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Analysis

Economic/ecological tradeoffs among ecosystem services and biodiversity conservation

A.M. Tanvir Hussain [a], John Tschirhart [b,*]

[a] Department of Economics and Social Sciences, BRAC University, 66 Mohakhali, Dhaka 1212, Bangladesh
[b] Department of Economics and Finance, 1000 E. University Avenue, University of Wyoming, Laramie, WY 82071, USA

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A B S T R A C T

An integrated economic/ecological model is built to address tradeoffs between biodiversity conservation and two marketable rangeland ecosystem services: cattle grazing and elk hunting. The ecology is represented by an eleven species food web in which individual optimizing plants and animals engage in competitive and predator/prey relationships. The ecological model defines a steady-state set of sustainable grazing and hunting options, and for each option, biodiversity is measured using an index defined over the eleven species. In linking the ecology to the economics, social welfare depends on grazing profits and hunter net benefits. The problem can be stated as maximizing economic welfare over two ecosystem services, subject to their sustainable use and subject to a target level of biodiversity. A numerical application with economic and biological data from the Western United States is used to determine sustainable grazing and hunting options for alternative biodiversity levels, and to select the option that maximizes welfare.

1. Introduction

People derive countless consumptive and non-consumptive goods from ecosystems. These goods, often referred to as ecosystem services, are derived from biodiversity according to the linkages recognized in the Millennium Ecosystem Assessment (2005): biodiversity ➔ ecosystem functions ➔ ecosystem services ➔ human well-being. However, tradeoffs across the services abound and the very act of acquiring the services puts biodiversity at risk, thereby, jeopardizing future service flows.[1] An important research goal is to identify and assess the tradeoffs. Doing so will promote efficient use of the services and avoid inefficient biodiversity losses.

The purpose here is to develop an integrated economic/ecological model to examine tradeoffs between two rangeland ecosystem services, while emphasizing how alternative levels of services impact biodiversity. The source of biodiversity is a rangeland food web in which predator–prey and competitive relations among eleven plant and animal species determine ecosystem functions that include primary and secondary production, energy and biomass flows, and regulation of populations. Human welfare is measured over the two provisional ecosystem services: cattle grazing and elk harvesting. There are tradeoffs between the services because grazing and harvesting create ecosystem externalities that underpin common conflicts in Western North America.[2] As Loomis (2002) states "One of the continuing issues in Bureau of Land Management (BLM) has been the conflict between the cattle stocking rates and effects on fish and wildlife resources." (p. 412). The problem can be stated as maximizing economic welfare over two ecosystem services, subject to their sustainable use and subject to a target level of biodiversity.

The rangeland is described by a general equilibrium ecosystem model (GEEM, Tschirhart, 2000). Identical individuals within each of the eleven species are assumed to be maximizing their incoming net energy by choosing how much biomass to grow in the case of plants or how much biomass to consume in the case of animals. Essentially, each individual organism is an optimum forager, and their demands and supplies are aggregated similar to how consumers and firms are aggregated in computable general equilibrium models. Species populations are updated depending on individuals' successes in obtaining net energy. This paper extends previous general equilibrium ecosystem modeling by: 1) applying it to eleven species and two services in a rangeland, 2) deriving a species growth function for the harvested species whose carrying capacity is dependent

* Corresponding author. Tel.: +1 307 766 2356.
E-mail addresses: abulmaala@gmail.com (A.M.T. Hussain), jtsch@uwo.edu (J. Tschirhart).

[1] Examples of tradeoffs are: 1) the conversion of mangroves to aquaculture thus gaining a provisional ecosystem service from food production, but losing supporting services from having fewer wild fish nurseries, and losing regulating services from diminished storm barriers (Barbier, 2009); 2) timber production and preserving the Monarch butterfly in Mexico as a cultural service at the loss of the timber production as a provisional service (Conrad and Salas, 1993).

[2] See Crocker and Tschirhart (1992) or Tschirhart (2009) on the definition and consequences of ecosystem externalities.

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on its relationships with the other ten species and cattle stocking, 3) using the growth function to establish a sustainable set of the two ecosystem services, and 4) showing how alternative sets of services impact two measures of biodiversity.[3]

In a related work, van Kooten et al. (2001) construct an innovative model that includes similar ecosystem services to those herein, namely, cattle grazing, hunting, in addition to wildlife viewing. Their model is dynamic which allows them to address optimal paths, whereas here only steady states are derived. Their net benefits, like here, consist of rancher profit and hunting values, and unlike here, wildlife existence values. Because data on existence values is sparse, wildlife values are replaced here with measures of biodiversity that are described below and that may be a constraint on the choices of the two consumptive ecosystem services. Also, with respect to harvesting, a distinction is made here between successful and unsuccessful hunters, and hunters' meat values versus their trip related values. But the principle difference between van Kooten et al. and here is the biology. Their logistic model places all non-harvested species into a carrying capacity term which omits individual plant and animal behavior that is the basis for ecosystem dynamics (Tschirhart, 2009). And because all their wild herbivores are collapsed into a single stock, there is no opportunity to measure biodiversity.

Other authors have investigated tradeoffs between provisional ecosystem services involving grazing. Examples include Cory and Martin (1985) and elk versus cattle, Bastian et al. (1991) and antelope versus cattle, Loomis et al. (1991) and deer versus cattle, and Bostedt et al. (2003) and timber versus reindeer. There are also studies of tradeoffs between provisional and cultural services such as Montgomery et al. (1994) and timber versus the northern spotted owl, Arthaud and Rose (1996) and timber versus ruffed grouse, and Nalle et al. (2004) and timber versus both porcupine and the great horned owl. The biological complexity in this work ranges from assuming a simple linear tradeoff between elk and cattle (Cory and Martin), to deriving a three-dimensional production possibility frontier over three outputs based on spatial population simulations that account for animal life histories and habitat preferences (Nalle et al.).

Direct comparisons between this paper and these other approaches are difficult owing to the different ways in which the biology is modeled. Unlike the other approaches, GEEM attributes behavior to the plants and animals such that their predator/prey activities depend on signals in the form of energy prices, while those prices are the result of their aggregate activities and human interventions. In economics, prices are commonly thought of as signals, consequently, integrating GEEM with economics highlights how economic and ecological agents constantly adapt to each other's signals. Specifically, integration can reveal unexpected results such as the sustainability boundary derived below which indicates that, over some range of values, stocking and elk harvesting are positively related in spite of the competition between elk and cattle for grass. Generally, integrating economics and ecology can capture important intersystem feedbacks that non-integrated modeling may miss (Barbier et al., 1994; Costanza et al., 1993; Crocker and Tschirhart, 1987; Perrings, 1987; Settle et al., 2002; Tilman et al., 2005; Wätzold et al., 2006).

The following section presents the rangeland ecosystem model and develops the elk growth curves. Section 3 introduces cattle stocking and elk harvesting into the ecosystem, and in Section 4 the sustainability set is built. Economic optimization is in Section 5, and biodiversity measures are introduced in Section 6. Section 7 presents a numerical example, and a discussion ends the paper in Section 8. Appendix A describes the biological data in more detail.

[3] GEEM has been used previously to examine commercial fisheries in partial-equilibrium (Finnoff and Tschirhart, 2003) and general-equilibrium economies (Finnoff and Tschirhart, 2008), optimal cattle stocking with invasive species (Finnoff et al., 2008), plant invasions (Finnoff and Tschirhart, 2005) and rodent invasions (Kim et al., 2007). For other examples of general equilibrium modeling of ecosystems see Eichner and Pethig (2007, 2009).

2. The Rangeland Ecosystem Model

2.1. General Equilibrium and Dynamics

The multispecies, rangeland ecosystem modeled is typical of the Western U.S. These rangelands support grasses, forbs, shrubs and trees in various combinations that provide habitat to many kinds of native and exotic species (Heady, 1996). There are approximately 760 million acres of rangelands in the U.S. including grasslands, prairies, desert shrublands, woodlands, etc. Approximately 262 million acres managed by the U.S. Fish and Wildlife Service (USFWS) and the BLM are leased for grazing (Skaggs, 2008). In 2006, 12.5 million people hunted and 71.1 million people were involved in at least one form of wildlife viewing on these lands (USFWS, 2006).

The food web for the rangeland ecosystem in Fig. 1 includes three trophic levels, with grass and shrub comprising the first trophic level, the grazers, browsers, and mixed feeder herbivores the second, and carnivores the third. Each species is indexed by a number between 0 (sun) and 11 (coyote (*Canis latrans*)). The arrows show the direction in which biomass (and energy) flow, and the accompanying numbers show the percentage of a predator's diet coming from a prey species: e.g., grass makes up 90% of the elk (*Cervus elaphus*) diet. The sun is the source of all energy, which is always in balance (Tschirhart, 2000), and it is turned into biomass by the two primary producers (grass and shrub). Grass and shrub are composites of different species of grasses and shrubs; species are often aggregated in ecological modeling (Solow and Beet, 1998). Plant species occupy a fixed plot of land; soil and moisture conditions are omitted.

Animal and plant behaviors are consistent with ecological principles, but modeled with microeconomic methods. The details about the period-by-period equilibrium calculations and the population updating can be found elsewhere (Finnoff and Tschirhart, 2003, 2005, 2008; Tschirhart, 2002, 2004), so the basic structure of GEEM is omitted for brevity. Briefly, individual plants and animals are assumed to behave as if they maximize their net energy over each reproductive time period (one year). Individual animals maximize over the biomass they consume from prey, where prey may be animals or plants. The choices about which prey to consume and in what quantities are driven by the energy prices for locating, capturing and handling prey. Biomass consumed is converted into energy, and energy per unit of biomass varies across prey species. The predation costs to an animal include the energy prices paid, the respiration energy lost to the atmosphere, and exposure to predators that may lead to their own capture. Plants maximize over how much biomass to grow, with more biomass meaning more exposure to sunlight and more energy from photosynthesis. Individual plants engage in intra- and inter-species competition for access to sunlight by growing photosynthetically active biomass. Plants also pay energy prices that depend on the intensity of competition with other plants for sunlight. Costs to the plants include the energy prices, the respiration energy lost to the atmosphere and biomass lost to herbivores. In each time period, there must be biomass balance: for animals the total biomass consumed by predators must not be greater than what prey are 'willing' to supply (prey are 'willing' because they too must consume which exposes them to predation risk (Lima, 1998)), and plant biomass cannot exceed the physical area they occupy.[4] The balance conditions determine the market clearing energy prices that animals pay to consume prey and plants expend to grow biomass. The calculations in each time period determine the biomasses consumed and grown, and the energy prices, and they are similar to the calculations in a computable general equilibrium economic model. The system is in general equilibrium in each time period, where general equilibrium is defined as a state where all plants and animals are optimizing and

[4] For simplicity, physical area and not volume is used.