Ecological-Economic Modeling for Biodiversity Management: Potential, Pitfalls, and Prospects

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Abstract: *Ecologists and economists both use models to help develop strategies for biodiversity management. The practical use of disciplinary models, however, can be limited because ecological models tend not to address the socioeconomic dimension of biodiversity management, whereas economic models tend to neglect the ecological dimension. Given these shortcomings of disciplinary models, there is a necessity to combine ecological and economic knowledge into ecological-economic models. It is insufficient if scientists work separately in their own disciplines and combine their knowledge only when it comes to formulating management recommendations. Such an approach does not capture feedback loops between the ecological and the socioeconomic systems. Furthermore, each discipline poses the management problem in its own way and comes up with its own most appropriate solution. These disciplinary solutions, however, are likely to be so different that a combined solution considering aspects of both disciplines cannot be found. Preconditions for a successful model-based integration of ecology and economics include (1) an in-depth knowledge of the two disciplines, (2) the adequate identification and framing of the problem to be investigated, and (3) a common understanding between economists and ecologists of modeling and scale. To further advance ecological-economic modeling the development of common benchmarks, quality controls, and refereeing standards for ecological-economic models is desirable.*

Key Words: biodiversity management, conservation, economics, interdisciplinary research

Modelado Ecológico-Económico para la Gestión de Biodiversidad: Potencial, Escollos y Prospectos

Resumen: *Tanto ecólogos como economistas utilizan modelos para desarrollar estrategias para la gestión de biodiversidad. Sin embargo, el uso práctico de modelos disciplinares puede ser limitado porque los modelos ecológicos tienden a no considerar la dimensión socioeconómica de la gestión de biodiversidad, mientras*

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que los modelos económicos tienden a descuidar la dimensión ecológica. Considerando estas limitaciones de los modelos disciplinares, existe la necesidad de combinar conocimiento ecológico y económico en modelos ecológico-económicos. No es suficiente que los científicos trabajen separadamente en sus propias disciplinas y que combinen su conocimiento solo cuando se trata de formular recomendaciones de gestión. Tal aproximación no captura la realimentación entre los sistemas ecológico y socioeconómico. Más aun, cada disciplina plantea el problema de gestión en su propia forma y propone su propia solución adecuada. Sin embargo, es probable que estas soluciones disciplinares sean tan diferentes que no es posible encontrar una solución que combine aspectos de ambas disciplinas. Las condiciones previas para una exitosa integración, basada en modelos, de la ecología y la economía incluyen (1) un conocimiento profundo de las dos disciplinas, (2) la adecuada identificación y encuadre del problema a investigar, y (3) un entendimiento común de modelado y escala entre economistas y ecólogos. Para avanzar en el modelado ecológico-económico es deseable el desarrollo de puntos de referencia comunes, controles de calidad y estándares de referencia para modelos ecológico-económicos.

Palabras Clave: conservación, economía, gestión de biodiversidad, investigación interdisciplinaria

Introduction

In economics and ecology, models play an important role in developing management recommendations for the sustainable use and conservation of biodiversity. Ecological models are used to describe and assess the effects of conservation measures and management strategies on the spatiotemporal dynamics and the persistence of ecosystems (Burgman et al. 1993; Huth & Ditzer 2001). The practical policy use of these models can be limited because they tend not to address the socioeconomic dimension, including economic, institutional, and political factors, which is the realm of economic models (Shogren et al. 1999). But economic models have their own problems when they make assumptions on the ecological effects of conservation that are oversimplified or do not represent current ecological knowledge. Disciplinary models reveal their limits when addressing issues that have an ecological and a socioeconomic dimension. Although a few integrated models have been developed to address biodiversity management issues (e.g., Johst et al. 2002; Baumgärtner 2004; Perrings & Walker 2004), ecological-economic modeling is still not used widely. Given the obvious shortcomings of purely disciplinary models, this lack of integrated models is unsatisfactory (Perrings 2002; Shogren et al. 2003).

We believe significant gains could be made for biodiversity management if models integrating ecological and economic knowledge were used more widely. So why is this not the case? Two roadblocks are usually cited. First, the existing structure and incentives of research institutions favor disciplinary research over research that integrates several disciplines. "My institution does not reward me for multidisciplinary research" is a common response to complaints about a lack of integrated research (e.g., Committee on Science, Engineering, and Public Policy 2004; Jakobsen et al. 2004; Rhoten 2004). The second roadblock is discussed less frequently but is probably equally or even more important and, therefore, deserves particular attention. This roadblock is related to the mindset of researchers and to challenges that arise when integrated models are developed. Some people do not see the advantages of ecological-economic modeling. Many scientists from both disciplines are unaware of the potential improvements in their work that could arise by integrating knowledge from the other discipline. And those scientists who have tried to cooperate with colleagues from the other discipline point to the conceptual and practical challenges that arise when crossing boundaries. Challenges include integrating differing perceptions of real-world phenomena by ecologists and economists, improving communication of style and substance between the disciplines, addressing fears that detailed knowledge from both disciplines is lost in the mix, and developing a common understanding between economists and ecologists of modeling and appropriate spatial and temporal scales (e.g., Roughgarden 2001).

We focus on the second roadblock. We address how to overcome explicit and implicit barriers for ecological-economic modeling, resulting from researchers' mindsets, and challenges in developing integrated models. Through this, we hope to encourage and facilitate the widespread development and use of ecological-economic models. We also discuss the advantages of ecological-economic modeling and then draw attention to challenges that impede a true integration of ecological and economic knowledge in models. We conclude by discussing how these challenges can be overcome and develop prospects on how ecological-economic modeling can evolve in future research.

Why Ecological-Economic Modeling?

A model may be described as a purposeful representation of a system (Starfield et al. 1990) that consists of a reduced number of (1) system elements, (2) internal relationships between these, and (3) relationships between system elements and the surrounding environment of the system. The specification of the system elements and the internal and external relationships determine to what extent we have a disciplinary or an integrated model and depend on the purpose of the model. If the purpose is to develop recommendations for biodiversity management, the answer to the question of whether integration of the two disciplines ecology and economics is to be preferred over a disciplinary approach depends on how this purpose can best be achieved.

Some aspects of the management problem can be well understood within a disciplinary approach. For example, estimating the size of the protected areas required to provide desirable conservation outcomes for threatened plant species (e.g., Burgman et al. 2001) may not require any economics. Similarly, analyzing how the lobbying process of environmental and industrial groups affects timber harvesting and thus conservation (e.g., Eerola 2004) may not require any input from ecology. But selecting between alternative sites or analyzing the ecological impacts of timber harvesting would certainly require an interdisciplinary effort. In fact most biodiversity management problems include aspects from ecological and socioeconomic systems, and adequate recommendations directed at such problems can be developed only if knowledge from economics as well as ecology is taken into account in an integrated manner.

This holds for many issues usually approached by only one discipline. Consider the following three examples: (1) The optimal selection and design of reserve sites has been the domain of ecology (Margules et al. 1988). But as Ando et al. (1998) and Polasky et al. (2001) show, cost savings of up to 80% can be achieved by integrating economic costs (i.e., land prices) into conventional ecology-driven selection algorithms for reserve sites. (2) Similarly, the analysis of the cost-effective spatial differentiation of environmental policy instruments is a domain of economics (e.g., Kolstad 1987; Babcock et al. 1997). But the benefit functions considered by economists in their discussions of policy instruments are typically based on abstract assumptions and do not include all possible benefit functions relevant in the context of biodiversity conservation. Wätzold and Drechsler (2005) base their benefit functions on ecological theory and show that benefit functions for biodiversity management exist that have not been considered previously by economists. The introduction of these new benefit functions into the analysis of the cost-effectiveness of spatially differentiated conservation instruments led to recommendations for management situations that were not captured by the purely economic models. (3) The development of optimal management strategies for endangered species is again a typical domain of ecology. But people value species for reasons other than just conservation. By integrating conservation, tourism, and hunting values in a model, Skonhoft et al. (2002) examined various management strategies for a mountain ungulate, the chamois (*Rupicapra rupicapra*), in the French Alps. Their findings illustrate how research that takes into account many values may lead to different optimal management guidelines than research that focuses only on conservation value. Applying ecological-economic modeling enabled Skonhoft et al. to capture different societal values related to biodiversity, to analyze conflicts between these values, and to devise strategies for optimal conflict management.

Ecologists and economists work on similar problems, and they obtain certain results through disciplinary research. But the three examples illustrate that disciplinary research could well produce suboptimal results relative to a modeling strategy in which both disciplines are involved to the full extent called for by the problem. As a consequence, the derived disciplinary management recommendation is likely to be less productive than it could be or may not be adopted at all by policy makers. Scientists might misattribute this to a "policy failure" (cf. Hahn 1989; Schneider & Kirchgässner 2003) instead of recognizing it as a "science failure."

To solve this problem, is it sufficient to carry out disciplinary research and take into account results from the other discipline only at the moment when it comes to designing management recommendations? The answer is no, for two main reasons: the incompatibility of disciplinary solutions and the lack of feedback between ecological and socioeconomic systems. First, if scientists work separately in their own disciplines, each discipline poses the problem in its own way and comes up with its own "most appropriate" solution. These disciplinary solutions, however, are likely to be so different that a combined solution considering aspects of both disciplines cannot be found. To illustrate, consider again the problem of reserve site selection. In a purely ecological reserve selection algorithm, the analyst maximizes the number of protected species within the constraint of limited total habitat area and derives a set of reserves to be protected. The corresponding purely "economic" problem—which, in a sense, is "complementary" to the ecological one—is to minimize economic costs of habitat area under the constraint of staying above a certain threshold on the total reserve area. Even though this total reserve area may be identical to the one in the "ecological problem," the economist derives a different set of reserves to be protected relative to the ecologist.

Although each of the two sets of reserves solves the distinct ecological and economic optimization problems, neither solution meets the integrated and superordinate objective of maximizing the number of protected species at given total costs. Even a clever combination of these two solutions is unlikely to meet that objective. Instead, the desired solution can be obtained only by framing the conservation management problem correctly in cooperation between the two disciplines right from the start. In the example of reserve selection this means that marginal contributions of individual reserves to the overall conservation objective are formulated as functions of costs rather than reserve area. The optimal combination of reserves for a given budget then is obtained where the marginal contributions to the overall conservation objective per unit cost are equal among all reserves (Possingham et al. 2002; Haight et al. 2004).

The second reason that it is not sufficient to first develop disciplinary models and then combine results from both disciplines is that this approach does not address the feedback loops between the ecological and the socioeconomic system. The importance of such feedback has been demonstrated by, for example, Settle et al. (2002) and Quaas et al. (2004). Settle et al. show how nature park visitors adapt their fishing behavior to the abundance of a fish species (cutthroat trout); the higher the abundance, the more people fish, which may either stabilize or destabilize the fish population. If no interaction of the cutthroat trout with other fish species is assumed, the described adaptive fishing behavior represents a negative feedback and has a stabilizing effect because population growth of cutthroat trout increases as fishing pressure decreases. But fishing also affects the abundance of another fish species, the lake trout, which leads to a positive feedback. Decreasing fishing pressure increases the abundance of lake trout, which increases their predatory pressure on the cutthroat trout, which in turn decreases the growth rate of cutthroat trout. As Settle et al. demonstrate, depending on the type of population management, this positive feedback could lead to the extinction of the cutthroat trout population that, without such feedback, would be viable. Ecological-economic modeling here has been crucial in detecting an important risk to the cutthroat trout population.

In Quaas et al.'s case of livestock farming in semiarid regions, a direct relationship exists between the land-use strategy of the farmer, the variability of a resource (e.g., grass eaten by livestock), and the farmer's income. A conservative grazing strategy leads to low variation in the ecological resource and the farmer's income and to higher persistence of the resource. A less conservative grazing strategy does the opposite. Therefore a risk-minimizing grazing strategy is also sustainable in that it maximizes persistence of the ecological resource. Without a feedback loop the farmer would not be "punished" for risky behavior, and even if the farmer was averse to risk he or she would overuse the ecological resource and reduce its persistence. In this case ecological-economic modeling demonstrates that short-term economic benefit and long-term biodiversity conservation need not necessarily be at odds with each other.

Fundamental similarities exist in the problems addressed by the two disciplines that facilitate cooperation and make it rewarding. Both disciplines, for instance, study stability properties of a system. Economists investigate the equilibria of a system, whether those equilibria are stable, and in which direction the system's state changes when certain constraints and parameters are altered. Ecologists are similarly concerned with stability, except they usually do not assume their system is in equilibrium (be it static or dynamic), and they allow for complex system behavior such as cycles, chaos, or a variation of key state variables within certain boundaries (Grimm & Wissel 1997; Jeltsch et al. 2000; Walker et al. 2004). Economists have begun to employ stability measures (specifically resilience) from ecology to explore the properties of coupled systems. Resilience refers either to the speed of return to equilibrium following perturbation (Pimm 1984) or to the perturbation needed to move a system from some basin of attraction (Holling 1973). The second concept is related to the sustainability of the productive potential of the system. System resilience is a measure of the robustness of that potential in the face of the stress induced by economic activity (Brock et al. 2002).

Another similar question addressed by both disciplines is the optimal use of limited resources. Ecologists explore how plant and animal species maximize their reproductive success and survival in the face of limited food and other resources, whereas economists examine how humans maximize their well-being within a budget constraint (Settle et al. 2002). In this context Baumgärtner et al. (2004) distinguish resources that are scarce in a relative sense (i.e., substitutable by other resources) and resources that are scarce in an absolute sense (not substitutable). According to Begon et al. (1990) optimal foraging theory as a field of ecology is largely based on the concept of relative scarcity. As Baumgärtner et al. (2004) point out, environmental economics is also based on that concept, which means that there is an overlap between ecological and economic theory. But they also note that a considerable part of ecological theory, and in particular biodiversity issues, contains many elements of absolute scarcity, a concept that is only rarely a matter of economic research. Consequently, although the concept of scarcity provides some common ground between ecology and economics, substantial differences exist between how the two disciplines use this concept. Baumgärtner et al. (2004) warn that ignoring these differences may lead to substantial misunderstanding. In this manner the concept of scarcity provides both a chance for integration of ecology and economics and a challenge if used inappropriately.

Challenges and Pitfalls

Ecological-economic modeling combines the knowledge and concepts of two disciplines through the methodological approach of modeling. To do this successfully requires (1) an in-depth knowledge of the two disciplines by the researchers involved, (2) adequate identification and framing of the problem to be investigated, and (3) a common understanding of modeling and scales between economists and ecologists. In fulfilling these requirements, impediments and pitfalls, which are typical for ecological-economic modeling, are likely to come up.

In-Depth Knowledge of the Two Disciplines

We do not exaggerate in saying—on average—economists' awareness of what ecologists do, and vice versa, is not well developed. Economics is sometimes confused by ecologists with business or finance. Some economists think ecologists are solely interested in collecting and studying plants and animals for their own sake, failing to appreciate that land management is a major issue in subdisciplines such as landscape ecology and conservation biology. Such confusions or prejudices are probably restricted to researchers who have limited or no experience with the other discipline. But even scientists who closely work with colleagues from the other discipline often do not have a good understanding of this discipline for numerous reasons, including the benefits of professional specialization.

Limited knowledge of the other discipline becomes an issue when scientists assume that their own simplified views represent a complete picture of the other discipline's concepts, ideas, and methods. Then, they miss the opportunity to make full use of the richness of knowledge that exists in the other discipline. Ecologists who assume that, by integrating costs of conservation measures into their models, the full knowledge available in economics has been incorporated may miss essential aspects of a problem (e.g., transaction costs, asymmetric information between policy makers and land users, property rights, and risk aversion of economic agents). Similarly, economists are often unaware of the knowledge ecologists have about the spatial, temporal, and functional structure of ecosystems and restrict themselves to simplified—spatially homogenous, static, or scalar—descriptions of ecological systems and processes.

Adequate Identification and Framing of the Problem

Ecologists and economists are educated to examine the real-world phenomena that interest them in different ways. When looking at the same biodiversity management problem, they identify different factors they consider to matter, formulate different research questions, and design different research projects. In fact, an inherent tension exists to frame a project from either an ecological perspective of "conservation at whatever cost" versus the economic perspective of "more conservation at less cost." The challenge is to integrate these self-imposed world views to provide more insight into the management problem.

Again a good example is the reserve-selection problem, which ecologists typically view as a problem of protecting as many species as possible in a given number of reserves. The focus of research projects is on compiling species lists for potential reserves, and most of the scientific effort and staff time go into designing and carrying out effective biodiversity surveys. The role of economics—if it exists at all—is of an "add-on" type. After compiling the species lists and formulating a conservation plan, one carries out a cost-benefit and/or acceptance analysis of the plan and at maximum devises one or two alternative plans. As discussed above, such an approach is unlikely to identify the "best" conservation plan. The reason is that economic knowledge is brought in after the problem has been identified and formulated from the ecological point of view.

Typically, an add-on of one discipline occurs when a call from a funding organization requires an interdisciplinary approach. Researchers from one discipline design the basic structure of the project proposal and much later in the process invite the "missing" discipline to join the project. Our experiences as invited participants in and evaluators of interdisciplinary project proposals indicate that a substantial majority of proposals are based on an "add-on approach." We believe it is essential that when it comes to adequate identification and framing of the problem, economics and ecology must be brought together on an equal basis and as early as possible in the process. By doing so, the researchers can then identify early on where the key feedback loops exist between the two systems, which will help determine later on their relative importance in both modeling and policy.

Common Understanding of Modeling and Scales

Even if the researchers of both disciplines acknowledge the richness of the other discipline, are willing to learn from each other, have agreed on the overall aim of the research, and will cooperate continuously during the course of the entire project, the different approaches to modeling and spatial and temporal scales applied in the two disciplines may hamper communication and integration of ecological and economic knowledge.

Drechsler et al.'s (2005) results from a survey of 60 models related to biodiversity conservation and randomly selected from eight ecological and economic journals show that economic models are usually general or conceptual and of low complexity, are formulated and solved analytically, are often static, and do not address uncertainty. Although sharing some similarities with economic models, most ecological models are usually solved numerically or through simulation. Many ecological models, however, have different properties: they are specific to a particular species and a geographic region, are relatively complex, are formulated via rules simulated step by step to model the dynamics of the system, and consider explicitly various uncertainties. (We are aware that computational models are applied in some fields of economics [Judd 1997; Tesfatsion 2002], but they are much less common than in ecology and are practically nonexistent in the economic analysis of biodiversity management.)

Economic and ecological models also approach spatial heterogeneity and temporal dynamics differently (Gibson et al. 2000; Drechsler et al. 2005). Space and time and their appropriate scaling receive comparatively less attention in economic than in ecological models. If space and time are considered, economic models mostly use abstract spatial and temporal scales (e.g., regions, periods) and future events are discounted. Ecological models frequently use concrete scales (e.g., square meters, hours) and give equal value to present and future events. The different approaches to scales have led some researchers to speak of the "incompatibility of economic and ecological scales" (Holub et al. 1999).

This position is too pessimistic because both disciplines do consider a relatively wide range of scales in their research. To successfully resolve the scale issue one needs a common rule for selecting the appropriate scale. In both disciplines the choice of scale in the process of model building depends on the management problem to be analyzed with the model. The same applies in ecological-economic modeling. The necessary precondition for resolving the scale issue is, therefore, the common identification and framing of the management problem. Once a common research problem has been properly defined it is generally easy to agree on a common scale (the references to ecological-economic models throughout this paper provide examples for the successful resolution of the scale issue). When ecologists and economists talk about modeling and scales, however, they should be aware that the words *modeling* and *scales* have different interpretations. We have to find a common approach and language related to modeling and scales and cannot take it for granted that this common approach is the approach with which we usually work.

Prospects for Ecological-Economic Modeling

The use of ecological-economic models has been the exception, not the rule, when model-based recommendations for biodiversity conservation management have been developed. We argue this is not because the approach is poorly suited, but because two roadblocks have slowed down ecological-economic modeling: (1) the structure of research institutions that favor disciplinary research and (2) the mindset of researchers and a lack of knowledge about how to carry out ecological-economic modeling. We sought explicitly to shed light on the second roadblock because the first has received comparatively more attention. Nevertheless, research structures that allow and facilitate a fruitful communication and collaboration of economists and ecologists are indispensable. Such structures include adequate funding, incentives, and opportunities in universities and research institutions for integrated research as well as publication opportunities that are attractive for both disciplines.

Regarding the second roadblock, the prospects for future advances in ecological-economic modeling depend on whether we can address the three identified challenges and pitfalls in developing ecological-economic models. Consider how to address the first two challenges—full knowledge from ecology and economics and equal involvement of both disciplines in identifying and framing the problem. Here the issue is learning and the mindset of scientists. Regarding the third challenge—common understanding of modeling and scales—more research on why differences exist in ecological and economic models would be useful. Increased understanding would improve modeling compatibility and the ability to determine the appropriate modeling approach. To illustrate, assume the differences between the two disciplines were purely "cultural" (i.e., they stem from different modeling preferences of ecologists and economists, say, due to differences in education). In this case, selecting the approach is a matter of convenience. If the reason for different modeling approaches is that ecological and socioeconomic systems genuinely ought to be modeled differently, then this has implications for how problems that require ecological-economic modeling should be modeled optimally.

Overcoming the difficulties we have outlined is necessary but not sufficient for "good" ecological-economic modeling. Economists and ecologists have debated the question of what constitutes good modeling (economics: e.g., Walsh 1987; Morgan & Morrison 1999; Mäki 2002; ecology: Bart 1995; Grimm 1999; DeAngelis & Mooij 2003), but little literature exists on what constitutes a good ecological-economic model. There are no benchmarks against which one can evaluate ecological-economic models and no established quality controls and refereeing standards (as they exist in disciplinary research) with which to assess the quality of research. To develop such benchmarks and standards a broader and more rigorous discussion on what constitutes good ecological-economic modeling is needed.

There are two possible starting points for such a discussion. The first is to survey existing ecological-economic models (see as examples the references in this paper), asking questions such as How do these models differ from disciplinary models? What are common features of these integrated models? Is it possible to derive from these features criteria for good ecological-economic modeling? In ecology, a similar comparative review of models has led to the formulation of the general strategy of "pattern-oriented modeling" (Grimm et al. 1996, 2005; Wiegand et al. 2003).

The second starting point is to compare methodological discussions on what are considered good modeling practices in the individual disciplines: To what extent is there consensus on good modeling practices? What are the differences? How do we evaluate ecological-economic models against these differences? Are there specific criteria needed if one evaluates models that integrate knowledge from two disciplines?

As scientists become increasingly aware of the advantages of ecological-economic modeling and knowledge improves regarding how to overcome difficulties, future research in this field looks promising. Problems addressed previously in a disciplinary manner can now be investigated through ecological-economic models. Future research fields that require ecological-economic modeling may result from developments in the political arena and from disciplinary research. An example of political stimulus is the discussions on how marketable permits might be applied to biodiversity conservation (e.g., through "tradable habitats"; Wätzold & Schwerdtner 2005). This application can be more usefully discussed by integrating ecological and economic knowledge. An example of disciplinary stimulus is the metapopulation concept. Although the dynamics of metapopulations are discussed extensively in ecology (Hanski 1999), relatively little is known about how their existence affects the optimal design of biodiversity management from an integrated perspective (see Groeneveld [2004] for an exception). It remains to be explored which other new concepts and ideas will be developed in ecology and economics that should be incorporated into ecological-economic modeling to enhance our understanding of how best to develop management recommendations for biodiversity conservation.

Nearly all biodiversity management problems have an ecological and a socioeconomic dimension. We believe these problems can be better addressed using a modeling approach that explicitly integrates ecological and economic knowledge and captures the feedbacks between the two systems. Admittedly the costs of ecological-economic modeling are not trivial; yet as we learn more by doing the integration the costs will fall. Plus this is an investment in creating a culture of communication, which is considerably less costly than each individual researcher acquiring in-depth knowledge of all disciplines. More important, the relative costs of not doing ecological-economic modeling—as measured by underproductive and cost-ineffective management recommendations—are probably much greater.

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