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Noah Revisits Biodiversity Protection Prioritisation

David Martin

IEG Working Paper No. 323

2013

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ACKNOWLEDGEMENTS

This paper has benefitted substantially from the questions and comments from seminar participants at the Madras School of Economics and at the Sálim Ali Centre for Ornithology and Natural History, who suffered through presentations of the first version of this paper. I benefitted substantially from presenting a second version at the United States India Educational Foundation South and Central Asia Conference and in a seminar at the Institute of Economic Growth. I thank all the sessions' participants for their comments and suggestions.

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ABSTRACT

The pledges to finance biodiversity preservation make up a fraction of the identified needs. Therefore, scientists must develop tools to help prioritise the many goals of biodiversity preservation. Analysts and policy makers often use the 'Noah's Ark' metaphor to imply that society must choose how much biodiversity to save and which specific components of it to save. Unfortunately, economic models proposed to answer these questions do not capture the complexity and inter-relatedness that enrich ecological perspectives, while ecological models often ignore the anthropogenic aspects that drive economic analysis. I develop a framework for prioritising species conservation policies that advances the integration of the economic and ecological perspectives. I first develop a macro-oriented model that builds from Norgaard's framework (*EcolEcon* 2010) to address how big an ark to build. Then, I develop a microeconomic model that prioritises species—one that starts with Weitzman's model (*Econometrica* 1998) and builds upon the work of Perry (*EcolEcon* 2010) and Arponen (*BiodiversConserv* 2012) to include ecological concerns. I demonstrate this methodology with two examples from current issues concerning protecting Keoladeo National Park, India. First, I look at maintaining the Gambhir River's natural flow (instead of impounding it behind the Panchana Dam) to help re-establish the Siberian Crane at the park. Second, I investigate the protection of satellite wetlands, which are part of the park's overall ecosystem, to enhance the Sarus Crane population.

Keywords: Biodiversity, Noah's Ark, natural capital

JEL Code: Q57

1 INTRODUCTION

A wide variety of analyses demonstrates that biodiversity is declining and will continue to decline in this century (Pereira et al. 2010). Both developed and developing countries have agreed to increase their funding for biodiversity protection by over $10 billion annually (Secretariat of the Convention on Biodiversity 20 October 2012). However, this funding is far less than the annual $76 billion that McCarthy et al. (2012) concluded was necessary, as well as the $93.3 billion annual cost (in 1990 dollars) of protecting biodiversity by moving 10 per cent of the world's forest and agricultural lands into ecological preserves (Lewandrowski et al. 1999). This paper addresses the policy challenge of picking the right quantity of the right components of biodiversity to save with limited funding.

Weitzman (1998) can be credited for bringing the Noah's Ark metaphor to this policy challenge. Derived from the Abrahamic religious traditions (*Torah* Book of Bereshit, *Bible* Book of Genesis, and *Qu'ran* Surah 11), the metaphor follows the belief that God destroyed the world by flooding it with the exception of the people, animals, and plants Noah saved in the ark.[1] As practitioners of a discipline focused on human decisions and so unable to utilise the divine guidance Noah received, economists interpret the metaphor to mean that society must decide how much of which bits of biodiversity to preserve given society's resource constraints. This metaphor contrasts sharply with the popular goal of zero human-caused extinctions (Roman 2009). Also, note that Bapat, Dixit, and Yadav (2012: 1377) claim: 'The aims of biodiversity conservation are to maintain the current level of biodiversity as well as to stop any further decline.' Noah must make important economic decisions about which elements of biodiversity to save because the financial constraints policy makers operate under are severe.

Of course, the understanding that valuing various bits of biodiversity is a complex endeavour is not new, even for economists. One hundred years ago, Gray (1913: 518–19) asked: 'What is the criterion of social value?' Thus, social value is a core issue in conservation economics. Van der Ploeg, Braat, and Van Lierop (1987) framed the relevant question as: how do economic models and ecological models integrate the other's perspective of value and methodologies, and how well do these do so? In a lecture reviewing the role of economics in protecting biodiversity, Gowdy (1993: 6) emphasised: 'To formulate policies to protect biodiversity, it is critical to broaden the standard economic view to include environment–economy interconnections, irreversibility, and the environmental context of specific resources.' About the same time, in a review of economic models for the American Society of Zoologists, Norgaard (1994: 152) noted: 'The process of [biodiversity] loss is

[1] Other religious traditions have similar flood stories, such as Matsya's (an avatar of the Hindu deity Vishnu) saving of Manu (the first man) as told in the *Śataphat Braāhmana* (I.8.I).

intimately related to human beliefs that the world is a very simple system which people can control, is very resilient to human interaction, and has infinite potential for human exploitation through new knowledge and technologies.' Economists have not been shy in recognising the importance of trying to integrate economic and ecological concerns. Yet, as literature reviews by Eppink & van den Bergh (2007) and Tisdell (2011) demonstrate, economists find it difficult to model the important ecological themes of complexity, interrelatedness, feedbacks, and irreversibility in productive ways.

In this paper, I develop and demonstrate two different economic models. The first is a sharply revised version of Norgaard's (2010) macroeconomic–ecological economics model; it represents the overall perspective of biodiversity protection (or any policy that protects natural capital). The second model is an extensive addition to Weitzman's (1998) 'Noah's Ark' model; it integrates ecological concerns into its microeconomic framework better. The macroeconomic model is important because Noah has to know how big an ark to build; the microeconomic model is important because Noah has to know what should go into it.

However, before introducing those models, in the next section I integrate the definition of biodiversity into the pre-analytic vision of economics (Daly & Farley 2004) because biodiversity is a more complex good than economists typically consider. After developing the macroeconomic model in the third section and the microeconomic model in the fourth section, I demonstrate this methodology using two examples from current issues concerning the protection of Keoladeo National Park, India (KNP). In the first example, I discuss facilitating the re-establishment of the Siberian Crane by allowing the natural flow of the Gambhir River to continue unimpeded by the Panchana dam. In the second example, I examine protecting the satellite wetlands near the park to protect the Sarus Crane. I offer concluding comments in the final section.

2 ECONOMISTS' PRE-ANALYTIC VISION AND DEFINING BIODIVERSITY

There is no consistent definition of biodiversity, as Simpson (2005) points out. However, it is convenient to start with E.O. Wilson's (1996: 1) popular definition: 'Biodiversity is defined as all hereditarily based variation at all levels of organisation, from the genes within a single local population or species, to the species composing all or part of a local community, and finally to the communities themselves that compose the living parts of the multifarious ecosystems of the world.' Expanding upon that definition, Naeem, Duffy, & Zavaleta (2012) describe seven different ways that organisms might exhibit such variation: taxonomic diversity, phylogentic diversity, genetic diversity, functional diversity, spatial or temporal diversity, interaction diversity, and landscape diversity.

So, it seems clear that biodiversity is part of our stock of natural capital (Costanza & Daly 1992). Nature creates it (hence 'natural') and nature and humans use it to produce goods and services that we value (so biodiversity is a form of 'capital'). One might consider the pasture in which cows graze as a form of natural capital because the flows of services the grasslands produce lead to the delicious sweet lassis we consume. One should note, following Vira and Adams's (2009) critique, that biodiversity is a complex form of natural capital, just as the pasture ecosystem is more complex than physical capital (the pail that holds the milk), financial capital (loan the farmer takes to buy the cow), human capital (the experience and education required to transform the cow's milk into sweet lassi), and other forms of natural capital (sugar cane). This complexity makes biodiversity preservation important and difficult.

We need to differentiate between the services that biodiversity provides and the stock of biodiversity itself. Humans exploit this diversity to produce a variety of services humans value directly, such as key functions within our agricultural system[2] and the raw material for bio-prospecting for pharmaceuticals.[3] Biodiversity also produces services to the ecosystem that we would likely value if we understood them better. For example, Cardinale et al. (2012: 60) describe the impacts of biodiversity with what they consider six consensus statements.

1. Biodiversity loss reduces the efficiency by which ecological communities capture biologically essential resources, produce biomass, decompose, and recycle biologically essential nutrients.
2. Biodiversity increases the stability of ecosystem functions through time.
3. The impacts of biodiversity on any single ecosystem process are non-linear and saturating (total benefits exhibit diminishing marginal returns).
4. Diverse communities are more productive because they contain key species that have a large influence on productivity, and differences in functional traits among organisms increase total resource capture.
5. Loss of diversity across trophic levels can influence ecosystem functions even more strongly than diversity loss within trophic levels.
6. Functional traits of organisms have large impacts on the magnitude of ecosystem functions, which give rise to a wide range of plausible impacts of extinction on ecosystem function.

[2] Altieri 1999; Drucker, Gomez, & Anderson 2001.

[3] Simpson, Sedjo, & Reid 1996; Rausser & Small 2000; Craft & Simpson 2001.

The grassland example used above is not the best example of biodiversity, because a grassland is both excludable (one cow can exclude another from consuming a specific bit of fodder) and rival (one animal's consumption of fodder affects the value placed on that same fodder by another animal). As Rands et al. (2010) point out, biodiversity is both non-excludable and non-rival, and so it is a public good. Two key results follow from this point, both of which Samuelson famously developed (1954, 1955). First, as we consider valuing a bit of biodiversity, we will be aggregating its value across all possible consumers instead of looking at its value to just one person. Second, in policy terms we need not worry about people enjoying the benefits of biodiversity but not paying for its preservation (the free rider problem). Noah's budget constraint is so severe because people do not pay for the biodiversity protection they value on the assumption that they can free ride on others' payments.

There is some confusion in the literature about the implications of biodiversity's public good nature. Some analysts suggest that biodiversity itself is an externality because it is a public good (Rands et al. 2010). This confusion might arise when the services generated by the stock of biodiversity are not priced appropriately (Buchanan & Stubblebine 1962) and/or are distributed by social–political institutions that have become inadequate (Ostrom 2010). These externality problems might lead to the extermination of the relevant species or habitats. The fodder itself is not the externality, but it might disappear if the water in the adjacent river is underpriced and the river is drained or if the traditional allocation of grazing rights breaks down under population pressures. Such important externality issues are distinct from the non-excludability and non-rivalry that define biodiversity as a public good.

Notably, the role of natural capital is under debate in the context of strong versus weak sustainability. This is especially so for ecosystems constructed as part of the ecological restoration efforts; see the reviews by Benayas et al. (2009) and by Jenkins et al. (2010). Åkerman (2003) framed this debate as a comparison between the David Pearce and the Herman Daly perspectives. Pearce considers natural capital similar to other forms of capital, such as man-made and human capital, and allows for weak substitution between these types of capital (albeit with an opportunity cost). In contrast, Daly views natural capital as a physical entity that ultimately constrains human activity; therefore, no substitution is appropriate under this strong sustainability. So, man-made ecosystems can be replacements for natural capital under the weak sustainability perspective but not under the strong sustainability perspective. The debate over the appropriate perspective is deservedly extensive.[4] For the purposes of this analysis, I will use the strong sustainability criterion that

[4] See, for example, Costanza & Daly 1992; Åkerman 2003; Figge 2005; Jackson & Hobbs 2009; Ang & Van Passel 2012.

relies upon Figge's (2005) portfolio-theory based analysis, which showed that weak sustainability alone is insufficient to achieve the goal of sustainable development. In sum, biodiversity is a public good that is part of our endowment of natural capital. In turn, it provides a complex array of goods and services to the ecosystem and to humans. Noah faces two critical questions in his financially constrained world:

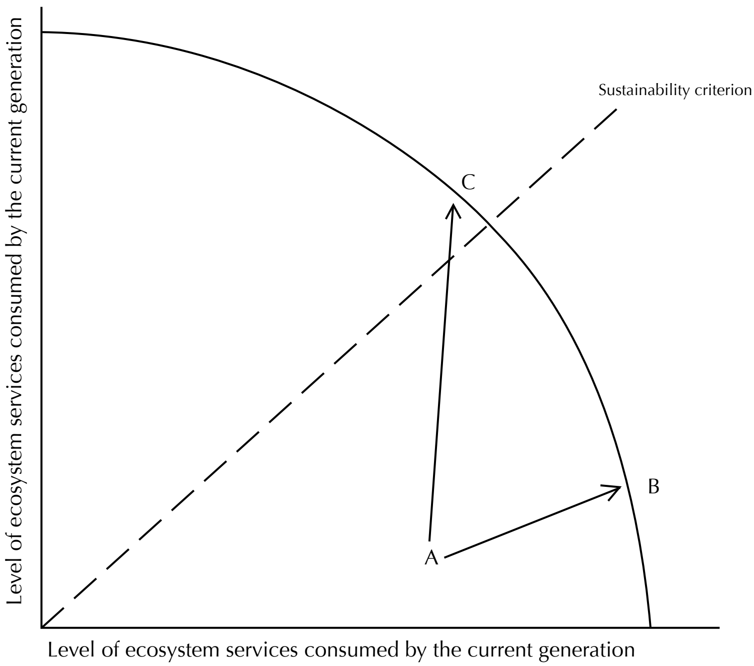
1. How big should he build his ark, or how much biodiversity should he protect from depletion?
2. Which species should he allow to enter it, or which bits of biodiversity should he save?

These questions naturally centre on the issue of how to value biodiversity. I address the macro question in the next section and the micro question in the following one.

3 A MACROECONOMIC MODEL

Norgaard (2010) proposed the graphical macroeconomic ecological economics model of sustainability presented in Figure 1.

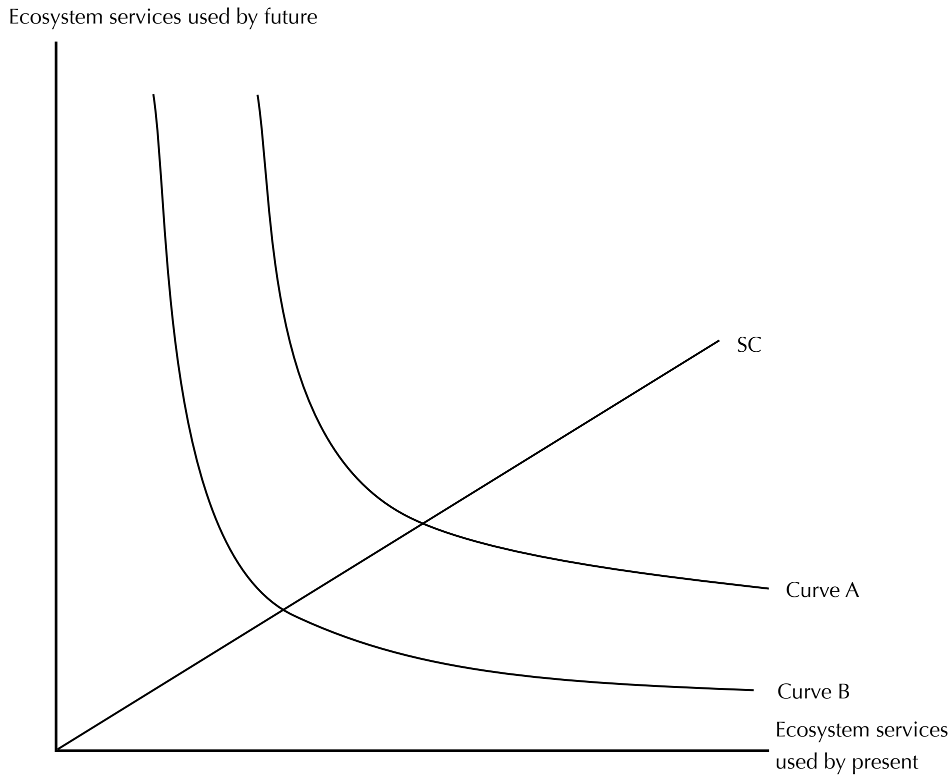
Figure 1: Norgaard's model (2010)



In this model, assume that society is currently functioning at point A, which shows that the current generation is operating inefficiently below the frontier that includes points B and C. The frontier uses more ecosystem services than point A both currently and in the future, because the social, political, and institutional arrangements (including pricing and other distributional mechanisms) allow society to use more services efficiently. So, to operate more efficiently, the society at point A needs to change its social, political, and institutional arrangements to permit greater efficiency. The curved slope of the frontier represents society's trade-off between current and future use of the ecosystem services, and so is based upon the social discount rate (including equity aspects). The strong sustainability criterion maps the limits of ecosystem service use before the depletion of natural capital begins. So, while Point B is more intra-generationally efficient than Point A, it is not socially efficient in an intergenerational sense because it depletes the stock of natural capital. At Point C, society is not depleting any natural capital in the present.

A different representation of the same ideas is presented in Figure 2, with the focus shifted to a traditional isoquant framework.

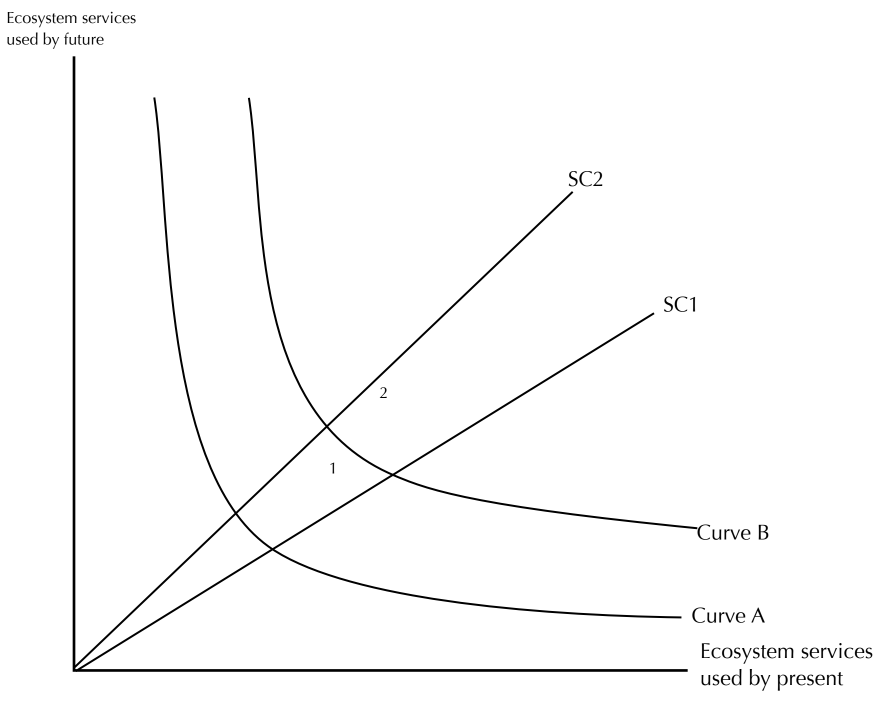
Figure 2: Introduction to model



Each point from (and including) Curve A outward represents a combination of ecosystem services used by the present (horizontal axis) or the future (vertical axis) to achieve a certain lifestyle with a given set of institutional arrangements. The curve itself is an isoquant representing the various least intensive combinations of ecosystem services to achieve the output goal. The curve is convex to the origin, representing the increasing difficulty of substituting between the two inputs given the current lifestyles and institutional arrangements. A different lifestyle or a different set of institutional arrangements would change the location of the curve. Investment in physical or human capital shifts the frontier in, say from Curve A to Curve B, representing the concept that fewer ecosystem services are required to achieve the output goal. The sustainability criterion (the ray from the origin labeled 'SC') represents the same concept as in Norgaard's model (2010) above. If one would want to account for uncertainty by adding an additional buffer to the sustainability criterion, as with Ciracy-Wantrup's Safe Minimum Standard (1968), one would simply pivot that ray downwards by an amount representing that buffer.

Figure 3 demonstrates the depletion of biodiversity (actually, the depletion of any component of natural capital).

Figure 3: Depleting biodiversity



Given an intra-generationally efficient set of social, political, and institutional arrangements, we see that Point 1 on Curve A depletes natural capital to the detriment of the future.

The first of three effects is for the intra-generationally efficient frontier to shift outward to Curve B, as society would have used the best natural capital first and made the remaining bits more costly to use. Curve B is drawn assuming that the same lifestyle can be achieved with the same set of social, political, and institutional arrangements while a curve between the two might represent a more efficient state if society were willing to make those adjustments.

Second, the sustainability criterion pivots upward to represent the same concept for the notion in an intergenerational sense. That is, given the depletion of the best natural capital first, it would be more costly to achieve sustainability across time.

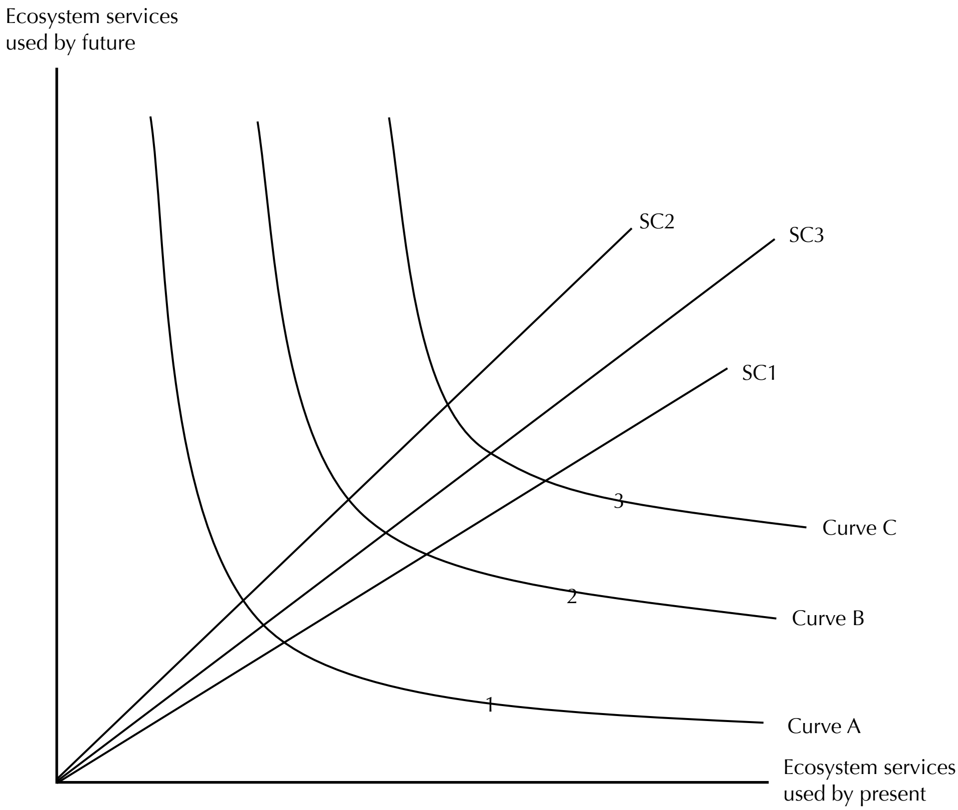
Third, society moves from starting at Point 1 to Point 2; the key is that Point 2 is now further away from the sustainability criterion than Point 1. The present generation will have to use even fewer ecosystem services than previously to try to move towards sustainability.[5]

Figure 3 is drawn as if the depletion of biodiversity resulted from an intra-generationally rational decision in the traditional neoclassical economic sense such that sustainability is not a criterion. On the other hand, the biodiversity depletion might also result from externalities. In that case, the resulting outcome—instead of being on Curve B—would be an inefficient point beyond the frontier. That outcome would represent the concept that social and/or institutional arrangements (some type of policy) would be required to move society to the intra-generationally efficient use of ecosystem services.

Figure 4 demonstrates how this model represents the impacts of policies designed to protect biodiversity from depletion.

[5] It is possible for society to be above the sustainability criterion (i.e., the current generation sacrifices too much for the sake of the future). It is also possible that biological growth could pivot the sustainability criterion downwards over time.

Figure 4: Impacts of biodiversity protection policy



Assume that we are starting from Point 1 on isoquant Curve A; so, typically, we would move to Point 2 on Curve B (as in Figure 3).

The first aspect is that the policy imposes opportunity costs on society today; so, it becomes costlier in terms of ecosystem services to maintain the current lifestyle. Two changes are happening here: the imposition of opportunity costs (the shift to Curve C) and the potential for lifestyle and institutional changes (not drawn, but Curve C would be lower than shown).

Second, because less natural capital is used because of protecting biodiversity, the sustainability criterion pivots downwards from SC 2 to SC 3 to reflect growth in the renewable components of biodiversity. That is, with the increased stock of biodiversity, more flows of services could be used without depleting the underlying stock.

Finally, society would shift from Point 2 to Point 3 because the policy would both be costly to the present (require more ecosystem services to maintain the current lifestyle) and save more ecosystem services for the future. Again, if society could make additional lifestyle changes, the location of the point could change so that even fewer ecosystems services are used. However, that element is an additional point of analysis.

Again, the macroeconomic question was: how big should he build his ark, or how much biodiversity should he protect from depletion? The answer is that Noah must build an ark big enough (expend enough funds) to move society to the sustainability criterion by protecting biodiversity. The cost of protecting the biodiversity is clearly a crucial component (how far the isoquant frontier shifts out) as is the extent of the services that the biodiversity provides (how far the sustainability criterion pivots). Also, the specific policy choices matter, too, as they affect how far out the isoquant frontier shifts out and how readily society moves along the isoquant towards the sustainability criterion. Also, the policy choices affect society's interest and motivation to adjust its lifestyle and institutions, which would shift the frontier inwards and society closer to the sustainability criterion.

Clearly, Noah can no longer avoid the issue of valuing biodiversity; assessing the size of his ark depends crucially on the benefits and costs of biodiversity protection. That is the focus of the next section: to develop a microeconomic model that prioritises biodiversity protection policies.

4 A MICROECONOMIC MODEL

The basic microeconomic model of biodiversity protection follows from the workings of the ubiquitous equimarginal rule. First, Noah should calculate the ratio of incremental benefits to incremental costs for every policy across every species and habitat. Second, he should load the ark by choosing the policy with the highest ratio and continue the loading by always choosing the policy with the next highest ratio. Given Béné and Doyen's (2008) conclusion—as biodiversity increases, the ecological and economic benefits of biodiversity jointly increase with diminishing returns—when the ark is filled the values of the ratio will be equal across all the marginal species and habitats. If Noah chose the size of the ark to be consistent with the macroeconomic model presented earlier, the amount of biodiversity allowed into the ark would allow society to develop in a strongly sustainable manner. If the budget constrains Noah to choose less than that amount of biodiversity, at least he will have saved the most valuable species and habitats. As an example of this process, Fuller et al. (2010) determined that Australian conservation efforts per dollar spent could be improved by selling the lands with a low cost–benefit ratio and using only those funds to buy unprotected areas with a higher cost–benefit ratio.

Such a sequential process is the basis of Equation (1), Weitzman's (1998) ranking (R_i) of species *i* in terms of the value per cost of saving that species (C_i). The term ΔP_i represents the change in the probability of the survival of that species because of that costly action, and allows for trade-offs between the benefits of a policy and the likelihood of the policy being successful (Weitzman 1992). Weitzman (1993) demonstrates this trade-off between the benefits of a policy and the likelihood of its being successful with an intriguing pedagogical example involving the crane family (*Gruiformes gruidae*). As an important foreshadowing of a later discussion, ΔP_i is small enough that it does not affect the probabilities of the survival of other species. U_i represents the utility gained from the species to measure the use value of the species. D_i represents the genetic distinctiveness of the species, a measure intended to capture the species' option value, the benefits that might flow from the species in the future.

$$R_i = [U_i + D_i]\frac{P_i}{C_i} \qquad (1)$$

There is a substantial literature that replaces both numerator terms in Equation (1)—the measure of economic value and the change in the probability— with a single measure of ecological value. This step is intended to incorporate a measure of biodiversity value independent of its value to humans and to implicitly assume that the protection policies will be successful. Generally, these analyses use various algorithms to identify ecologically rich areas and to allocate funding for preservation efforts so that diversity loss is minimal (see the review of nine of these strategies by Brooks et al. 2006). Dinerstein & Wikramanayake (1993) presented an early example of this 'hotspot' type of analysis for the Indo-Pacific region. Conservation International supported Myers et al.'s (2000) well-known identification of ecological hotspots worldwide. Withey et al. (2012) prioritised the conservation potentials of all counties in the conterminous US by ranking them by the number of saved species per land cost.

Recently, Perry (2010) replaced [$U_i + D_i$] in Equation (1) with ecological importance, leaving the probability term in the equation. He used Equation (2) below as an example of such an ecological importance measure, where the ecological importance of a species ($M_{i,I}$) increases as the number of species in the i^{th} species function group ($F_{i,I}$) decreases (a keystone species has $F_{i,I} = 1$) and as the number of species affected by the i^{th} species function ($N_{i,I}$) increases. Other variables[6] might be used to measure ecological importance but the intent—shifting the focus of benefits away from the anthropomorphic measures economists use—is consistent with a wide range of other studies.

[6] For example, see Pereira et al. 2010; Farnsworth, Lyashevska, & Fung 2012; Jetz, McPherson, & Guralnick 2012; Lyashevska & Farnsworth 2012; & Periera et al. 2013.

$$M_{i,l} = \frac{\sqrt{N_{i,l}}}{F_{i,l}} \tag{2}$$

Arponen (2012) suggests a straightforward resolution to the apparent dilemma of including either ecological values or economic values. By multiplying the change in the total economic value of the focal species due to the project with the change in ecological importance, we get the combined impact on that species. The value of multiplication is that economic value and ecological value are both considered so that a large change in one measure offsets a small change in the other.

Equations (3), (4), and (5) represent building on that idea. Let the ranking ($R_{i,l,p}$) of policy p to preserve species i on a specific hectare of land l be determined by the change in the value of the service flows from that species due to that policy (ΔVi,l,p), the cost of that policy ($C_{i,l,p}$), and the change in the probability of its survival (ΔPi,l,p) due to that policy.

The impacts of policy p are compared to the status quo (state 0). Equation (3) basically introduces that notation, while Equation (4) represents Arponen's (2012) suggestion, with total economic value (TEV, discussed further below) and Perry's (2010) measure of ecological importance representing the economic and ecological benefits, respectively. Equation (5) simply inserts Equation (4) into Equation (3).

$$R_{i,l,p} = (\Delta V_{i,l,p}) \frac{\Delta P_{i,l,p}}{C_{i,l,p}} = \frac{(V_{i,l,p} - V_{i,l,0})(P_{i,l,p} - P_{i,l,0})}{C_{i,l,p}} \tag{3}$$

$$V_{i,l,p} = (TEV_{i,l,p} - TEV_{i,l,0})(M_{i,l,p} - M_{i,l,0}) \tag{4}$$

$$R_{i,l,p} = \frac{(TEV_{i,l,p} - TEV_{i,l,0})(M_{i,l,p} - M_{i,l,0})(P_{i,l,p} - P_{i,l,0})}{C_{i,l,p}} \tag{5}$$

Gray (1913) introduced temporal dynamics into the economics of natural resource use; he argued that a low interest rate was one of the most important social conditions for creating the proper motives for resource conservation. Clark (1973) related the growth rate of a species to the rate of return from other economic activities. As Duffy (2009) and Reich et al. (2012) have discussed, the concept of evaluating ecological changes over time is also critically important. So, all economic and ecological values described here is in terms of present value, although the notation is not explicit and how such discounting should be done is not discussed.

As noted in Equation (1), Weitzman (1998) measured the economic value gained from preserving a species as the sum of the use value and the option value of the flows of services from the species. This definition is consistent with economic tradition: Hammar (1931: 290) defined conservation as 'that branch of economics which seeks to insure to future generations as great an income (or a greater) from the exploitation of natural resources as is enjoyed by the present generations.' Both Hotelling's (1931) and Clark's (1973) foundational theoretical works develop resource value as the discounted presented value of use value.

However, it is much more appropriate to use broader measures of economic value than simple use value. Krutilla (1967) emphasised that the irreproducibility of natural phenomena and the irreversibility of the decisions that affect ecosystems create non-use values. For examples of the measurement of such use values, see Smith (1996). Also, it is important to acknowledge the types of social, cultural, and religious values discussed by Thompson and Starzomski (2007), Bryan et al. (2011), Rutte (2011), and Daniel et al. (2012). Further, it is important to include the value of ecosystem services (e.g., Kareiva et al. (2011) and Atkinson, Bateman, & Mourato (2012)) and shown by Turner et al. (2007) to be consistent with conservation importance. Equation (6) below follows the example of Walsh, Loomis & Gillman (1984). It adds the use of biodiversity service flows *in situ*, the existence value (which measures the value placed on the knowledge that these flows exist even if one will never use them), and the bequest value (which measures the satisfaction gained from knowing that one endows future generations with those flows) to the types of economic values ascribed to biodiversity. The focus here is to ensure that the complete range of values from biodiversity is included in some category; it is not to debate the specific categorisation of certain types of biodiversity.

$$TEV_{i,l,p} = \left[Harvest_{i,l,p} + Option_{i,l,p} + InSitu_{i,l,p} + Existence_{i,l,p} + Bequest_{i,l,p}\right] \quad (6)$$

Weitzman's (1998) Equation (1) and the starting point of Equation (3) above are still incomplete rankings of the species because of the limited nature of the ΔP_i term. Again, to keep the mathematics relatively simple, Weitzman's (1998) ΔP_i is small enough that it does not affect the probabilities of the survival of other species. In other words, a policy designed to protect the tiger will not affect the probability of deer surviving nor have any impacts on vegetation that the deer might graze on. Obviously, that was an important, albeit necessary, simplification as (for example) Wardle et al. (2011) stress that biodiversity changes are not just about species losses. The loss of some species in an area can lead to complex ecological changes that in turn drive gains for some species and losses for others. So, Equation (7) augments Equation (3) (the first right-hand side term in Equation (7)) by literally adding the impacts to other species on the same hectare (the second right-hand side term) as well as the impacts to all species including the focal species elsewhere (the third right-hand side term).

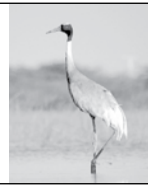
It is important to stress that measures of economic value typically assume the income distributions as given and base economic value in part upon people's income. Similarly, the economic analysis of the costs of biodiversity protection policies might be skewed because many of the costs of biodiversity protection fall upon relatively poor people (see Adams et al. 2004; Chapin 2004; Ferraro, Hanauer, & Sims 2011; Turner et al. 2012). Barrett, Travis, & Dasgupta (2011: 13907) give a qualitative assessment of the relationship between areas with high biodiversity and low incomes:

> The persistence of extreme poverty and continued rapid loss of biodiversity appear intimately related. Extreme poverty and biodiversity hot spots are geographically coincident, concentrated in rural areas where livelihoods depend disproportionately on natural capital embodied in forests, rangelands, soils, water, and wildlife. Colocation naturally gives rise to closely coupled human-managed ecosystems that are in a precarious balance at best. Lack of resources, institutions, and governance structures often leaves local people ill equipped to institute mechanisms to ensure long-term resource maintenance. Compounding this problem, the conditions of the human and nonhuman species within ecosystems co-evolve in response to subtle shifts in any of several subsystems.

Fisher and Christopher (2007) developed some empirical evidence for that assessment by using Conservation International's 'hotspot' maps with political maps to ascertain the overlap between poverty and biodiversity. At least 50 per cent of the population live below the poverty level in 25 of the 91 countries with Conservation International's 'hotspots' for which there were data. Further, the six hotspots most imperilled by socioeconomic conditions constitute 64 per cent of the land area in all the 34 hotspots (calculated using Fisher and Christopher's (2007) Figure 1, Table 3, and the on-line Supplemental Data, Table 1A). Consequently, it is important that neither the measures of the benefits from biodiversity protection policies nor their costs are distorted due to their reliance upon income.

There have been several critiques of Weitzman's (1998) approach in mainstream economics literature. Mainwaring's (2001) critique is probably the most direct. He describes the approach as rarely possible (as data are available for only a few species), impractical (the lack of data is amplified by the lack of information on species interrelationships), and misguided (there is no evidence of the relationship between genetic dissimilarity and value). While the broadening of economic value to total economic value and incorporating ecological importance does address his third point, his first two critiques stand. Nonetheless, the examples in the following section demonstrate the approach developed here.

Table 1: Characteristics of the birds used in the example

Siberian Crane *Grus leucogeranus* 	**Indian Sarus Crane** *Grus antigone Antigone* 	**Greater Spotted Eagle** *Aquila clanga* 
Height: ~140 cm, ~ 5 ft **Weight:** 6 kg, 13 lbs **Wingspan:** ~220 cm, ~ 7 ft **Population:** ~3,000 **Trend:** Rapid decline	**Height:** ~176 cm, ~6 ft **Weight:** ~6.35 kg, 14 lbs. **Wingspan:** ~240 cm, 8 ft **Population:** ~20,000 **Trend:** Declining	**Height:** ~65 cm, ~2 ft **Weight:** ~2 kg, ~4½ lbs **Wingspan:** ~168 cm, ~ 5½ ft **Population:** ~10,000 **Trend:** Declining
• Most specialised member of the crane family in terms of habitat requirements. • *Most aquatic cranes use only wetlands for nesting, feeding, and roosting.* • In winter, they excavate nutrient rich roots and tubers from wetlands	• This is the tallest crane species. • *Nests consist of wetland vegetation. In India, nests located in flooded rice paddies are constructed entirely of rice stalks.* • Indian Sarus Cranes breed primarily during the rains.	• *It occurs in lowland forests near wetlands.* • It feeds on un-retrieved quarry, small mammals, water birds, frogs and snakes, hunting over swamps and wet meadows.
• This species is now only found in two populations, the eastern and western. • *A central population once nested in Siberia and wintered in India (2002).* • Likely victims of hunting along the 4,000-mile migration route.	• The current range of the Indian Sarus Crane includes the plains of northern, northwestern, and western India. • *Sarus cranes are mostly non-migratory in India.*	• It breeds from northern Europe across Asia, and winters in southeastern Europe, the Middle East and South Asia. • *In winter, it occurs in the range of the Indian Spotted Eagle (A. hastata).*
• Re-establishing migratory Whooping Cranes by training captive-reared birds to follow ultra-light aircraft along a traditional migration route. • But it is pointless to restore the populations of Siberian Cranes unless their security can be provided along the migration route.	• Destruction of wetlands due to agricultural expansion poses a significant threat. • The future of the Indian Sarus Crane is closely tied to the quality of small wetlands in India.	• The primary threats are habit degradation and habitat loss, as well as human disturbance during the mating season. • *Suitable habitat mosaics have been lost to deforestation and wetland drainage.* • Birds are intolerant of permanent human presence in their territories.
(International Crane Foundation nd a) (Various Authors 2013a)	(International Crane Foundation nd b)	(BirdLife International 2013) (Various Authors 2013b)

5 EXAMPLE

In this example, two different biodiversity protection policies will be assessed, both involving the Keoladeo National Park (KNP) in Rajasthan, India (see Frank's (2011) discussion of the issues). The first policy example focusses on reintroducing the Siberian Crane to KNP by allowing the water of the Gambhir River to flow freely instead of impounding it by the Panchana Dam for irrigation. The Sarus Crane and the Greater Spotted Eagle will be used as the other species affected by this policy. The second policy example looks at compensating farmers near KNP for voluntarily maintaining the satellite wetlands on their property, which are part of the same ecosystem as KNP. The focal species for this example is the Sarus Crane, and the Siberian Crane and the Greater Spotted Eagle are the other affected species.

Information on the three birds is summarised in Table 1, but the salient facts are as follows. The Siberian Crane (*Grus leucogeranus*) used to winter in KNP, but the cranes in that flyway were likely hunted to extinction. To let cranes return to the flyway, the Gambhir River should be restored and let to flow freely (instead of being impounded for irrigation); hunting must be prevented; and captive-reared birds must be trained to migrate. If this policy succeeds, the crane would still be endangered and found in only a few areas. Even then, bird watchers would consider the possibility of spotting it valuable and contribute substantially to the local economy. The Indian Sarus Crane (*Grus antigone antigone*) is found frequently in KNP and the local ecosystem in part because of the Park and in part because of the series of satellite wetlands around the park. This crane is valuable for bird watchers, although not as valuable as the Siberian Crane. The Greater Spotted Eagle (*Aquila clanga*) is a commonly seen migratory raptor in that ecosystem that utilises both local wetlands and forests on their fringes. Its range overlaps with the range of the Indian Spotted Eagle (*Aquila hastata*).

Referring to the macroeconomic model described in Figure 4, and to be consistent with the earlier discussion of that figure, assume that today society is at Point 1 on Curve A. Because that point is not sustainable, society would shift to Point 2 on Curve B in the future. Also, due to the depletion of natural capital, the sustainability criterion would pivot upwards from SC 1 to SC 2.

The first macroeconomic impact of each policy is to impose opportunity costs upon society, thereby shifting society towards a farther-out isoquant like Curve C. For example, because of the policy of allowing the Gambhir River to flow freely to benefit the Siberian Crane, society incurs the loss of irrigated agriculture upstream of the dam net of the benefits from the increased water flows for irrigation downstream. For the illustrative example of protecting the satellite wetlands, the farmers who protect wetlands on their property would have to constrain their agricultural practices to prevent their degradation.

The second macroeconomic impact of each policy example shown in Figure 4 is that each policy would pivot the sustainability criterion downwards from SC 2 to a ray like SC 3 by preserving natural capital. In each case, the amount of the pivot would depend primarily upon the ecological benefits offered by the three birds.

The third macroeconomic impact of each policy is to shift society from Point 2 to Point 3 in Figure 4. Again, as Point 3 is closer to its sustainability criterion (ray SC 3) than Point 2 is to its ray (SC 2), the policy is costly to the present generation but saves ecosystem services for the future. Putting Point 3 on Curve C implicitly assumes that the actual policies chosen are the efficient policies; otherwise the points would fall outside the frontier. In the case of permitting the Gambhir River to flow freely, an efficient policy might involve some impounding of water behind the dam and/or timing the releases of water from behind the dam more effectively. In the case of protecting the satellite wetlands, an efficient policy might charge visitors (especially foreign visitors) to KNP a special tax and use it to fund a compensation programme for farmers who voluntarily maintain the wetlands. This would spare already constrained government budgets.

The microeconomic model of Equation (7) has four components (each of the three numerator terms and the common denominator). The discussion below follows those four components with one summary table (Tables 2A-2D) for each component. The first numerator term of the ranking examines the impacts upon the focal species itself; so, in one case, the focus will be on the Siberian Crane in KNP while in the second case the focus will be upon the Sarus Crane at the satellite wetlands. The second numerator term reflects the impacts upon the other species in the same place. Therefore, in the first example, the discussion will be on the Sarus Crane and the Greater Spotted Eagle at KNP. In the second example, the issue will be the impacts on the Siberian Crane and the Greater Spotted Eagle at the satellite wetlands. The third numerator term looks at the impacts of the policies on all species elsewhere, so for the first example the impacts on all three birds outside of KNP will be the issue while for the second example the discussion will centre on the impacts on all three birds outside of the wetlands (but including KNP). The final component (the common denominator term) is the cost of each policy. For the purposes of this illustration purposes, the changes in the economic benefits, ecological benefits, and policy costs are ranked on a scale from 1 (low) to 4 (high) and the changes to the probability of success assume that under the status quo the probability of success is zero.

If successful in re-establishing the Siberian Crane, maintaining the natural flow of the Gambhir River would have significant economic impacts due to the benefits gained by the birdwatchers as well as from the benefits to the local community gained from the birdwatchers' spending. It would also have important ecological benefits from the restoration of what is now essentially an extinct flyway. However, the probability that restoring the river's flow alone would be sufficient to accomplish this goal is very low given that the river's flow has nothing to do with preventing the hunting along the flyway. Paying the local farmers to protect the satellite wetlands would have minimal economic benefits, as bird watchers would not be entitled to visit these wetlands. However, the enhancement to the Sarus Crane's ecosystem would valuably strengthen their capabilities by offering nesting and feeding opportunities beyond KNP. In addition, the likelihood of this policy succeeding is high given the simplicity of its monitoring and enforcement combined with the importance of the wetlands to the cranes. These ideas are summarised in Table 2A.

Table 2A: Each focal species at each focal place

	Natural Gambhir River Flow		Pay Farmers Save Satellite Wetlands	
Focal Species @ Focal Place	Siberian @KNP		Sarus @Satellite	
$TEV_{i,l,p}$-$TEV_{i,l,0}$	4	High bird watching value Tourist money for locals	1	Bird watchers (and money) can't visit these
$M_{i,l,p}$-$M_{i,l,0}$	4	Restoring 'dead' flyway	3	Protect local ecosystem
$P_{i,l,p}$-$P_{i,l,0}$	0.1	Requires no hunting	0.9	Easy to monitor/ enforce
Product	1.6		2.7	

Restoring the Gambhir River's natural flow would benefit the Sarus Crane, and the bird watchers would find the enhanced Sarus Crane population in KNP economically valuable. The ecosystem would also benefit from improving the crane population's health. However, it is difficult to assess whether the population of the Greater Spotted Eagle or the Indian Eagle would grow and what the net impacts to bird watchers and to the ecosystem would be of the change to the Greater Spotted Eagle's ecosystem. The probability that this policy will be successful is very high. Paying the farmers to protect the satellite wetlands might allow some Siberian Cranes to visit them, but that result would have little impact on the bird watchers, as they would not be allowed there. The ecological benefits of improving the Siberian Crane's habitat would be high, but again it would be difficult to assess whether the ecological benefits would flow to the Greater Spotted Eagle or to the Indian Eagle. This policy would do nothing to prevent the hunting of the Siberian Crane and nothing to protect the wooded areas near the wetlands that the Greater Spotted Eagle needs. The values in Table 2B demonstrate these concepts.

Table 2B: The other species the focal place

		Natural Gambhir River Flow		Pay Farmers Save Satellite Wetlands
Other Species @ Focal Place	Sarus Eagle		Siberian Eagle	
$TEV_{i,l,p}$-$TEV_{i,l,0}$	1.5	Sarus = 3 Bird watchers Eagle = 1 Bird watchers	1	Bird watchers (and money) can't visit these
$M_{i,l,p}$-$M_{i,l,0}$	2	Sarus = 3 Eagle = 1 Indian Eagle	2	Siberian = 4 Eagle = 1 Indian Eagle
$P_{i,l,p}$-$P_{i,l,0}$	0.9	Benefits the entire ecosystem (food chain)	0.1	Siberian: hunting Eagle: deforestation
Product	2.7		0.2	

The policy of re-establishing the natural flow of the Gambhir River will benefit the Siberian Crane, Sarus Crane, and the Greater Spotted Eagle all along the river. This will likely lead to some economic benefits to other places as bird watchers will travel to publicly accessible areas along the river, but the primary benefits will be ecological. Given the natural resilience of river ecosystems, there is a high likelihood of obtaining these benefits. The policy of saving the satellite wetlands will have spillover effects to KNP, which will bring additional bird watchers there. However, the policy will also provide ecological support to KNP and the rest of the Gambhir River ecosystem. But the probability of doing so successfully will be mitigated by the continued external pressures caused by an increasing population. Table 2C illustrates these ideas.

Table 2C: All three species at other places

	Natural Gambhir River Flow		Pay Farmers Save Satellite Wetlands	
All Species @ Other Places	Siberian, Sarus, Eagle		Siberian, Sarus, Eagle	
$TEV_{i,l,p}$-$TEV_{i,l,0}$	2	Bird watchers (and money) will not go elsewhere	2	Spillover benefit to KNP brings bird watchers
$M_{i,l,p}$-$M_{i,l,0}$	3	Ecology along River will improve for all species	2	Satellites support other ecosystems in area
$P_{i,l,p}$-$P_{i,l,0}$	0.9	River's ecosystem resilient	0.5	External pressures dominate
Product	5.4		2	

The sum of the three numerator terms is shown in Table 2D. As constructed, these examples demonstrate that re-establishing the natural flow of the Gambhir River is much more valuable overall than paying farmers to save the satellite wetlands on their lands. The illustrative example in Table 2D implies that the costs of re-establishing the natural flow of the Gambhir River are only twice the costs of paying farmers to protect the satellite wetlands, since benefits to farmers downstream would offset some of the losses to farmers upstream. This example suggests that the geographically focused policy of protecting the satellite wetlands would be more efficient than re-establishing the Gambhir River's flow.

Table 2D: Summary, costs, and ranking of example policies

	Natural Gambhir River Flow		Pay Farmers Save Satellite Wetlands	
Product Focus	1.6		2.7	
Product Species	2.7		0.2	
Product Others	5.4		2	
Value = ∑ Products	9.7		4.9	
Cost	2	Benefits to downstream farmers offset losses to upstream farmers	1	Only paying a few farmers to protect some of their lands
R_i = Value/Cost	4.85		4.90	

As noted in the macroeconomic section of this example, benefits to downstream farmers might outweigh the costs to upstream farmers when re-establishing the natural flow of the Gambhir River. If that were the case, economically speaking, the dam should not have been constructed in the first place. Also, and more directly relevant to this example, with a negative cost (negative denominator) the ranking result would be negative. That result would imply that restoring the Gambhir River's natural flow should be undertaken immediately and, assuming that the initial set of policy funds are still available, the policy of paying farmers to protect the satellite wetlands should also be implemented. Returning to the macroeconomic model, that result would be consistent with an inward shift of the isoquant in Figure 4, from Curve C to somewhere between Curves A and B, thereby allowing society to use less ecosystem services in both periods.

6 CONCLUDING COMMENTS

Noah faces the difficult task of deciding how big to build his ark and how many species to have on board. The macroeconomic and microeconomic models developed here advance the integration of ecological concerns into economic models. The examples used here illustrate that the models can be used effectively, especially if good quality data are available.

In addition to the caveats discussed earlier, Noah needs to be alert to the possibility that humans place too much value on charismatic or common species.[7] However, that issue arises whether one is discussing the economically-oriented aspects of the ranking or the ecologically-oriented aspects of the ranking. For example, the value of the Siberian Crane to bird watchers might have been overvalued as might have the ecological value of recreating its flyway.

Finally, Norgaard (2010: 1220) warns Noah against over-relying upon the ecosystem services construct: 'The ecosystem services metaphor now blinds us to the complexity of natural systems, the ecological knowledge available to work with that complexity, and the amount of effort, or transactions costs, necessary to seriously and effectively engage with ecosystem management.' In short, the models presented here are simply that: simplifications of complex realities that rely upon substantial data requirements for their applicability. On the other hand, their value is that by better integrating ecological and economic concerns than previous models do, these models better illustrate the important trade-offs that must be balanced as policy makers grapple with getting the most from their limited budgets.

[7] See, for example, Metrick and Weitzman 1998; Tisdell, Nantha, & Wilson 2007; Wilson & Tisdell 2007; Maresova & Frynta 2008; Richardson & Loomis 2009; Gaston 2010; Morse-Jones et al. 2012.

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