



Analysis

A spatial bioeconomic model of the harvest of wild plants and animals

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ABSTRACT

The intensity of harvest of wild plants and animals often varies with the distance from human settlements, processing facilities, markets, and transportation routes such as roads and rivers, resulting in marked spatial gradients in the abundance of such resources. Spatial modeling of the harvest of wild species has therefore emerged as an important research approach. The literature on such modeling is, however, fragmented between different resource types, and empirical validation of the models is often weak or absent. This paper presents a model that is intended to have validity for a wide variety of wild plant and animal resources. It combines a logistic model of resource growth with an economic model assuming that costs associated with harvest consist of three components, namely transport, search, and handling, and a one-dimensional spatial structure where resource harvesters are based at a “central place” surrounded by infinite extensions of habitat for the harvested resource. Model outcomes show that the spatial distribution of harvest heavily depends on the carrying capacity and the catchability coefficient, i.e. the ease of finding and harvesting a resource unit. An empirical study of wildlife hunting and palm leaf harvest in indigenous villages in Ecuadorian Amazonia confirmed the validity of model outcomes.

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1. Introduction

Harvest of wild species of plants and animals is an economically very important activity for many people around the world, in particular where human population densities are low and ecosystems are relatively intact. At the same time, however, excessive harvest often leads to resource depletion and cascade effects affecting entire ecosystems (e.g. Milner-Gulland, 2008; Salo et al., 2014). Much research has therefore been dedicated to assessing the impacts of the harvest of wild species and attempting to identify policies that would contribute to halting overexploitation. Model building has been one important approach within such research. Many models, however, ignore spatial variability, in spite of that empirical research has shown that the intensity of harvest of various wild species of plants and animals often varies with the distance from human settlements, processing facilities, markets, and transportation routes such as roads and rivers, resulting in marked spatial gradients in the abundance of such resources (e.g. Peres and Lake 2003; Sirén et al., 2004; Grogan et al., 2010; López-Feldman and Wilen, 2008; Veríssimo et al., 1998; Barros and Uhl, 1995; Salo et al., 2014, Ch. 18). It has therefore been argued that sustainability must be

redefined as a “spatial and temporal concept rather than as a ‘Yes or No’ question” (Levi et al., 2011), and spatial modeling of the harvest of wild species has emerged as an important research approach. Some spatial models are purely biological, analyzing how resource abundance is affected by an empirically established or assumed spatial pattern of resource extraction (e.g. Levi et al., 2009, 2011; Sirén et al., 2004), whereas others are purely economic, focusing on how costs relate to distance but disregarding the dynamics of the resource itself (e.g. Albers, 2010). When a biological and an economic harvest model are combined, and either one, or both, incorporates some sort of spatial variability, the result is a spatial bioeconomic harvest model. Such models have since long been used for the study of marine fisheries (e.g. Schaefer, 1957; Holland et al., 2004; Clark, 2007; Smith et al., 2009). More lately they have also been increasingly used in the study of hunting (e.g. Damania et al., 2005; Ling and Milner-Gulland, 2008; Skonhoft and Armstrong, 2005; Sirén et al., 2013a, 2013b), and the gathering of non-timber plant resources (e.g. López-Feldman and Wilen, 2008; Robinson et al., 2008). The purpose of such modeling studies is often to analyze how changes in e.g. management practices, national and international policies, economic incentives, or socio-economic conditions may affect harvest levels and resource abundance.

For example, a review article about the “spatial economics of non-timber forest product extraction” (Albers and Robinson, 2013) turns out to focus just on plant resources, disregarding that wild animals often are more significant non-timber forest resources than plants,

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both in terms of their importance for local economies, and the ecological impacts of their extraction. On the other hand, Flaaten and Mjølhus (2010) made a model for the analysis of nature reserves as management tools for optimizing harvest levels, with the explicit ambition to make it so general that it could be applicable to a wide variety of wild species resources, in terrestrial as well as marine environments. Both harvest models that are made for very specific cases, and those that are intended to be very general and provide universally applicable results, run the risk of overlooking how the specific characteristics of a resource may influence harvest practices and their impacts.

Modeling in itself is a purely mathematical exercise, and only by validating models against empirical data one can know to what extent they have relevance for understanding the real world around us. Nevertheless, many articles based on spatial bioeconomic harvest modeling provide no validation at all except, at best, anecdotal evidence (e.g. Clayton et al., 1997; Flaaten and Mjølhus, 2010; Robinson et al., 2008; Skonhoft and Armstrong, 2005). Only relatively few articles provide empirical validation of either ingoing assumptions (e.g. Sirén et al., 2013a), or model outputs (e.g. López-Feldman and Wilen, 2008). Critical discussion of ingoing assumptions is often lacking and some published models actually build on assumptions that are questionable or simply wrong. For example, Johannesen (2007, Eq. 5) assumes that harvest per unit of labor increases both with resource density and land area, something which is not only contradictory to prevalent models in the field, but also ungrounded in empirical data and simply illogical.

In fact, even the basic mechanisms that create the spatial gradients of resource harvest, so commonly observed in real life, remain relatively poorly understood. In order for such a gradient to emerge in a homogeneous environment, there must be some spatial variability in the net benefit acquired per harvested resource unit. Without doubt, such variability often exists. Obviously, for example, anybody hunting for other purposes than pure entertainment would rather hunt an animal near home than at a distance of several hours of travel. The underlying reasons for such preferences, however, can be manifold, and in order to introduce this spatial variability into bioeconomic harvest models, different authors have used different assumptions. Sirén et al. (2013a) empirically documented an increasing marginal cost of distance for Amazonian subsistence hunters who walked away from their village out into the forest. Authors of other models have introduced this spatial variability using various other respective assumptions, some of which are more specific, but which seldom are supported by stringent empirical evidence. Such assumptions have been e.g. a maximum duration of harvesting trips due to the perishability of the harvested resource (Clayton et al., 1997), an increasing opportunity cost of labor time (Robinson and Albers, 2006; Robinson et al., 2002), a fixed “bag size limit”, i.e. a maximum amount of harvested resource that can be carried back to the point of departure (Ling, 2004), a walking speed that decreases with distance or weight of the harvested resource carried (Robinson et al., 2008), or diminishing marginal benefits from extraction (Albers, 2010).

The present study is aimed at building a spatial bioeconomic harvest model that would be applicable to a wide variety of wild plant and animal resources, at least in terrestrial ecosystems. Rather than providing simple outcomes applicable to all kinds of resources, however, it should explicitly help explain how the specific characteristics of each resource may lead to differences in harvest practices and their impacts. Moreover, we validate model outputs against empirical data of two very different types of resources, namely, the leaves of the *Pholidostachys synanthera* palm, and hunted game animals, in places near each other and similar in terms of natural as well as socio-economic conditions in Ecuadorian Amazonia. The specific purpose of the empirical validation is to evaluate to what extent the model correctly predicts how the spatial distribution of harvest differs between the two resource types.

2. The Model

2.1. Model Assumptions

The model, which is further described in Appendix A, is an analytical deterministic equilibrium model based on the assumption that the resource grows according to the logistic equation:

$$\frac{dN}{dt} = rN \left(1 - \frac{N}{K}\right) - H$$

where N is the resource population size (density), r is the intrinsic growth rate, t is time, K is carrying capacity, and H is harvest. Harvest, H , is directly proportional to the resource density, as well as to the time spent searching, S , and to the so-called *catchability coefficient*, q , which is a measure of the proportion of resource units present which are found by a harvester during one unit of time spent searching:

$$H = qSN.$$

Spatially, the model is one-dimensional, consisting of an infinite number of equidistant and equally sized patches, one of which is a “central place” from which harvesters depart and to which they return after harvesting. This mimics e.g. situations where people live along a road or a river, and travel in a perpendicular direction from these out into the forest in order to harvest wild species resources.

The price, p , per unit of harvested resource, is fixed, such that revenues are linearly proportional to harvest, H . The costs incurred to harvesters are assumed to consist only of the opportunity cost of the time spent. A distinctive feature of this particular model is how this time is considered to consist of three different activities; travel, search, and handling. Harvesters are assumed to travel, at constant speed from the origin to some site where they stop, and instead begin to search for the resource. Then, once a resource unit is encountered, harvesters stop searching and instead start handling, which means the converting of the wild living resource into something that can be transported back to the harvester's origin, e.g. pursuing and eviscerating an animal, cutting leaves and packing them into bundles, or felling a tree and cutting it into boards. Finally, once a harvester has encountered and handled the maximum number of resource units that he can carry, he transports them back to where he came from. The total cost incurred by harvesting in any patch can thus be represented by the following expression:

$$C = c \left(S + \frac{H}{v_h} + \frac{dH}{v_t} \right)$$

where C is total cost in a patch, c is the opportunity cost of time, v_t is the speed of transport, d is distance, and v_h is the speed of handling. As the amount of search labor, S , in each patch determines the revenues as well as the costs incurred, this is the choice variable in the model. The profit from harvesting resulting from searching time S , when the resource level is N can be written as

$$\Pi = pH - C = P(d)H - cS = S(P(d)qN - c),$$

where $P(d) = p - c \left(\frac{1}{v_h} + \frac{d}{v_t} \right)$ is the profit from handling, transporting and selling one unit of resource.

2.2. Model Results

Based on the simple set of assumptions described above, we modeled the spatial distribution of search labor, S , resource abundance, N , harvest, H , and profit, Π , for two different scenarios regarding how

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