under most modifications, that the model follows the inexorable fact that a susceptible individual becoming infective removes one from the S class and adds ones to the I class; and similarly an individual moves from the I class to the R class. And, of the two parameters, γ is easy to estimate as the inverse of the mean duration of the infective stage. Thus, this is a model which involves only one parameter and process that is difficult to observe and measure, namely the infection process itself. This simplicity is part of the reason for its success. Another simplifying aspect is that control measures are often relatively straightforward.

Nonetheless, some of the issues raised above in the fisheries example do arise here. There are problems with variability, and with spatial structure. There is also a public goods issue in that even if the risk of vaccination is small, most of the benefit goes to the group. A single unvaccinated individual in a population that is vaccinated will not get the disease in question. But, if enough individuals are present that are not vaccinated outbreaks can occur as has happened with whooping cough in parts of the US.

What is also instructive is that attempts to use simple models to understand epidemics of sexually transmitted diseases (STD's) did not succeed until some very basic simple ideas were included that took into account deviations from the assumptions of the simplest models. In

particular, the modification of the basic structure describing infections to include the idea that contact rates differed greatly among individuals, *and* that individuals with high contact rates were more likely to interact with individuals with high contact rates (Hyman and Stanley 1988) was key to understanding the dynamics of STD's. This observation is just one aspect of using ideas about networks (May and Lloyd 2001) for understanding the dynamics of diseases and their management.

Invasive Species

This is a class of problems that ends up being much less well specified than the fisheries and epidemiology examples. Invasive species are an extremely large problem from both an economic standpoint, and from a sustainability framework. This is a class of problems that is much less well understood than either the fisheries or epidemiological problem. There have been extensive studies of the problem of spread of an invading species that are truly elegant mathematically, but there are many complexities in the biological and management problem.

The dynamic of an invasive species has been expressed as a series of stages: arrival, establishment, spread, and saturation. An overall difficulty that underlies this question is the difficulty of properly assigning value to damages by invasive species, which is clearly not the cost of control measures though that is sometimes taken to be the cost. As far as management goes, there is the obvious effort at preventing arrival through screening. The spread stage is the one where much effort has gone into management and designing effective strategies.

There are relatively simple models for the spread of a species (Hastings et al. 2005), based on the classic Fisher reaction diffusion equation, or on an integro-difference equation form. And, these models can be used to design control strategies. The difficulties come in dealing with realistic levels of heterogeneity, realistic levels of variability, and trying to understand the biological issues of dispersal. More important challenges arise, however, in trying to understand issues of valuation and impact (Epanchin Niell and Hastings 2010). In order to do this, the dynamics of the invasive species need to be put into the context of the dynamics of ecological communities over space and time, which is a very difficult problem, indeed.

More Complex Systems

Even the simple systems described in depth here show that management of coupled natural and human systems is potentially problematic, with complexities arising because of both biological and human aspects that are both difficult to model and to manage. It is important to go through the simpler examples first, because none of the problems that are present in these simpler areas will disappear as more complex systems are considered.

A variety of issues that are problematic in dealing with more complex systems are present to some extent in the examples above:

- Multiple species

- Uncertainty
- Political pressure
- Time lag issues
- Unknown or complex interactions
- Variability
- Problems with model specificity
- Difficulty of assigning economic values
- Discounting

More complex systems will raise new issues as well. From agricultural systems (Tilman et al. 2002) to issues related to carbon cycling (Luo 2007) to changing ocean circulation (Bond et al. 2003) to dealing with the effects of other aspects of climate change new issues related to scale and uncertainty arise.

Ideas of how to describe the long term persistence, let alone the management of complex systems has been a focus of much study over the past decades. Because of problems of model specificity, much attention has been focused on looking for essentially system independent indicators of the possibility of system change, where a literature has grown up around the concept called ‘regime shifts’ (Scheffer 2001, 2009, Scheffer et al. 2009).

Beginning with the early paper by Ludwig et al. (1978), the role played by saddle –node (or fold) bifurcations in the understanding of changes in system state in natural systems has received increasing attention. A recent specific example is the analytical model of a coral-algal system in Mumby et al. (2007), where the bifurcation parameter is an externally defined grazing rate and the shift would be from a coral dominated state to an algal dominated state. Other regime shifts include desertification, eutrophication of a lake, or possibly on a global scale shifts associated with carbon dioxide levels in the atmospheres. These kinds of shifts have led to the idea of looking for early warning signs of these bifurcations as the bifurcation parameter is varied (Scheffer 2001, 2009, Scheffer et al. 2009), with the goal of finding system independent indicators. One possible difficulty (Hastings and Wysham 2010) is that systems with more complex dynamics may not exhibit the same early warning signs because the potential for the system may not exist or may not be smooth. The problem of detecting and predicting regime shifts is a difficult one in itself. Adding issues of management and economics only make the problem more complex (Walker et al. 2004, Biggs et al. 2009).

These general issues highlight the directions for future research beyond the issues that arose in thinking about the three examples of fisheries, epidemiology, and invasive species. As we move to more complex environmental systems and larger spatial scales how much effort is needed to develop specific mathematical models for the systems, versus obtaining more general results? How robust are the general results to the assumptions made? And, this is before the economic and management aspects are considered. How are valuations to be included? How can various issues of spatial and temporal scale be appropriately addressed? The mathematical problems are truly challenging and the solutions to the problems can only come about from truly interdisciplinary approaches.

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