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Optimal harvesting of a spatial renewable resource

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ABSTRACT

In this paper we investigate the optimal harvesting of a renewable natural resource. While in most standard approaches the resource is located at a single point, we allow the resource to be distributed spatially. Consequently, an agent who exploits the resource has to travel from one location to another. For a fixed planning horizon, we investigate the speed and the path of harvesting chosen by the agent. We show that the agent adjusts this speed so as to visit each location only once, even in the absence of travelling cost. Since the agent does not return to any location for a second harvest, it is optimal to fully deplete the resource upon arrival. A similar type of bang–bang solution results when we drop the assumption of a constant harvesting rate: allowing for a variable harvesting rate, the agent chooses to fully exploit the resource either in the last or in the first travelling period. A society interested in conserving some of the resource thus has to take measures to limit the exploitative behaviour of the agent.

1. Introduction

The economics of the optimal harvesting of renewable resources is well established. The fundamental papers for the case of fisheries by both Gordon (1954) and Scott (1955) are almost 60 years old by now. Whereas the former pointed to the problem of overexploitation due to the absence of property rights at sea, the latter established the path of sophisticated dynamic modelling of optimal resource management, providing the foundation for many refined research efforts in more recent decades.

Indicating current research trends and opportunities in natural resource economics, Deacon et al. (1998, p. 390) are critical of the plethora of such refinements due to their tendency to suppress important (but technically challenging) details when seeking analytical insights from simpler constructs. As the most important insights from standard models have already been obtained, an extension of these models should be attempted to incorporate more of the "real world circumstances" with which the managers of fisheries, biologists, and others are concerned.

A most urgent extension of this kind is the recognition of the *spatial dimension* prevalent in harvesting contexts. Despite its obvious relevance, none of the previous extensions along this line can be found in recent comprehensive textbooks on the topic (*e.g.* see Conrad, 2010; Perman et al., 2011). Emphasizing this extension, Hannesson (2011a) observes that "The spatial distribution of fish is rarely analysed in the existing literature, but it could make a difference."

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Our aim in this paper is to elaborate on this difference. We thus follow the agenda put forward in Deacon et al. (1998) who also forcefully demand increased realism of resource economics models by acknowledging spatial dimensions: "The spatial dimension of resource use may turn out to be as important as the exhaustively studied temporal dimension in many contexts. Curiously, the profession is only now beginning to move in this direction" (p. 393). In their survey paper on "The economics of spatial-dynamic processes," Smith et al. (2009) similarly note that whereas there is a long tradition in resource economics of being concerned with the dynamic aspects of resource use, and economics has a long history addressing spatial aspects of economic activity, the two approaches have rarely been integrated into a single model ever since Hotelling separated them in his two seminal papers (1929) and (1931).

Some authors have taken this call seriously. Recent work that simultaneously allows for spatial characteristics and a time dimension includes Sanchirico and Wilen (2005) and Costello and Polasky (2008). Both papers work within the framework of *meta-population models* with discrete patches, but with connectivity between these (*e.g.* diffusion).[1] Sanchirico and Wilen (2005) characterize the optimal way to distribute harvesting effort over space and time in order to maximize discounted profit and compare it with the results derived when ignoring these spatial processes. Once the biological dispersal process is further specified, optimal instruments are shown to be sensitive to spatial gradients of both rents and the chosen disposal, and first and second best solutions are compared.

Costello and Polasky (2008) allow for a meta-population model with random events, that is, stochastic growth of the resource within each patch and stochastic dispersal of the resource between patches. Economic variables can also be spatially heterogeneous. In this very general setting they are able to derive optimal spatially explicit harvesting strategies that maximize the expected present value of profit from harvesting. Whereas interior solutions will be time and state independent, the optimal strategy will in general vary across space. In the case of corner solutions, it may be optimal to close some patches for some periods.

Similar to Deacon et al. (1998), Smith et al. (2009, p. 105) conclude that "research addressing integrated spatial-dynamic processes is needed and arguably overdue." Wilen (2007, p. 1135) contrasts this lack of attention by (resource) economists with the prominence of spatial dynamic systems in the *hard sciences* such as mathematics and physics whose tools have been employed by scholars even to study biological and ecological issues (see *e.g.* Neubert, 2003; Kellner et al., 2007; Neubert and Herrera, 2008). The latter assume that the fish itself can move by introducing a diffusion coefficient. This particular extension, where the resource is assumed to move from areas of high to low concentration, is also taken up in recent comprehensive work of Brock and Xepapadeas (2010) and their investigation of commercial fishing in Brock et al. (2013), and allows them to investigate robust methods to control such interconnected spatiotemporal systems.

An alternative approach is to bundle the choice of an agent's harvesting speed with the amount that can be extracted, making the analysis more manageable. This approach, which is usually referred to as a *search model*, has been followed by a series of papers, among them Robinson et al. (2002, 2008) in a resource extraction (timber gathering) model. A similar approach has been chosen by Belyakov et al. (2013), whose paper is the closest to ours. These authors make similar assumptions about the spatial dimension of the renewable resource (that is, it is a single-aged, homogeneous population of a motionless resource)[2] and the harvesting technology. However, while their model also allows for heterogeneous space, the speed of movement and the harvesting intensity are interdependent, thereby effectively reducing the set of controls to a singleton. Also, the harvesting agent may decide to wait for some time in each round, but will optimally decide not to do so if the heterogeneous data of the model reveals a sufficiently large regeneration-harvesting effectiveness ratio. In our setting, though, the speed and the harvesting intensity are treated as separate choice variables (this was motivated by thinking about fishing nets as harvesting tools), while temporary waiting is not allowed. Also, in Belyakov et al. (2013) there is no discounting of future yield. Still, their approach has important similarities in method and intuition and should be seen as highly complementary to our paper.

While we believe our approach to be more general and broadly applicable, *e.g.* to agriculture and various renewable natural resources, we follow the literature and use the case of fishery for illustration and motivation.[3] The critical point from which virtually all the existing resource models abstract is that fish are (as are other resources) distributed spatially, namely in oceans, seas, and rivers. A fisher thus has to travel by boat to catch fish at each spot visited.

We assume that the boat starts at some harbour, follows a given route,[4] and eventually returns to its point of departure. The time of this journey (round-trip) depends on the speed of the boat, which is controlled by the fisher. We assume that the planning horizon of the fisher is finite. This may be interpreted as either that the fisher is concerned with only one season of fishing (or harvesting), or possesses a fishing license with fixed finite maturity, or that the planning horizon equals the fisher's working lifetime—and other interpretations may also come to mind. For this fixed planning horizon, the number

[1] Further examples of this line of research are given in Smith et al. (2009, footnote 11).

[2] As pointed out by an anonymous referee, this is equivalent to assuming a continuum of independent homogeneous stocks. With an age-homogeneous population, spatial diffusion of the resource would result in inflows to and outflows from a location to net out. Therefore, only if we allowed for a heterogeneous population *and* diffusion would movements affect the age-structure of the resource. Since the focus of our paper, similar to Belyakov et al. (2013), is on the movement of the agent, not that of the resource, we refrain from adding these additional complications at this point to the benefit of clear cut analytical results.

[3] Since the resource will not move, the reader may prefer to think of the resource as some (generic) plant or agricultural product rather than fish.

[4] The assumption of a route given at the beginning of the trip does not represent any restriction as long as there is no uncertainty about the location of the resource and hence no necessity to search: we may simply think of the given route as the most lucrative route available, determined beforehand.