

Environmental Change, Species Coping Ability and the Insurance Value of Biodiversity

Mintewab Bezabih

Environmental Economics Unit

Department of Economics

Göteborg University

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Mintewab.bezabih@economics.gu.se

Abstract

This paper develops a measure of the value of biodiversity by incorporating a stochastic change in the environmental factor into an economy-ecosystem model of biodiversity. The analysis draws from an ecological model specifying the relationship between aggregate productivity, responsiveness to environmental change, and diversity. The value of biodiversity is derived as the contribution of diversity in enhancing the ecosystem's adaptive response to environmental change. The results are relevant to biodiversity conservation efforts that target areas with differing degrees of environmental variation. In addition, our analysis of some features of global warming the results imply that with increased concerns of global warming, more needs to be invested in biodiversity.

JEL codes: C61, C88, Q51, Q57

Key words: Biodiversity valuation, Ecological model, Hamilton-Jacobi-Bellman
Equation, Simulations

1. Introduction

The desire to conserve biodiversity¹ is essentially motivated by two major concerns. One is that when a species becomes extinct, the social value associated with its possible future use is lost. In addition, as Blockstein (1998) argues, the loss of species could lead to cascading changes, since natural ecosystems are complex and highly interdependent, and small perturbations can lead to far-reaching changes with unexpected repercussions (Heal, 2004). Thus, individual species possess not only social benefits of their own; they also carry a joint value shared with other species, which is associated with an uncertainty in the functioning of an ecosystem composed of different species (Fromm, 2000). Measuring and assessing this joint value has attracted considerable interest and this paper is one such endeavor to add to this effort. The major contribution of our approach is its reliance on an ecological framework that objectively specifies species interrelationships and accounts for species' dynamic responsiveness to stochastic environmental change² in an aggregate manner. This realistic yet aggregate representation gives us the advantage of assessing the contribution of diversity to environmental adaptation in the context of complex species relationships and without relying on simplifying assumptions.

When valuing individual species, the focus has been on attaching values to benefits related to the use and existence of each species. Since use and existence values are inherent to people's preferences and hence to their willingness to pay (Moran and Bann, 2000), conceptualization of the values has been less difficult. Stated preference methods have been popular, assigning monetary values to threatened or extinct species and their habitats (e.g. Loomis and White, 1996; Montgomery et al., 1999). On the other hand, valuing diversity with respect to species interdependencies has been characterized by wide-ranging definitions and metrics. One explanation to this is that there are many different assumptions about species inter-relationships and their interaction with the environment. A unifying approach could be having a comprehensive account of such

¹ Biodiversity is defined as the variety of life at all levels of organization, from the level of genetic variation within and among species to the level of variation within and among ecosystems and biomes (Tilman, 1997).

² In the context used in this study, the environmental factor represents an exogenous phenomenon which conditions the performance of the ecosystem, and which exhibits an unpredictable change over time. Norberg et al. (2001) use temperature or predator abundance as examples.

relationships. However, Crepin (2002) argues that with such approaches, species multiplicity and richness, and the resulting non-linearities in the relationships, make valuation exercises cumbersome and practically unmanageable.

Thus, appropriate biodiversity valuation calls for a framework that balances off the need to account for complex species interrelationships on the one hand, and to be simple enough to analyze theoretically, on the other.

In line with this, earlier approaches focus on specific species relationships. Examples include Principe (1989) where species values are additive; Solow et al. (1993) where adjustments should be made to possible redundancies in species use; and Polasky and Solow (1995) where species interdependences should also be valued.

Incorporating ecological information to the measurement of biodiversity value has been increasingly popular in recent studies. A pioneering work in this regard is Weitzman (1998) who used a genetic distance concept in deriving a diversity function. Brock and Xepapadeas (2003) refined this measure by integrating the genetic distance concept to an economically desirable measure of species responsiveness to environmental stress. However, in their analysis, the evolution of the environmental factor (pest) follows a predictable pattern and species' response to environmental stress is fixed i.e. an underperforming species will remain so even when the environmental factor changes. On the other hand, Kassar and Lasserre (2004) argue that environmental changes are uncertain and species value evolves following the impetus from the environment in continuous evolution. However, their analysis is restricted to species that are perfectly substitutable in their use. Other studies which employ ecological models to assess the role of diversity in ecosystem functioning include Tilman et al. (2005) and Eichner and Pethig (2006).

In light of this, our approach employs an ecological model of diversity developed by Norberg et al. (2001), which aggregates the behavior of a group of species with respect to overall productivity, diversity, and the group's ability to respond to environmental stress. The model has a thorough specification of species interdependencies and incorporates explicit species-environmental factor relationships in a manner that allows dynamic species responses to environmental stress. Thus, our approach has the advantage of not only specifying complex species interrelationships objectively, but also of accounting for their changing performances with respect to

changes in the environment. In addition to its thorough specification, it explains the behavior of the ecosystem using aggregate measures making it theoretically manageable to analyze.

We derive the gain (loss) from biodiversity by considering outcomes under myopic and full information management regimes. This approach borrows from Brock and Xepapadeas (2003) where the difference between two species and one species value functions gives the endogenous value of biodiversity.

Section 2 presents the ecological model, which is the basis of our analysis. In Section 3, we set up the optimization problems and obtain the corresponding solutions under myopic and fully foresighted management regimes. Simulation results are given in Section 4, and Section 5 concludes the paper.

2. The ecological model and its relation to biodiversity value

As mentioned in the introduction, we base our analysis on an ecological model developed by Norberg et al. (2001), which defines species interrelationships and their responsiveness to environmental change. By using moment approximation methods, the model captures the dynamics of the macroscopic/aggregate characteristics of the group of species in terms of total biomass, average phenotype³ and phenotypic variance. The total biomass aggregates the productivity of all the different species at a given point in time. Similarly, the average phenotype measures the average successional response of all the species to environmental change. The phenotypic variance, which we use as a measure of diversity,⁴ represents the spread of individual species phenotypes around the mean.

The resulting model provides a framework that is simple enough to analyze theoretically but which captures essential aspects such adaptive complex systems. The model also has an intuitive economic appeal since the total biomass, average phenotype, and phenotypic variance represent overall productivity, responsiveness to environmental stress, and a measure of diversity of the ecosystem, respectively.

The mathematical formulation of the model is given as:

³ Phenotype is defined as the morphological, physiological, biochemical, behavioural, and other properties of an organism that develop through the interaction of genes and environment (World Resources Institute, 1992).

⁴ While there are other measures of diversity, Norberg et al. (2001) argue that phenotypic variance may be a more appropriate measure of diversity when relating diversity to ecosystem functioning.

$$\frac{dQ}{dt} = (f_o + \nu f_2)Q + a \quad (1)$$

$$\frac{dX}{dt} = \nu f_1 + b \quad (2)$$

where Q is the total biomass; $\frac{dQ}{dt}$ is the rate of change of biomass; X is the average phenotype of the whole group of species; $\frac{dX}{dt}$ is the rate of change of the average phenotype; f_o is the aggregate growth function of the different species; f_1 and f_2 are the first and second derivatives of the growth function with respect to X ; ν is the phenotypic variance; a is a constant representing the amount of biomass immigrating from the external environment; and b is the corresponding average phenotype of the immigrating species.⁵

The growth function, f_o , and its first and second derivatives with respect to X , f_1 , and f_2 are specified as:⁶

$$f_o = \left(1 - \frac{Q}{K}\right)(1 - (E - X)^2) \quad (3)$$

$$f_1 = 2\left(1 - \frac{Q}{K}\right)(E - X) \quad (4)$$

$$f_2 = -2\left(1 - \frac{Q}{K}\right) \quad (5)$$

where E is the environmental factor and K is the carrying capacity.

Substituting the expressions for f_o , f_1 , and f_2 into equations (1) and (2) gives:

$$\frac{dQ}{dt} = \left[\left(1 - \frac{Q}{K}\right)(1 - (E - X)^2) - 2\nu\left(1 - \frac{Q}{K}\right)\right]Q + a \quad (6)$$

$$\frac{dX}{dt} = 2\nu\left(1 - \frac{Q}{K}\right)(E - X) + b \quad (7)$$

⁵Unlike the original model, we assumed the addition of external input of biomass to be a constant. Thus, expressions related to external input of biomass that appear in the original model are not included here. In addition, in the original model, the value of the phenotypic variance changes over time due environmentally determined immigration of species from the surroundings. In our case, phenotypic variance is constant since we assume immigration of species to be constant.

⁶The specification of the growth function was kindly given to us by Jon Norberg.

Equation (3) specifies the growth equation f_o as a logistic growth equation extended to incorporate the role of the environmental factor, diversity, and responses to environmental change. The first bracket represents a standard logistic growth equation. The second bracket is an expression for the difference between the optimal average phenotype and the current average phenotype.⁷ Thus, the larger the expression $(E - X)^2$ is, the farther the system is from optimal performance with respect to the environmental condition, and vice versa.

Equation (4) gives an expression for the first derivative of the growth equation, f_1 . The slope of the growth function increases, f_1 , when $(E - X)$ is positive, or when the average phenotype is moving towards the environmental optimum. Similarly, f_1 decreases when $(E - X)$ is negative, i.e. when the average phenotype is moving away from the environmental optimum. Equation (5) gives the expression for the second derivative of the growth function, f_2 , which is always negative.

This approach essentially decomposes the impact of biodiversity on ecosystem functioning into two components. The first component, which corresponds to equation (1) relates the growth of the total biomass, $\frac{dQ}{dt}$, to the diversity measure, v , holding the average phenotype, X , constant. The second component is represented by equation (2), which relates the dynamics of the average phenotype, $\frac{dX}{dt}$, to the diversity measure, v , where the total biomass, Q , is held constant.

As can be seen in equation (1), the growth of the total biomass, $\frac{dQ}{dt}$, decreases with diversity, v , since the second derivative of the growth equation, f_2 , is always negative. The negative relationship between biomass growth, $\frac{dQ}{dt}$, and the diversity measure, v , indicates that higher diversity reduces the growth of total biomass, holding the average phenotype, X , constant, among other factors. In other words, for a given value of the environmental factor and the average phenotype, there will be one species

⁷ The current state of the environment, E , corresponds to the environmentally determined optimal average phenotype, X_{opt} . A positive change in X corresponds to a movement towards the environmental optimum, X_{opt} while a negative change in X corresponds to a movement away from it.

outperforming all the others. With diversity, the presence of underperforming species increases, which decreases the overall productivity of the system. Intuitively, diversity would imply that there is one outperforming species (corresponding to the given environmental factor), while all the other species are underperforming. The suboptimal species take up space and resources, which could be used more efficiently by the outperforming species. As a result, the more diverse the ecosystem, the slower the rate at which its productivity increases. Thus, equation (1) depicts the cost of diversity to the productivity of the system.

Equation (2) specifies the relationship between the rate of change in the average phenotype of the whole species, $\frac{dX}{dt}$, and the diversity measure, v , holding the total biomass, Q , constant. According to this relationship, the rate of change of the average phenotype, $\frac{dX}{dt}$, falls when f_1 decreases. Similarly, the rate of growth of the average phenotype increases when f_1 increases. A positive change in the average phenotype, $\frac{dX}{dt}$, corresponds to movement towards the environmentally determined optimum average phenotype and vice versa. This implies that the system moves away from an environmentally determined optimum when f_1 is positive, while it moves towards the environmentally determined optimum when f_1 is negative. Since diversity, v , multiplies f_1 in the equation, it determines the rate at which the system moves towards/away from the environmental optimum.

Intuitively, since the dynamics of the average phenotype captures the system's adaptive response to environmental stress, the ecosystem may be in a state where it is negatively or positively responding to the stress. Higher diversity enhances the ecosystem's ability to have positive adaptive responses if the system is moving towards the optimal average phenotype. If the system is moving away from the optimum, diversity further dampens the coping ability of the system. In sum, while equation (1) depicts the cost of having diversity at any point in time, equation (2) depicts the responsiveness of species to the environmental factor which is conditioned by diversity.

Our approach is to measure the value of diversity in terms of the gain in the present value of harvest (from the total biomass) from having diversity. In order to

derive the value of diversity this way, we consider two management regimes that give alternative values for the present value of harvest. We call the management regime that only considers the dynamics of the biomass only (i.e. equation 1) myopic management. The second regime is a fully foresighted management, where both the dynamics of the biomass (equation 1) and the dynamics of the average phenotype (equation 2) are considered. Our premise is that since biomass is a source of harvest, its dynamics is of direct economic interest. On the other hand, the dynamics of the average phenotype depicts the system's responsiveness to environmental change, which represents its adaptation to the environment and hence the system's long term productivity. Since average phenotype is not a direct factor in the system's immediate productivity and harvest does not (directly) depend on it, it is not of direct economic importance. If optimization only considers biomass dynamics, then it leaves out an important indirect effect. Thus, by disregarding the dynamics of the average phenotype, the myopic management fails to account for the indirect effect, which captures the ecosystem's adaptive response to environmental stress. On the other hand, fully foresighted management takes into account both the dynamics of the total biomass and the average phenotype. Based on this, this paper intends to obtain the gain (loss) of biodiversity as the difference in outcomes under the two management regimes.

In the ecological model, E is a time varying factor that could be characterized by a constant or variable rate of change over time. The variable rate E leads to more complicated dynamics (Norberg et al., 2001: p11377),⁸ but is also more interesting since it can accommodate unpredictable changes in the environment.

Based on this, we take E to be a stochastic variable, and consider a random value of the environmental factor with a Brownian motion. Accordingly, the following stochastic differential equation specification is chosen.

$$dE = \alpha dt + \sigma(t) dz(t) \tag{8}$$

⁸ Their analysis involving variable rates of environmental change considered seasonally oscillatory and reddened noise time series types of environmental behaviour.

where α could take a zero value or could be a non-zero constant⁹, σ is the instantaneous standard deviation of the environmental variable, and $dz(t)$ is the increment to a standard Gauss-Weiner process.

3. Alternative management outcomes

This section develops a framework that enables derivation of the value of biodiversity. The basis of our analysis is the ecological model (discussed in Section 2), which specifies that short term productivity is reduced by diversity due to the presence of suboptimal species, while long term productivity may be enhanced by diversity due to its possible contribution to environmental adaptation. Accordingly, the first management regime we consider, myopic management, takes into account the impact of diversity on short-term productivity. The full-foresighted management regime incorporates impacts of diversity both on short and long-term productivity.

Our approach is to evaluate the outcomes of the two management regimes by computing the corresponding present values of harvest. Each of the management outcomes are assessed using a bio-economic model that consists of a sole owner-manager who maximizes the present net value of benefits from harvesting part of the biomass.

The benefit from harvesting is a function of price, p , and biomass harvest, q . Harvest is a function of harvesting effort, y , and total biomass, Q . The total benefit from harvesting is, thus, pyQ . The cost of harvesting is given as sy^2 , where s is a constant. The net benefit from harvesting at a specific point in time (where the time index is omitted) is the difference between the total benefit and the cost of harvesting, $pyQ - sy^2$.¹⁰ The sole manager would seek to maximize the sum of the discounted stream of net benefit from harvesting the biomass with the a risk-free, positive discount rate given by r .

It should be noted that, to come up with such a net benefit function, we relied on certain assumptions with respect to harvest and prices. We assumed a harvest function linear in effort and aggregate biomass. Given that harvest functions are commonly

⁹ With $\alpha(t) = 0$, the pattern of the environmental variable will be purely random. Any other positive and constant value of $\alpha(t)$, the pattern exhibits an increasing trend.

¹⁰ By doing so we have assumed a quadratic objective function.

specified as quadratic (e.g. Crepin, 2002), our choice of the functional form is a simplification.

To value the harvest, we have assumed a single price corresponding to the total biomass. As we argued in the introduction, our focus is on the contribution of biodiversity to ecosystem functioning. In our analysis, species derive their distinct features from their individual contribution to the total biomass¹¹ and their individual response to environmental stress. Thus, different species contribute different amounts of biomass and have different levels of environmental responsiveness, at every point in time. An additional difference could be that the qualities of biomass contributed by different species may be different leading to different market prices of the biomass corresponding to the different species (Tilman and Polasky, 2006)¹². While the value of biomass for the different species could be different, we assumed away the price differences. Our analytical framework, which is realistic in many respects and hence complex, did not allow us to incorporate the possible price differences of the species with respect to biomass.

Below, we present our analysis of alternative management strategies of a biologically diverse ecosystem. The outcomes of the two strategies are evaluated in terms of the respective present net benefits from harvest. Our objective is to find the insurance value of biodiversity by computing the difference in the values of harvest under full-foresighted and myopic management regimes.

3.1. Myopic management

The myopic manager maximizes the present value of net benefits from harvest, subject to the growth of biomass over time. However, she disregards the impact of a changing environment on the performance of each of the different species. In other words, she does perceive the environmental factor as a variable that has an impact on the dynamics of the biomass. However, she treats the average phenotype of the different species in the system as a constant, with no dynamics as a response to the change in the environmental factor over time. Mathematically, the problem is stated as:

¹¹ Note that the total biomass is the sum of individual species biomasses.

¹² It should be noted that the ecological model conveniently aggregates the amounts of biomass contributed by the different species, for each period of time. In addition it also aggregates the contribution to environmental responsiveness by each species. What is not taken into account in the model is, as opposed to the biomass amounts, the quality of biomass contributed by each species.

$$W(0, Q_o, E_o, T) = \max_y \int_0^T e^{-rt} (pyQ - sy^2) dt \quad (10)$$

s.t.

$$\frac{dC_T}{dt} = \left[\left(1 - \frac{Q}{K}\right) (1 - (E - X)^2) - 2v \left(1 - \frac{Q}{K}\right) \right] Q + a - yQ \quad (11)$$

$$dE = \alpha dt + \sigma(t) dz(t) \quad (12)$$

where $Q(0) = Q_o$, $E(0) = E_o$, T represents the end time and W is the value of the opportunity to exploit the multispecies ecosystem. Following Malliaris and Brock (1982), the Hamilton-Jacobi-Bellman's equation for the above problem is given by:

$$-W_t = \max_y \{ (pyQ - sy^2) + W_Q \left[\left(1 - \frac{Q}{K}\right) (1 - (E - X)^2) - 2v \left(1 - \frac{Q}{K}\right) \right] Q + a - yQ \} + W_E \alpha + \frac{1}{2} W_{EE} \sigma^2 \quad (13)$$

From (13), the solution to the optimal level of effort, y , is:

$$y^* = \frac{pQ - W_Q Q}{2s} \quad (14)$$

Substituting the optimal effort into the HJB equation transforms the expression into:

$$-W_t = (py^*Q - sy^{*2}) + W_Q \left[\left(1 - \frac{Q}{K}\right) (1 - (E - X)^2) - 2v \left(1 - \frac{Q}{K}\right) \right] Q + a - y^*Q \quad (15)$$

It should be noted that the functional form of the value function, W , is not known, which also implies that its derivatives, W_t , W_Q , W_E , and W_{EE} are not known either. Since our problem is not in the class of stochastic optimization problems that are quadratic in the objective function and linear in the constraints, the functional form cannot also be approximated (Dockner, 2000). Thus, we find a numerical solution for W that is piece-wise linear¹³. The program C⁺⁺ was used to obtain the numerical solution in a number of discrete points. The program Matlab was then used to do linear interpolations between the discrete points to get a solution for W that is piecewise linear. With a solution for W , equation (15) could be used to solve for W_Q , which transforms expression (14) into

$$y^* = \frac{pQ - W_Q^* Q}{2s} \quad (16)$$

¹³ I would like to thank Tobias Göbak, for his help in coding the problem in C⁺⁺ and Matlab.

The solution for Q that corresponds to the optimal effort, y^* , is obtained by solving the following system of differential equations

$$\frac{dQ}{dt} = \left[\left(1 - \frac{Q}{K}\right) (1 - (E - X)^2) - 2v \left(1 - \frac{Q}{K}\right) \right] Q + a - y^* Q \quad (17)$$

$$dE = \alpha dt + \sigma(t) dz(t) \quad (18)$$

$$\frac{dX}{dt} = 2v \left(1 - \frac{Q}{K}\right) (E - X) + b \quad (19)$$

It should also be noted that although the rate of change of the average phenotype is not taken into account in the manager's decision making, its evolution would naturally impact upon the evolution of the biomass. Thus, the solution for Q for would also incorporate the solution to X . The corresponding numerical solution is coded using Matlab.

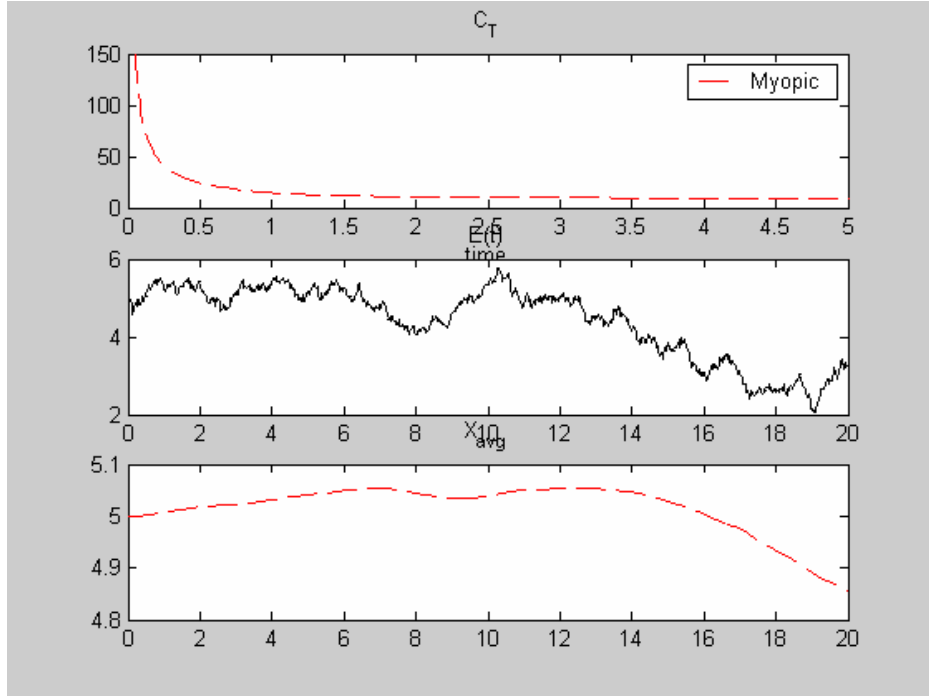
The parameters in the systems of equations are given in the Appendix. Our choice of many of the parameters is closely based on Norberg et al. (2001). These include parameters like the initial values for the total biomass and the average phenotype, and the external inputs of biomass and phenotype.¹⁴ Due to the nature of the growth function and the resulting equations for the dynamics of the total biomass and the average phenotype, we were restricted to using a diversity measure less than 1. We chose the price, interest rate, and carrying capacity values arbitrarily but in a manner that allowed for convergence.

Figure 1 shows the patterns of environmental change over time when the growth of the average phenotype is not taken into account in the planner's decision making. Hence the figure depicts the myopic management scenario. The first panel in the figure shows the dynamics of the total biomass over time, where the end time is 20 units. The second panel depicts the movement of the environmental variable over time, while the third panel shows the pattern of the dynamics of the average phenotype over time. The environmental variable, E , depicts an environmental change with Brownian motion which also follows a roughly cyclical pattern with a slightly upward pattern followed by a downward pattern. The average phenotype roughly follows a similar direction as the

¹⁴ It should be noted that, in the case of Norberg et al. [14] the simulations were run for individual species to study the aggregate characteristics.

environmental variable albeit with a smoother pattern. The total biomass follows a steadily falling trend.

Figure 1: Behaviors of Q , E , and X under random environmental change with Brownian motion



3.2. The fully foresighted management

Under this management regime, the dynamics of the average phenotype, or the responsiveness of the multispecies ecosystem to environmental stress, is considered in addition to the dynamics of the total biomass. Thus, the average phenotype of the group of species is (correctly) perceived to be evolving over time. This is the difference between this management scenario and the myopic scenario, where the average phenotype is perceived to be a constant and not responsive to environmental changes.

Given a perfect foresight scenario, the manager's problem is stated as:

$$W(0, Q_o, X_o, E_o, T) = \max_y \int_0^T e^{-rt} (pyQ - sy^2) dt \quad (18)$$

s.t.

$$\frac{dC_T}{dt} = \left[\left(1 - \frac{Q}{K}\right) (1 - (E - X)^2) - 2v \left(1 - \frac{Q}{K}\right) \right] Q + a - yQ \quad (19)$$

$$\frac{dX}{dt} = 2v \left(1 - \frac{Q}{K}\right) (E - X) + b \quad (20)$$

$$dE = \alpha dt + \sigma(t)dz(t) \quad (21)$$

where $Q(0) = Q_o$, $E(0) = E_o$, T represents the end time and W is the value of the opportunity to exploit the multispecies ecosystem. The corresponding Hamilton-Jacobi-Bellman equation becomes:

$$-W_t = \max_y \{ (pyQ - sy^2) + W_Q \left[\left(1 - \frac{Q}{K}\right)(1 - (E - X)^2) - 2v\left(1 - \frac{Q}{K}\right) + a - yQ \right] + W_X [2v\left(1 - \frac{Q}{K}\right)(E - X) + b] + W_E \alpha + \frac{1}{2} W_{EE} \sigma^2 \} \quad (22)$$

From equation (22), we solve for y, which is the optimal level of effort corresponding to the optimal harvesting rule:

$$y^* = \frac{pQ - W_Q Q}{2s} \quad (23)$$

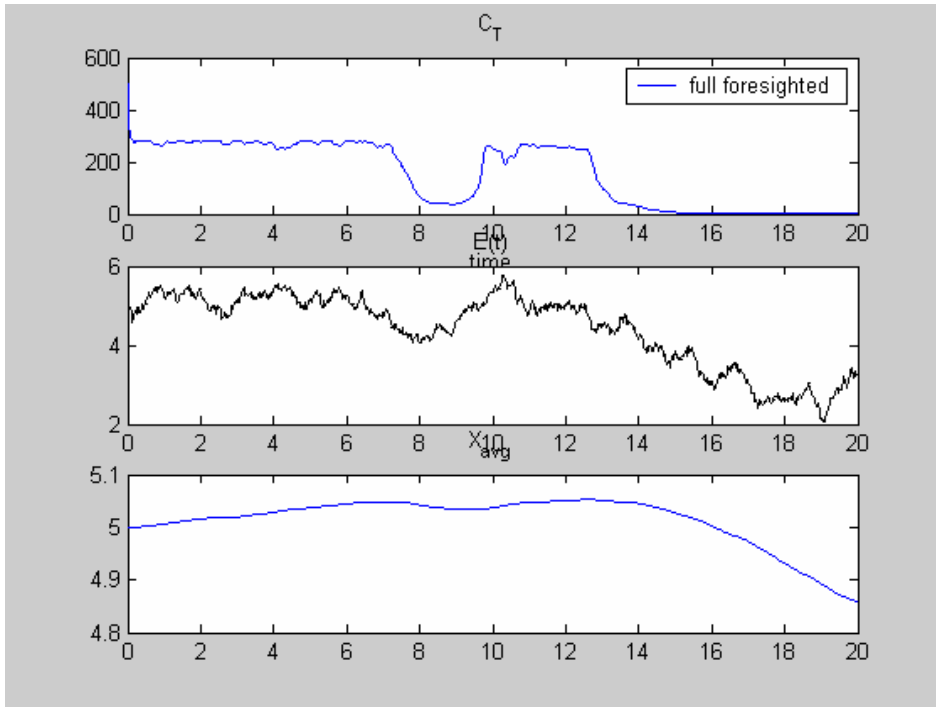
Substituting the optimal effort into the HJB equation transforms the expression into:

$$-W_t = py^*Q - sy^{*2} + W_Q \left[\left(1 - \frac{Q}{K}\right)(1 - (E - X)^2) - 2v\left(1 - \frac{Q}{K}\right) + a - y^*Q \right] + W_X [2v\left(1 - \frac{Q}{K}\right)(E - X) + b] + W_E \alpha + \frac{1}{2} W_{EE} \sigma^2 \quad (24)$$

Figure (2) analyzes the dynamics of the biologically diverse ecosystem under fully foresighted management. The pattern of the environmental change is similar to the myopic case because the environmental change is exogenous and is not affected by the dynamics within the model. Similarly, the pattern of the dynamics of the average phenotype is similar to that under myopia. As can be seen in equation (18), the average phenotype is not a function of the total biomass, Q, or harvest, y. Thus the harvest decisions that differ between the myopic and the full foresight management regimes do not affect the evolution of the average phenotype. Due to this, the patterns of the average phenotype under the two management regimes (i.e. in Figures 1 and 2) are identical.

The dynamics of the total biomass follow an interaction of the pattern of the environmental factor and the average phenotype: when the environmental factor and the average phenotype move close to each other, the total biomass tends to increase over time and decrease whenever the environmental factor and the average phenotype move apart.

Figure 2: Behaviors of Q , E and X under random environmental change with Brownian motion (high standard deviation).



4. Biodiversity value based on simulation results

As explained earlier, the value of biodiversity is computed as the difference between the present values of harvest under fully foresighted and myopic management regimes. For each regime, optimal harvest/effort and the corresponding total biomass values at each point in time are computed, which are, in turn, used to calculate the stream of net benefits from harvest. Discounting and summing up the net benefit values gives the present values of harvest under each management scenario.

The basis of our analysis is the case where the environmental variable exhibits a random value with a Brownian motion. Since the environmental factor is a stochastic variable, its realized value is one out of the many possible random values. In order to account for the randomness, we run ten simulations, each representing (an arbitrarily) low environmental variation. Each simulation is run for myopia and full foresightedness, under a given environmental outcome, and the results provide the present value of harvest corresponding to the two management regimes. Table 1 presents the present value of harvest for the myopic and fully foresighted management

under (an arbitrarily) low environmental variation. The first column gives the present value of harvest under myopia; hence the results represent the harvest value of the ecosystem disregarding its responsiveness to environmental stress. The second column corresponds to the present value of harvest under full foresight, i.e. when the ecosystem's responsiveness to environmental stress is taken into account. The difference between the two values is computed to give the value of diversity. The average of the differences gives the expected value of diversity, and the standard deviation of the differences gives the spread of the actual diversity values around the expected value of diversity.

The result shows that the biodiversity value is positive for all the considered cases, and hence diversity enhances the system's adaptive response to environmental stress. This is in line with Brock and Xepapadeas[3], who found that biodiversity increases productivity through providing an insurance mechanism that controls the system's adaptation to pest dynamics.

However, the value of diversity for given environmental outcomes differ from very high to zero depending on how close/far apart the present values of harvest are from each other under the two management regimes.

Table 1: Comparison of Fully Foresighted and Myopic Management Regimes under Low-Variation Environmental Change (Low Standard Deviation)

Present value of harvest (Full foresight)	Present value of harvest (Myopia)	Difference
88.90	0.29	88.61
1.30	1.30	0.00
216.20	0.81	215.39
0.77	0.73	0.04
0.48	0.48	0.00
0.88	0.86	0.02
175.80	0.68	175.12
1.90	1.90	0.00
1.40	1.10	0.30
0.88	0.87	0.02
	Mean	47.95
	Standard Deviation	62.65

In order to assess the impact of the magnitude of environmental uncertainty, we consider a case where the standard deviation of the environmental variable is higher. We compute the value of biodiversity based on the same set of parameters as in the earlier case (see Appendix) but with a higher standard deviation of the environmental change. Table 2 presents the corresponding simulation results. In this case too, the difference between the present values of harvest under full-foresighted and myopic regimes is positive, indicating that biodiversity has a positive value. Comparing biodiversity values under high and low standard deviation (mean values in Table 1 & 2), however, the average biodiversity value is higher with a higher standard deviation. Thus, biodiversity is more valuable when the environmental variability is higher. Similarly, comparing the standard deviation of biodiversity values in Tables 1 & 2, it is shown that the standard deviation of the value of biodiversity is higher when the environmental factor has a higher standard deviation. This implies that, for a given environmental pattern, the value of biodiversity will be far higher or lower than the average when the environmental variation is greater. This result is in line with the finding by Kassari and Lasserre (2004) which shows that environmental volatility raises the value of diversity by increasing species' option value and by expanding the target conservation area through substitution of currently used species for unused ones.

Table 2: Comparison of Fully Foresighted and Myopic Management Regimes under High-Variation Environmental Change (High Standard Deviation)

Present value of harvest (Full foresight)	Present value of harvest (Myopia)	Difference
1.10	0.82	0.28
146.20	1.80	144.40
0.99	0.79	0.20
111.70	1.00	110.70
1.20	0.84	0.36
157.80	1.50	156.30
1.80	1.60	0.20
27.90	0.66	27.24
0.59	0.57	0.03
115.90	0.82	115.08
	Mean	55.48
	Standard Deviation	81.18

In order to assess the possible impact of global warming on biodiversity value, we consider additional patterns of the environmental factor. We assume that, with global warming, environmental variables like temperature exhibit increased higher volatility and assume positive trends, and consider a case where the average value of the environmental variable has an increasing trend and its standard deviation is (arbitrarily) high.

Table 3 presents the results for our assessment of the impact of global warming on biodiversity value. The results show that the average value of biodiversity increases when the average environmental variable increases combined with a higher standard deviation. This indicates that with global warming, biodiversity becomes more valuable. This suggests that, with global warming concerns, biodiversity conservation might deserve a special attention where features of global warming make biodiversity more valuable.

Table 3: Comparison of Fully Foresighted and Myopic Management Regimes under High-Variation Environmental Change (High Standard Deviation)

Present value of harvest (Full foresight)	Present value of harvest (Myopia)	Difference
62.20	0.82	61.38
1.20	0.89	0.31
0.59	0.59	0.00
170.10	1.30	168.80
134.40	1.70	132.70
135.80	1.10	134.70
0.96	0.80	0.15
1.10	1.00	0.10
1.20	0.70	0.50
166.70	1.70	165.00
	Mean	66.36
	Standard Deviation	73.27

4. Conclusion

Biodiversity conservation has been one of the great global environmental concerns due to the tremendous loss of diversity (Thrupp, 2000), the threat of rapid future depletion and huge uncertainty about the consequences (Heal et al., 2004). Designing sound

conservation policies and wise use of funds calls for a proper understanding of the value of biodiversity. The focus of this paper is on assessing the value of biodiversity with respect to the joint value shared by different species by emphasizing on species inter-relationships and their interaction to the environment.

Following recent trends in incorporating ecological information into a biodiversity valuation framework, this study employs a unique ecological model that gives an aggregate characterization of a multiple species ecosystem in terms of measures of productivity, responsiveness to environmental change and diversity. The model depicts that diversity reduces instant productivity of the system because of the presence of suboptimal species under a given environmental condition. On the other hand, higher diversity may enhance the ability of the ecosystem to have positive adaptive responses to changes in the environment.

Following Brock and Xepapadeas (2003), our approach develops a measure of the value of diversity in terms of the gain in the present value of harvest by comparing alternative management regimes. The myopic management corresponds to optimization, which takes into account the cost of diversity only. The fully foresighted management considers both the costs and potential benefits of diversity. Using techniques of stochastic dynamic optimization, the optimal effort (harvest) rules corresponding to myopic and fully foresighted management are obtained. The value of biodiversity is calculated as the difference in the discounted stream of net benefits from harvest between the two management regimes. Analytical computation of the solutions was not possible due to non-linearities and unknown form of the value function. Hence, the solutions are based on numerical simulation.

In existing analyses, biodiversity was shown to have a positive insurance value in the presence of environmental stress. Our analysis, which is based on stochastic environmental change, also supports this result. In a similar manner, our results show that biodiversity assumes a higher value with increase in environmental variability. This implies that the positive correlation between biodiversity value and environmental volatility is not restricted to species with substitutability in their current use value, as shown in previous studies; environmental uncertainty raises the biodiversity value irrespective of whether species are compliments and substitutes in their use.

The principal implication of our analysis is that biodiversity conservation efforts should target high environmental-variation areas. This paper has also suggested that with global warming concerns, biodiversity conservation might deserve a special attention where features of global warming make biodiversity more valuable.

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Appendix: Parameter values used in the simulations

Parameter	Base case	Higher environmental uncertainty	Global warming
r	0.01	0.01	0.01
p	0.0001	0.0001	0.0001
s	0.05	0.05	0.05
K	1000	1000	1000
a	0.1	0.1	0.1
b	0.005	0.005	0.005
v	0.01	0.01	0.01
E _{mean}	5	5	5
E _{std}	0.25	0.5	0.5
A _{amp}	0.5	0.5	0.5
A _{per}	10	10	10
CT ₀	0.5	0.5	0.5
X _{avg0}	5	5	5
T _{end}	20	20	20
epsilon	0.008	0.008	0.008
const	0.00	0.00	0.01