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Abstract

Characteristic of ecosystems is that different organisms can have similar functions and hence provide similar ecosystem services. Consequently *functional diversity* can maintain the rate of services despite environmental fluctuations. In this paper we present a method for estimating the resilience value of biodiversity. Central to a resilience perspective on biological conservation is consideration of uncertainty about the future. To do this we propose stochastic simulation as a practical approach for valuing resilience due to the ease of incorporating uncertain variables. We demonstrate the approach by developing a stochastic simulation model for valuing soil biodiversity in agriculture. Our results indicate that the long time frames involved in soil processes create a significant incentive to perpetuate unsustainable farming systems and hence there might be a need for policy intervention. However we also show that investing in soil biodiversity conservation can provide significant risk diversification benefits that are not accounted for in a deterministic evaluation. These benefits can be estimated through stochastic simulation.

1 Introduction

The benefits that humankind receives from ecosystems and constituent biodiversity are known as *ecosystem services* (Ma 2005). Agriculture for example utilizes soil biodiversity to produce food, fiber and energy for human consumption (Chavas 2008). Soil biodiversity also provides a range of other benefits to society such as carbon storage, water filtration, and pest and disease control that are crucial for sustaining life on Earth (Barrios 2007). Soil biota do this by performing ecosystem functions such as nutrient cycling, nitrogen fixation, phosphorus acquisition, decomposition of organic materials, mineralization of carbon and soil structure modification. In natural ecosystems the soil functions as a dynamic regulator whereby biodiversity influences the magnitude and temporal distribution of carbon (C) and nutrients that are essential for plant growth. In *intensively* farmed agro-ecosystems biological regulation has, in contrast, been largely replaced by mechanical soil management, artificial fertilizers and chemical protectants. In these systems the soils' capacity for self-regulation in response to environmental fluctuations is reduced and greater reliance is placed on external inputs (Swift, Izac et al. 2004). The loss in soil biodiversity following from intensification is associated with declines in the complexity and functions of soil food webs which results in reduced C storage and nutrient retention, greater instability of soil structure, less resistance to invasions of exotic species and increased outbreaks of pests and pathogens (Maeder, Fliessbach et al. 2002). Overall conservation of biodiversity is important for soil fertility and consequently a potential resource for the sustainable management of agriculture. Whether current agricultural systems are sustainable or not is the cause of intense academic debate and driving widespread comparisons of alternative agricultural systems (Pimentel, Hepperly et al. 2005).

An important reason for this divergence in opinions about is the absence of evidence of declining yield trends in well managed intensive systems (i.e. those using ostensibly sound tillage and nutrient management practices). On the contrary, average yields are still rising in e.g. Europe and the USA. There is on the other hand evidence of declining soil organic matter (SOM) which is an indicator of species diversity in soil communities and hence fertility (Riley and Bakkegard 2006). In the short run it is obvious that external inputs (e.g. new crop varieties, fertilizers, etc.) can substitute for species diversity and thereby augment yields. The unanswered question is whether declining SOM levels represent a threat to the sustainability of agriculture as we know it today? Despite simplification of the soil organism community it can still have impacts on agricultural productivity (i.e., yield/inputs). These can be direct when specific organisms affect crop yield immediately and indirect as those provided by organisms participating in carbon and nutrient cycles, and food web interactions (De Ruiter, Neutel et al. 1994). Thus if biodiversity and external inputs are complements then farmers could be degrading biodiversity below the optimal level even from a short-run perspective (Omer, Pascual et al. 2007). From the long-run perspective there might even be *threshold effects:* once some minimum level of species diversity has been breached, a sudden and permanent drop in yield could occur (Riley and Bakkegard 2006).

Critical to resolving the sustainability conundrum is developing knowledge about how soil ecosystem behaviour is affected by losses in species—especially responses to shocks—and the implications for human welfare; now and in the distant future. Theoretically, ecosystem behaviour can be characterized by stability and resilience: stability represents the ability of a (dynamic) system to return to an equilibrium state after a *disturbance* (i.e., exogenously induced species mortality); the more rapidly it returns and the less it fluctuates, the more stable it would be. To be stable a system

has to have forces in it that bring it back to equilibrium if it is not there to begin with: it is self organizing. In ecological systems these forces are determined by the assemblage of species (May 1972; de Ruiter, Neutel et al. 1995). Resilience on the other hand is used in ecology to describe the persistence of a system and its ability to maintain its basic functions and controls (or self-organization) under disturbances (Holling 1973). Holling's notion of resilience is the maximum amount of disturbance a system can absorb in a given stability domain while still remaining in that domain (where a domain is defined by the underlying relationships between variables in the system). The difference between the two is exemplified by Roughgarden *(1998)* using the analogy of a marble lying in a bowl: *"stability refers to whether the marble will return to the bottom if nudged away from it, while resilience refers to whether the marble will stay near the bottom if the bowl is shaken [or end up somewhere else]."*.

Sufficient loss of resilience through soil degradation implies that a chance and rare event that previously could be absorbed by the system can trigger a sudden dramatic change and loss of structural integrity of the system (e.g. a change in climatic, environmental or chemical parameters, or fluctuation in competitors or predators). The implication is that once resilience has been reduced a disturbance will have increased probability of causing such a system *shift*. The economic relevance of resilience is that a flip from a high yielding state to a low yielding state would entail significant welfare losses. Stability on the other hand can be interpreted as the time it takes the system to return to the normal (yield distribution) after a random but not surprising event. As a result greater stability and resilience in agricultural systems would seem preferable to less. Mathematically stability usually implies resilience. From a practical modeling perspective it seems also adequate to distinguish between the two characteristics only in respect to the time it takes the system to return to normal after a disturbance. A stable system would return to normal within the confines of the time horizon under consideration (e.g. 20-30 years as will be used in this paper) whereas a loss in resilience implies the productive potential of the soil would not return to normal within the time horizon after a particular disturbance, and hence have the characteristic of a permanent change or at least only slowly reversible (e.g. Perrings and Stern 2000). In this way we focus on *"the capacity [of the soil] system to reorganize and regain a desired state after a disturbance"* which is the key aspect of the resilience perspective on ecosystem management (Folke, Carpenter et al. 2004). In agro-ecosystems the species mix is simplified for the purposes of agriculture and hence are particularly at risk of losing resilience, which may be interpreted as a loss in productive potential and\or increased risk associated with a given set of environmental conditions (Perrings 1995).

Tools for analyzing and managing farm risk are well developed in agricultural economics (Hardaker, Huirne et al. 2004). These tools have only recently been identified as being applicable for the management of ecosystems and biodiversity, but empirical applications are lacking (Armsworth and Roughgarden 2003; Baumgärtner 2007; Baumgärtner and Strunz 2009). In this paper we propose stochastic simulation combined with optimization as a method for estimating the resilience value of soil biodiversity due to its ability to handle uncertain variables and events. In the short term protecting biodiversity in agricultural landscapes is likely to be costly for farmers as increasing numbers of species may reduce productivity levels of the main crop through greater competition for resources. On the other hand biodiversity can increase agricultural output in the long run by enhancing ecosystem services (Omer, Pascual et al. 2007). Another problem in the short run is that more extensive production systems that conserve biodiversity such as organic agriculture might suffer from greater variability in production (Gardebroek, Chavez et al. 2010). For example in organic

farming the ban on using non-natural pesticides increases the vulnerability to outbreaks of pests and diseases. Once again the long-term effect might be quite different, when high levels of ecosystem services provide natural protection. To begin with we characterize the value of resilience based on the concept of the risk premium.

2 The value of soil biodiversity in an uncertain world

Characteristic of species communities is that different organisms can have similar functions and consequently provide similar services. What is known as *functional diversity* can therefore maintain the rate of ecosystem services despite environmental fluctuations if the individual species respond differently to specific disturbances (Tilman 1999). In this way species and functional diversity can mitigate the influence of uncertainty on human well-being and hence provide *insurance* against future environmental change (Armsworth and Roughgarden 2003; Baumgärtner 2007). Taking this perspective soil biodiversity can be characterized as a portfolio of species' assets where species survival is uncertain (Swanson 1994): no matter what conservation measures are taken we can never be certain that any particular species will survive, only augment the probability of its survival. It follows that resources devoted to conservation can be thought of as investments in species, and extinction of a species through *lack* of conservation measures, as disinvestment from the species portfolio. Accordingly, the expected benefits from protecting or exterminating a species are characteristic of a risky investment. The farmer's rational objective in this case can be conceived as managing the *portfolio* of species so as to achieve some expected level of ecosystem services (i.e. benefits) at minimal risk, which is the well known—but potentially complex—act of balancing risk with expected returns.

2.1 The insurance value of biodiversity

Uncertainty exists in agriculture because the many potential future states of the world can affect income differently. Consequently agriculture can be thought of as an income lottery over various potential states of the world. Most people dislike the risk associated with an uncertain income—they are said to be risk averse—preferring a sure payout to an uncertain but otherwise identical payout. The existence of risk aversion means that analysis of risky choices in terms of their expected return is an inadequate decision criterion. Farmers like most people will not wish to choose an investment that will pay best on average if it exposes them to an unacceptable chance of loss. A person who is risk averse is therefore willing to forgo some expected return for a reduction in risk. The amount that makes one indifferent between a certain income and an uncertain alternative is known as the *risk premium (e.g. Hardaker, Huirne et al. 2004)*. In this section it will be shown how the risk premium can be used to measure the resilience or risk reducing value of soil biodiversity (i.e. insurance value).

To begin with note that farmers indirectly determine the level of soil biodiversity through their choices of farming practices. This can be expressed as

$$z(t) = f\left[x(t), z(t)\right] \quad \text{for } t = 0, 1, 2, ..., T \quad (1.0)$$

where $z(t) \in [0, Z]$ is an index of species diversity and $x(t)$ a measure of the intensity of farming (or disturbance) in period t. The level of a particular ecosystem service $s(t)$, let us consider this to

be yield for clarity, will be a function of the level of biodiversity, intensity and stochastic environmental factors denoted $\Phi(t)$ at any particular point in time

$$s(t) = g\left[z(t), x(t), \Phi(t)\right] \tag{1.1}$$

The ecosystem service, s (the time variable t is now dropped for convenience), is therefore a random variable with mean $\mu_s(z, x)$ and standard deviation $\sigma_s(z, x)$ implying that the distribution of s is conditioned on the level of biodiversity and choice of intensity. For simplicity let us assume that s is normally distributed (in the stochastic simulations below we use empirically justifiable distributions) implying it is fully described by

$$s \sim N\left(\mu_s, \sigma_s\right). \tag{1.2}$$

Protecting biodiversity is most likely costly to farmers because it can entail more time consuming management practices or using fewer chemicals that result in lower yields in the short-term. Let the cost to a farmer of managing biodiversity be represented by the cost function

$$C(z) \quad \text{with} \ C'(z) > 0, \ C''(z) \geq 0. \tag{1.3}$$

Assuming that the benefits to farmers of protecting biodiversity are represented by s (through a suitable normalization such as crop price) then farm profit (or net income) is

$$y = s - C(z), \tag{1.4}$$

which is a random normally distributed variable with mean μ_y and standard deviation σ_y:

$$\begin{aligned} \mu_y(z) &= \mu_s(z) - C(z) \\ \sigma_y(z) &= \sigma_s(z). \end{aligned} \tag{1.5}$$

Consequently the farmer chooses a particular income lottery as a result of the uncertain generation of ecosystem services

$$y \approx \left(\mu_y, \sigma_y\right). \tag{1.6}$$

The farmer's preferences over their uncertain income can be represented by an expected (or von Neumann-Morgenstern) utility function

$$U = E\left[u(y)\right] \tag{1.7}$$

where $u(y)$ is their utility function and, assuming that farmers are risk averse, $U' > 0$ and $U'' < 0$. In brief, by choosing the level of biodiversity z the farmer chooses a particular income lottery which is uniquely characterized by z. The standard microeconomic method to value the riskiness of an uncertain income to a decision maker is to calculate the risk premium, *RP*:

$$u\left(E[y]-RP\right)=E\left[u\left(y\right)\right]. \tag{1.8}$$

In this case the risk premium is an implicit function of intensity x and biodiversity z and is the amount that would leave the farmer indifferent between choosing an intensity that would reduce the risk of an additional species going extinct or taking no precautionary action. The insurance value $V\left(z\right)$ of soil biodiversity is the marginal change in the risk premium given a marginal change in biodiversity (Baumgärtner 2007)

$$V\left(z\right)=-RP'\left(z\right), \tag{1.9}$$

or explicitly

$$V\left(z\right)=-\rho\sigma_y\left(z\right)\sigma_y'\left(z\right)>0, \tag{1.10}$$

where ρ is the farmer's subjective valuation of risk (or risk aversion parameter) and σ_y is the standard deviation in income as affected by the level of biodiversity. The optimal level of biodiversity z^* is characterized by

$$\mu_s'\left(z^*\right)+V\left(z^*\right)=C'\left(z^*\right), \tag{1.11}$$

which implies that the change in mean income generated by protecting an additional species plus the change in the insurance value should equal the cost of protecting that species. It follows from (1.11) that the higher the farmer's risk aversion ρ the higher the optimal level of biodiversity z^* since

$$\frac{dz^*}{d\rho}>0, \tag{1.12}$$

or equivalently the higher the farmer's risk aversion the higher the insurance value of biodiversity

$$\frac{dV\left(z\right)}{d\rho}>0. \tag{1.13}$$

In conclusion the insurance value of biodiversity and hence the optimal level of biodiversity will comprise both objective and subjective components depending on the farmer's attitude to risk. In the next section we describe a method that can be used to calculate the risk premium and hence estimate the value of protecting soil biodiversity to farmers given uncertainty about future events (i.e. resilience value).

3   Stochastic simulation for valuing resilience

Stochastic simulation is a modelling approach that can be used to incorporate random or stochastic variables in a model to reflect the sources of uncertainty in a system (Hardaker, Huirne et al. 2004; Lien, Hardaker et al. 2007). Repeated sampling (e.g. Monte Carlo simulation) from specified distributions of input variables (e.g. states of nature, yields, prices, etc.) is used to generate

distributions of output variables (e.g. revenues, farm profit, etc.) within a predefined timescale. From the resulting distributions the probability of the system achieving a target level of an output variable can be determined (via calculation of a confidence interval). In this way the output probability distribution provides a complete picture of all the possible outcomes because it is based on all the possible values of the input variables. This can be compared to traditional sensitivity analysis which might just use best and worst case scenarios for input variables and hence cannot provide any indication of the probability of an outcome. To achieve a monetary valuation of risk and hence resilience we propose to combine stochastic simulation with optimization.

We begin development of the stochastic simulation model with some background and basic assumptions. Farmers are assumed to be risk averse which doesn't mean they are not willing to take risks—otherwise they certainly would not have chosen farming— but that the *certainty equivalent* (CE) they assign to any risky production activity will be less than the *expected money value* (EMV) of that activity (i.e. they are willing to accept a lower valued 'sure thing' of value X than take the risky investment if given a choice). Hence, the difference between these two measures, RP=EMV-CE, is another way of defining the risk premium. As shown above the insurance value of a conservation measure is the change in the risk premium due to a marginal change in the level of biodiversity.

Two major sources of risk faced by farmers are production risk which is due to stochastic yields and market risk which is due to stochastic prices of agricultural inputs and outputs. If conservation of soil biodiversity can reduce exposure to either forms of risk then conservation measures will amount to self protection. For example if biodiversity reduces reliance on external inputs then farm profits will be less dependent on fluctuations in input prices. The most obvious example of this is the substitution of nutrient cycling services by imports of artificial fertilisers. Another is biological control which can reduce the need to purchase crop protectants.

In summary there are two ways in which soil organisms can affect yield. First there are direct effects where soil organisms contribute to nutrient cycling and secondly there are indirect effects when soil fertility affects the yield response to fertiliser applications. To obtain a full valuation of soil biodiversity we need to account for all of these effects.

3.1 Definition of stochastic input variables

3.1.1 Distribution of crop yield as a dynamic variable

There is a clear parallel between valuing crop insurance premiums and the insurance value of biodiversity. Accurate pricing of crop insurance contracts requires accurate estimation of the conditional yield densities (Ker and Coble 2003). To value biodiversity we need to know how the yield distribution is affected by the level of biodiversity. Usually the parameters describing a particular yield distribution are estimated on the assumption that soil biodiversity is constant (or at least very stable in the sense that it returns quickly to equilibrium after a perturbation). In this case variations in yield given identical management practices are assumed to be due to random fluctuations in the weather. From a short-term perspective (5–10 years) this is a reasonable assumption since changes in soil organism communities tend to occur slowly. In the long term the resilience and hence sustainability of agro-ecosystems might be seriously reduced as gradual degradation of soil biodiversity snowballs or thresholds are passed.

We extend the standard stochastic variable description of yield to that of a stochastic dynamic variable, implying that the yield distribution is affected by events that have occurred in previous time periods. These events—whatever they might be—are reflected in the state of soil biodiversity (i.e. the stock of soil organisms). The yield distribution in this case is conditioned on the state of soil biodiversity: for different levels of biodiversity, random weather events will result in different yields. Recognizing yield as a dynamic variable makes the relevance of stability and resilience immediately obvious as these are defining characteristics of a dynamic system. The conditional Beta-distribution can be utilized as a stochastic production function of agricultural output (Nelson and Preckel 1989). The Beta-distribution for random crop yield y over the interval $(0 \leq y \leq \bar{y})$ is

$$B(y,\alpha,\beta) = p(y) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \frac{y^{\alpha-1}(\bar{y}-y)^{\beta-1}}{\bar{y}^{\alpha+\beta-1}}$$ (2.1)

where $\bar{y} > 0$ is the finite upper bound on random crop yield and $\alpha, \beta > 0$ are parameters. The distribution can be conditioned on a vector of inputs, *x*, by expressing the parameters α and β as functions of *x*. A log-linear functional form is probably suitable:

$$\alpha(x) = a_0 \prod_{i=1}^{m} x_i^{a_i}$$

$$\beta(x) = b_0 \prod_{i=1}^{m} x_i^{b_i}$$ (2.2)

where *m* is the number of inputs (e.g. biodiversity) and a_i, b_i is the percentage change in α, β respectively as x_i rises by 1 %. The variable $\bar{y}$ is not expressed as a function of the inputs because regularity conditions for maxium likelihood estimation would be violated.

An important consideration that is not solved by sampling is stochastic dependency between variables. Yields of different crops are likely to be positively correlated due to the pervasive influence of the weather. Since the weather is the main underlying cause of correlation between yields we relate crop yields to stochastic weather variables to deal with this dependency.

The conditional Beta-distribution implies that the farmer through his input choices indirectly determines the distribution of yield (i.e., mean, variance, etc. as required by the theoretical model Equ. (1.11)). Since these choices also affect the level of soil biodiversity in future periods there is a dynamic dimension to the problem: input choices affect not only the distribution of the current yield but also the distribution of future yields. This affect can be accounted for by modeling soil biodiversity as a function of relevant inputs, e.g. nitrogen, for a particular cropping system.

The yield function for a particular crop in year *t* is

$$y(t) = f[x(t), z(t)] \approx B[\alpha(x,z), \beta(x,z), \bar{y}]$$ (2.3)

where biodiversity in year t, $z(t)$, is a function of inputs in year t and the level of biodiversity

$$z(t) = h\big[x(t), z(t)\big].$$ (2.4)

Expected yield in year *t* is

$$E[y] = \int_0^{\bar{y}} yB\big[\alpha(x,z), \beta(x,z), \bar{y}\big]dy$$ (2.5)

where y is potential yield and B the probability of y, i.e. $p(y)$.

3.1.2 Distribution of input and output prices

In addition to output prices we include prices of important inputs as stochastic variables. Whilst it is not usually necessary to treat input prices as a stochastic variables in a short-term analysis because the price is known at the time of planting a crop, this is not the case when making investment decisions. Since we characterise biodiversity conservation as an investment the uncertainty of future prices needs to be considered. Prices are readily observable on markets and hence historical data can be used to estimate joint distributions of prices so as to account for potential dependencies. Energy is a particularly interesting input to study because its price is likely to show dependencies not only with inputs such as fertiliser but also with crop prices. Since crops can be converted to bioenergy the world market price for energy will act as a floor price for agricultural crops. (We suppress details to keep within the word limit).

3.1.3 Risk averse farmers optimization problem: maximize expected utility

Assuming farmers' preferences over their uncertain profit π can be represented by an expected utility function, their decision problem can be framed as the optimal choice of a particular income lottery which is uniquely characterized by *x*.

$$\max \; E\big[u(\pi)\big] - cx$$ (2.6)

where U is concave utility of income and hence E[.] is an expected utility function, and *c* is the unit cost of input *x*. Inserting the yield function the expected utility maximization becomes

$$E\big[u(\pi)\big] : \max \int_0^{\bar{y}} u(P_y y) B\big[\alpha(x,z), \beta(x,z), \bar{y}\big]dy - cx$$ (2.7)

For later reference note that the utility of expected profit is calculated as

$$u(E[\pi]) : \max \; u\left(P_y \int_0^{\bar{y}} yB\big[\alpha(x,z), \beta(x,z), \bar{y}\big]dy\right) - cx \,.$$ (2.8)

If $u(E[\pi]) > E\big[u(\pi)\big]$ then the farmer is risk averse.

4 Results of stochastic simulation model

The time horizon of the analysis is naturally critical for interpretation of results. Lynam and Herdt (1989) suggest that 5-20 years is a relevant time frame for analysis of farming system sustainability. It is long enough to allow detection of threats to sustainability whilst also maintaining relevance for livelihood goals of individual farms. After this the realism of assumptions about economic, policy and

technological inputs to the farming system becomes increasingly difficult to defend. As a consequence our simulations stretch a maximum 25 years into the future.

To illustrate the merits of stochastic simulation as an approach for valuing biodiversity we develop a stochastic simulation model of winter wheat production in Sweden. We began by taking a standard enterprise budget for the production of 1 ha wheat (i.e. a static deterministic budget model) and extended it by modeling yield, crop price, nitrogen fertilizer price and energy price as stochastic variables. Stochastic crop yield was conditioned on nitrogen fertilizer input and the state of soil biodiversity. We model two alternative cropping systems under two different assumptions about the impact of intensity on biodiversity. Conventional (CONV) refers to continuation of the current system of production which does not consider potential negative effects of high intensity on soil biodiversity. The second is a biodiversity enhancing system (BIO) which uses one third less N-fertilizer than the conventional system. Since the effects of management practices on biodiversity are part of our ongoing research and results are not yet available, we value biodiversity based on two alternative assumptions about the influence of intensity on biodiversity. In the first or static scenario we simply assume that intensity has no impact on biodiversity and hence the distribution of yield over time. Both systems however generate identical expected yield because of a higher level of biodiversity in the BIO system (we ignore the cost of achieving this higher level). In essence all we are saying is that the BIO system substitutes more soil biodiversity for less N-fertilizer. We do this to make the systems comparable from a short-term perspective and to see how the systems perform over time in response to stochastic prices. In the second or dynamic scenarios we make biodiversity a function of fertilizer input (i.e. a proxy for intensity). We assume that biodiversity is being degraded over time in the high intensity CONV system and increasing in the low intensity BIO system. However in this scenario expected yield is initially lower in the BIO system to reflect the cost of building up biodiversity. The resulting four stochastic simulations summarized in Table 1 were run over 20 years (2011-2030).

Scenario	CONV-wheat	BIO-wheat
1 (static)	Constant low biodiversity	Constant high biodiversity
2 (dynamic)	Declining biodiversity	Increasing biodiversity

Table 1. Scenarios used to evaluate implications of biodiversity for farm profits

The BIO-system provides a way of reducing both output and input price risk because output price and the price of nitrogen fertilizer are stochastic. The significance of this effect will be illustrated in the results.

To highlight the implications of taking a long-term or sustainability perspective on managing biodiversity we present results, i.e. distributions of profits, for the years 2011 and 2030 only. Figure 1 shows the distributions of profits generated by assuming constant biodiversity in both systems. As might be expected the distributions generated in both the short term (top panel) and long term (bottom panel) are very similar and it would be difficult to recommend one system over the other. Nitrogen fertilizer substitutes for biodiversity and the quantities of fertilizer saved in the BIO system are not large enough to have a significant impact on the variance of profits. If measures to protect

biodiversity are costly, which they most likely are, then the farmer taking a myopic view will continue with the conventional system.
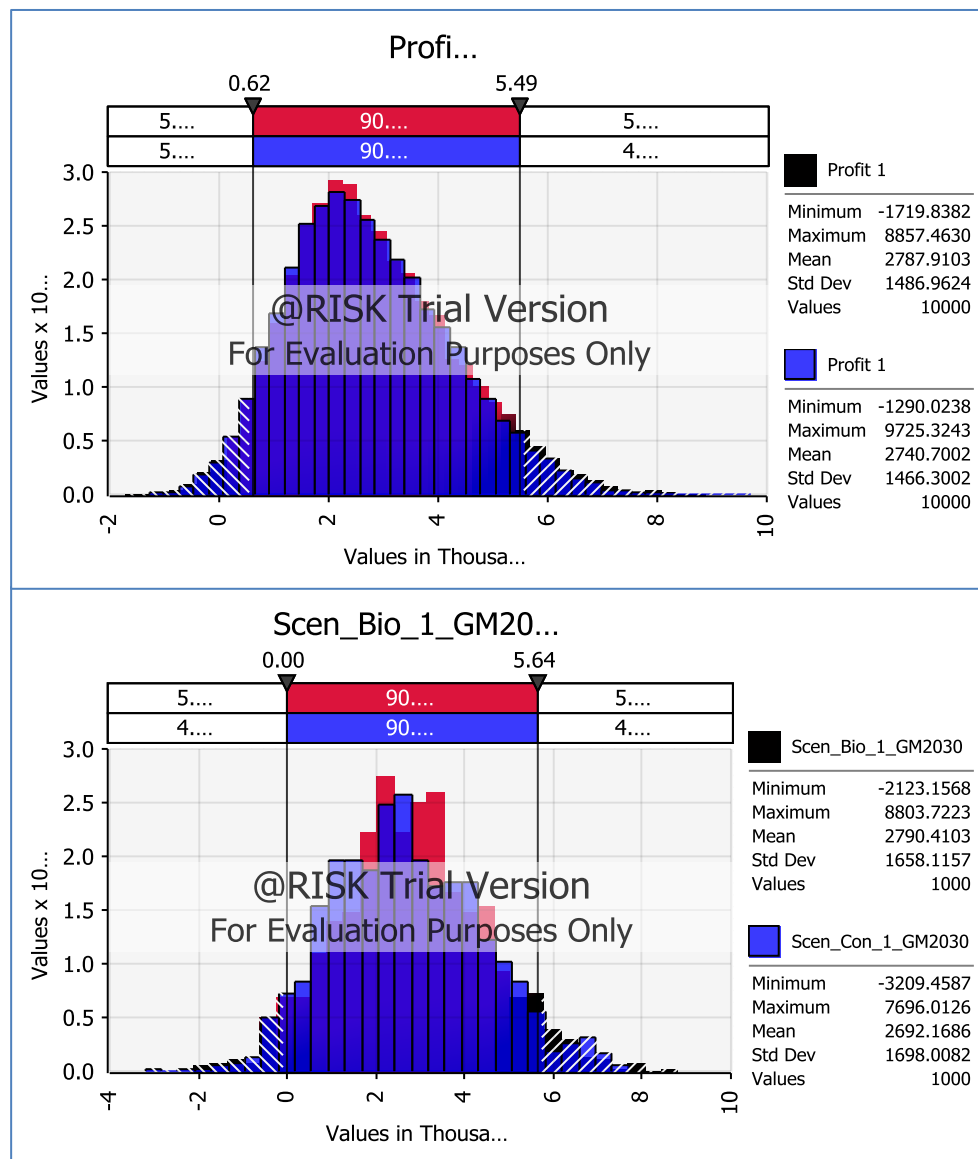

Figure 1. Distribution of profits ignoring impacts on soil productivity. Conventional (blue) v. biodiversity enhancing agriculture (red) (a) Year 2011 and (b) 2030

In the dynamic scenarios the results are very different, because changes in biodiversity affect the distribution of yield. The top panel in Figure 2 shows that in the short term the conventional system is preferable because it generates a probability mass to the right of the BIO-system: for all likely outcomes of the input variables the probability of any particular profit is higher in the CONV-system. The lower panel shows the implications of a gradual decline in soil biodiversity in the CONV-system and a gradual rise in the BIO-system (actual rates are 1 % per annum). Over the 20 year simulation period this scenario results in the CONV profit distribution moving to the left and the BIO distribution moving to the right. Not only does the BIO system raise soil productivity over time and hence

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expected crop revenues for each price outcome but it also relies on less N-fertilizer and hence lower variable costs for each input price outcome. Over time this results in higher expected profit and significantly reduced risk in the BIO system, a highly desirable situation for a risk adverse farmer.
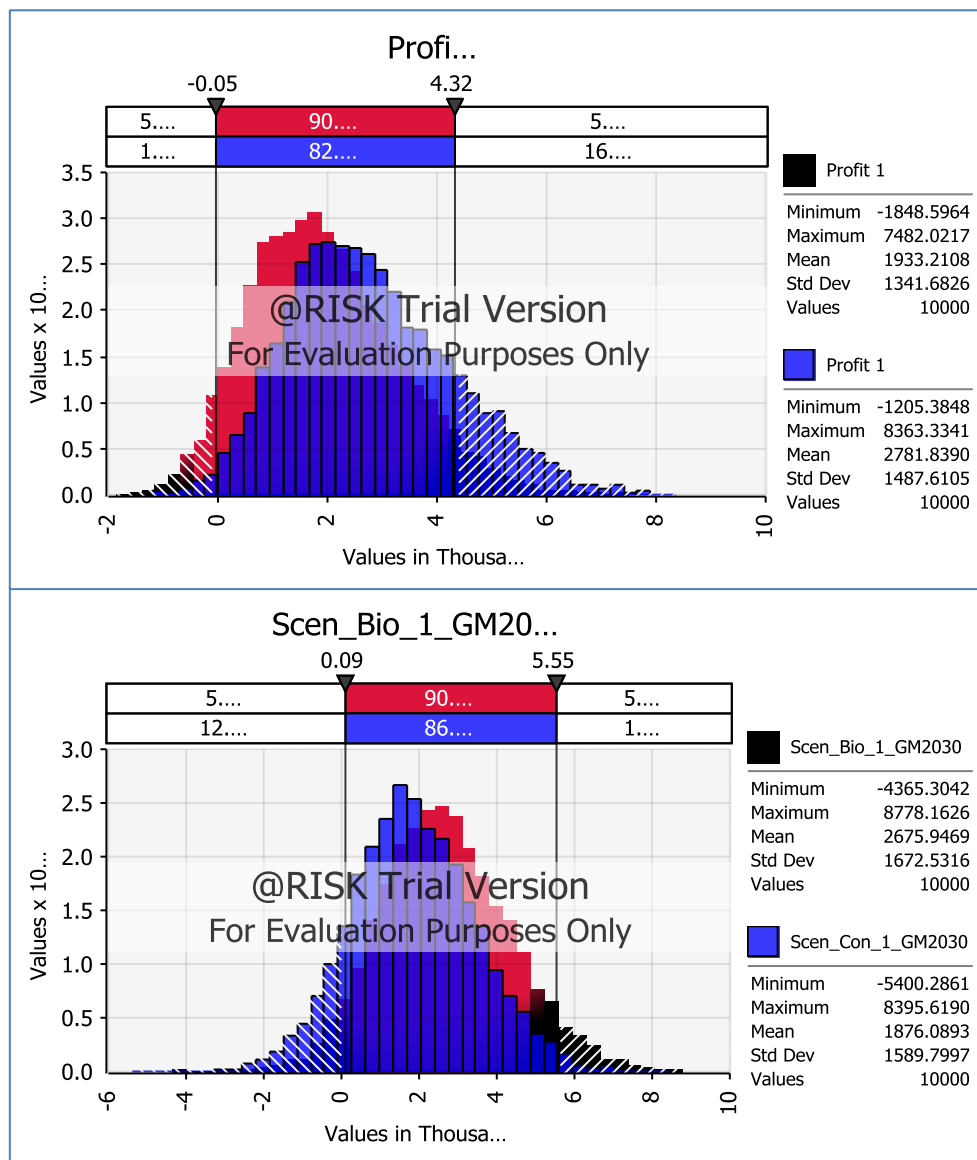

Figure 2. Distribution of profits Conventional (blue) v. biodiversity enhancing agriculture (red) (a) Year 2011 and b 2030

This result is illustrated in Figure 3 by comparing the cumulative distribution functions (cdf) for profits in 2030. As can be seen the cdf for the BIO-system completely dominates the CONV-system for all profit levels. This implies that conserving biodiversity increases the probability of higher profits for all probable outcomes of the input variables and hence represents a more rational choice at this point in time.
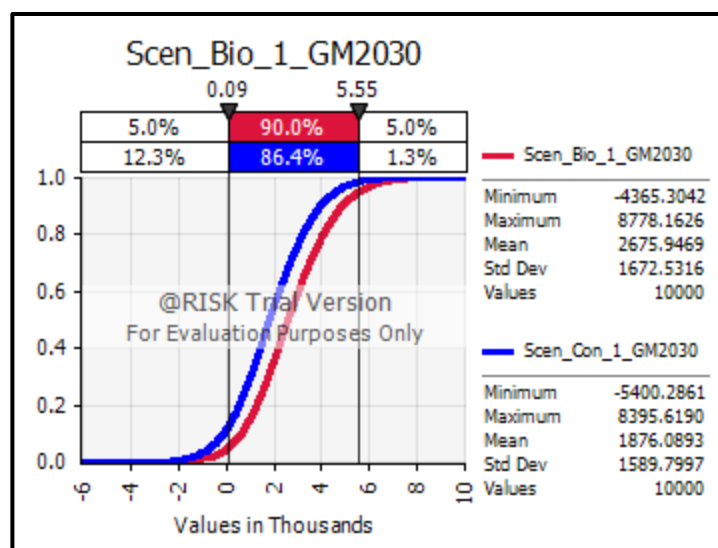
Figure 3. Simulated cumulative distribution functions for CONV and BIO sytems in 2030

When it comes to making investment decisions today—such as conserving more biodiversity—the appropriate decision criteria is to compare the net present value (NPV) of alternative management options. In Table 2 we summarize the results from the four stochastic simulations and provide the NPV each simulation based on a low discount rate of 2 %. Even with such a low rate the BIO_2 scenario which dominated the conventional system when compared in 2030 loses to it on the NPV test. This points to a significant policy problem as the private incentives of farmers are working against managing soils sustainably. In particular the risk reducing value of biodiversity in the long run is all but discounted away in the NPV calculus. Note also that the marginal value product (MVP) of biodiversity is high in the CONV_1 scenario. This implies that if the cost of conserving an additional species is less than 69 kr then it would pay the farmer to do so.

Table 2. Summary of results and insurance value of biodiversity in 2010 and 2030

| Scenario | 2010 | | | | | 2030 | | | | | |
	B(t)*	N(t)*	Mean Profit	Risk Premium	MVP§	B(t)	N(t)	Mean Profit	Risk Premium	MVP§	NPV
CONV_1	1.0	159	2,771	40	69	1.0	159	2,778	39	69	45k
CONV_2	"	"	"	"	"	0.83	178	1,920	28	43	38k
BIO_1	1.15	100	2,766	41	47	1.15	100	2,754	39	34	45k
BIO_2	1.0	100	2,016	31	71	1.20	85	2,708	38	25	38k

* B(t) is state of biodiversity in period t and N(t) is nitrogen fertilizer input in kg/ha. § MVP or marginal value product of biodiversity assuming a 1 % change in biodiversity.

5   Discussion and conclusions

In this paper we have illustrated how stochastic simulation can be used for valuing biodiversity, including its resilience or insurance value. Despite the recognition of resilience as a fundamental ingredient of sustainable social-ecological systems and having a theoretical value, there are few examples of attempts to quantify resilience value. Especially in regard to agriculture where soil biodiversity represents part of the productive capital of the farm little attention seems to have been

given to this issue. A fundamental reason for this is most likely the relatively long-time frames that are required to seriously damage soil organism communities and hence realize reduced yields (10-20 years). Nevertheless from a sustainability perspective the longer term and the uncertainty clouding the future are central to the value of biodiversity.

Stochastic simulation provides a way to consider both soil dynamics and future uncertainty. Through simulation and appropriately specified functional relationships one can model the consequences of management decisions on chosen output variables 20-30 years in the future. Standard approaches rely on using single metrics as input parameters to an economic model and sensitivity analysis to gauge the implications of different values e.g. price might be low, medium or high. The problem with this approach is that it provides no indication of the probability of different outcomes and it is tedious to compare combinations of parameter values. One is quickly faced with innumerable simulations and output data that are difficult to summarize and communicate to decision makers. Stochastic simulation allows one to represent the input variable as a complete probability distribution and even relate distributions that are correlated in some way. In this way Monte Carlo sampling from each of the input distributions is used to generate a distribution of output variables. From the distribution of an output variable the decision maker can quickly judge the likelihood of different occurrences.

We show how the stochastic simulation approach can also be used to value unpriced inputs to a production process. In this case soil biodiversity is unpriced capital the value of which is reflected in the change in expected profits and the risk premium due to a marginal change in biodiversity. Since the distribution of profits is generated by a stochastic simulation, expected profit and the risk premium can be calculated from this output. We used this approach to determine the insurance or resilience value of soil biodiversity for wheat production in Sweden.

From these preliminary results it is clear that the long time frames involved in soil processes create a significant incentive to perpetuate unsustainable farming systems. We show though that investing in soil biodiversity conservation can provide significant risk diversification benefits that are not immediately obvious in the short term. The cost of risk can be estimated through stochastic simulation.

The subjective nature of risk valuation implies that farmers' motivations and risk attitudes will be important for their valuation of soil biodiversity and should not be ignored when developing policy recommendations, e.g., encouraging uptake of technically more sustainable methods, (Greiner, Patterson et al. 2009).

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