Valuing Ecosystem Services Associated with Biodiversity:
An Exploration Using the Blackfly-Livestock System in
South Africa

Paper for Presentation at the 9th Annual BIOECON Conference
Kings College Cambridge, 20-21 September 2007

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April 2007
Abstract

The valuation of biodiversity is an emerging field with a variety of potential applications to different species mixes, habitats and ecosystem types. This paper first reviews progress in valuing biodiversity, paying particular attention to the approach proposed by Brock and Xepapadeas (2003). Then we develop a bioeconomic model of a representative agricultural activity subject to a pest whose population dynamics are regulated by an environmental driver (e.g. freshwater flows, hedgerow systems). Changes in the driver are linked stochastically to pest outbreaks, which are associated with dramatic shifts in the biodiversity state. Further, pest outbreaks lead to agricultural losses so that there is a linkage between changes in the environmental driver, biodiversity state and economic welfare. The formulation permits valuation of marginal changes in the drivers of biodiversity loss and, therefore, differs from the Brock and Xepapadeas approach. Using the example of the blackfly pest problem in the livestock economy of South Africa, we parameterize our model and show that the Brock and Xepapadeas measure can be derived from our results. Finally, the merits of the two alternative formulations are discussed. A need to emphasize the drivers of biodiversity change and adopt a marginal formulation for management purposes suggests that our valuation approach may be useful for a certain class of biodiversity problems.

Key words: valuation, freshwater, environmental flows, stochastic, bioeconomic
Challenges in Valuing Biodiversity: An Exploration Using the Blackfly-Livestock System of the Upper Great Fish River, South Africa

1. Introduction

A number of biologists argue that greater biodiversity leads to greater ecosystem stability (Tilman and Downing, 1994). While much of the research suggesting this correspondence has focussed on terrestrial systems, it appears true of freshwater systems as well (Dudgeon et al., 2005). Greater stability allows an ecosystem to resist or to recover more quickly from perturbations (Holling, 1973). From an economics point of view, this better responsiveness to disturbance can result in higher economic value associated with a system characterized by greater biodiversity than one with lower. Nevertheless, major losses of biodiversity are occurring worldwide, driven by changes in habitat, altered freshwater flows, invasive alien species, etc. If biodiversity is necessary for ensuring the stability of ecosystems and maintaining the economic values associated with these ecosystems, then the conservation of biodiversity must become an even greater priority. Realistic economic valuations of biodiversity are an important step in increasing awareness of the importance of biodiversity and for conserving it.

The purpose of this paper is to explore the value of biodiversity in a particular context; that is, where maintaining more biologically and ecologically diverse ecosystems generates higher levels of economic production than less diverse systems. We develop a stochastic bioeconomic model of a representative natural system that regulates a pest population. Outbreaks of the pest dramatically alter the biodiversity of the natural system. The resulting biodiversity “state” is associated with reduced productivity in nearby agricultural operations. To motivate the analysis, we rely on a case study involving the blackfly problem in the livestock system of South
Africa. Furthermore, we demonstrate that our notion of the value of biodiversity can be linked to others in the literature and argue that the formulation in this paper may have greater usefulness in management applications.

Much of the earlier literature concerned with the valuation of biodiversity concentrated on what Pearce (1999) described as the valuation of individual biological resources, demonstrated by illustrations of the economic contributions of single species, instead of the diversity of these resources. More recently it has been recognized that biodiversity has a somewhat different economic interpretation, associated more correctly with the latter concept of “diversity”. In the Weitzman approach, genetic distance is used to value the preservation of species. Somewhat related to this approach, Simpson et al. (1996) valued biodiversity for pharmaceutical use by multiplying the probability of finding a commercially valuable species by the value of such a discovery and then develop a demand model to estimate willingness to pay for a “marginal species”. Such an approach, while an improvement over the earlier single species studies, has been criticised by ecologists for employing too narrow a concept of biodiversity (for example, see Noss 1990).

In an effort to integrate the genetic distance and marginal species approaches, Brock and Xepapadeas (2003) present a bioeconomic model of a cropping system relying on one or two species for food production. They show that the value of the system increases when the crop mix is more diverse and measure this as the difference in the maximized value function under the competing states. What is of interest here is that the value of biodiversity stems directly from a comparison of the valuation of alternative biodiversity states. Thus, it does not recognize possible discontinuities and non-marginal shifts between biodiversity states that result from changes (perhaps marginal) in environmental drivers. In referring to the presence of thresholds,
Mulder and van den Bergh (2001) argue that: “Below such a level the ecosystem ‘runs down’. Marginal changes, say harvesting another species, can therefore have non-marginal effects when exceeding the critical level … This makes theoretically correct marginal valuation impossible.” We return to this point later on.

A shift away from single species valuations and measures of genetic distance has prompted some economists to attempt a clarification of the range and nature of the benefits from biodiversity. Several taxonomies are available for this purpose. For example, Nunes and van den Bergh (2001) take a total economic value approach (TEV) and describe four types of value associated with biodiversity: values arising from genetic and species diversity, values associated with natural areas and landscape diversity, benefits from ecosystem functions and ecological service flows, and nonuse values stemming from biodiversity.¹ Heal (2004) sets out a competing taxonomy where biodiversity has value by directly generating higher economic production, by providing insurance against unforeseen events that may lead to economic losses, by providing genetic information that has economic value and because of its contribution to the functioning of ecosystems that support economic activity.

In this paper we concentrate on a notion of biodiversity value that is closest to Nunes and van den Bergh’s idea of benefits from ecosystem functions and ecological services flows and Heal’s description of the contribution of biodiversity to ecosystem functioning in support of economic activity. Naylor and Ehrlich (1997) use this approach to value the benefits of maintaining natural enemies of agricultural pests in European cropping-hedgerow systems. More diverse agro-ecosystems support higher populations of natural enemies and these in turn reduce  

¹ The TEV approach applied to biodiversity and other environmental resources dates back several years and is best expounded in Pearce and Turner (1990).
the necessity and expense of pesticide spraying. Similarly, undisturbed freshwater systems can regulate the population of agricultural pests, thereby supporting economic output in nearby cropping and livestock systems, as is the case in the blackfly zone of South Africa (Myburgh and Nevill, 2003).

In the following sections we focus our attention on a subset of biodiversity value: the ecosystem services associated with a given biodiversity state. We recognize the importance of clarifying the valuation perspective when modelling biodiversity value, e.g. *ex ante* versus *ex post*, marginal versus non-marginal, especially in light of competing methodologies (such as Brock and Xepapadeas, 2003). Subsequently, we develop a stochastic model of the value of biodiversity that is consistent with the notion of value described above and with the features of our later case study. Finally, we parameterize this model and discuss the results in light of other approaches to value biodiversity.

2. **Modelling biodiversity and ecosystem service benefits in an agricultural system**

To capture our case study adequately, while maintaining a sufficiently general formulation, we develop a stylized model of the value of ecosystem services where these services are associated with the state of biodiversity in the resource system. It is imperative to establish the correct valuation perspective. For our analysis, we interpret biodiversity broadly, recognizing that it involves such constituents as properly functioning ecosystems that support the provision of ecosystem services (Noss, 1994). Examples referred to earlier include hedgerow systems that support natural enemies of agricultural pests or natural freshwater flows that maintain biodiversity conditions associated with the control of undesirables species (e.g. blackfly). Biodiversity may be manipulated directly, as in the Brock and Xepapadeas sense of
different crop varieties that are planted or indirectly, as in the modification of hedgerow or freshwater systems that then alters biodiversity characteristics.

Furthermore, we are concerned with an *ex ante* stance, and in keeping with Freeman’s (1993) approach to the value of environmental resources, we concentrate on a marginal value. However, the presence of a stochastic element in the analysis complicates matters. We wish to consider the value of biodiversity where the relationship between biodiversity, conceived in a broad sense, and the drivers of biodiversity change (e.g. in-stream flows or hedgerow area) is non-linear and discontinuous. As a result, the relationship between measured biodiversity and economic activity similarly is non-linear (see Perrings and Pearce, 1994). The implication is that small or marginal changes in these associated drivers may not cause a measured change in biodiversity, as this may only occur once critical thresholds are met. Thus, a stochastic formulation recognizing this situation is used. Such an approach contrasts with the deterministic and arguably *ex post* valuation of biodiversity, where this is conceived as a non-marginal value, i.e. a significant change in biodiversity has occurred and the decline in economic values associated with the ecosystem is measured (Brock and Xepapadeas 2003). In the modelling that follows we show how these different approaches to valuing biodiversity are related and that the latter, or Brock-Xepapadeas measure, can be formulated from the more general model we present.

We model an agricultural activity that is influenced by the biodiversity conditions of the local environment. We consider a livestock industry or large enterprise, as described by Rosen (1987), but this could equally be a hedgerow or similar system. We assume that demand for the output of this agricultural activity is perfectly elastic so that social welfare consists of producers’ surplus only. The objective of this enterprise is to maximize profits, \(\pi\), which are a function of
the offtake rate, $S$, and the stock of livestock, $X$. The resulting profit expression for this enterprise is:

$$\pi(S, X) = (p - m)SX - hX(1 - S) = (p' - h)X$$

(1)

where $p$ is the price of offtake, assumed to be fixed in international markets, $m$ is the marketing cost of offtake, $h$ is the holding cost of livestock retained in the herd and $p' = p - m + h$.

In addition, we include a pest species, whose stock is designated as $B$ (measured as density, biomass or numbers), that reduces livestock productivity. Livestock herd size is subject to its own growth function but also influenced by growth in the stock of the pest. To model this predator-prey type system we draw on Wilman (1996), who considered a similar problem in the context of introduced pests in Australia and New Zealand. We use the following coupled differential equations to describe the population dynamics of the livestock species and pest:

$$\dot{X} = F(X, B, S) = (a - S - bX - cB)X$$

$$\dot{B} = G(X, B) = (d + eX - fB)B$$

(2)

where the dot overhead indicates a time derivative, e.g. $dX/dt$, and $a$ to $f$ are parameters with $a, \ldots, f > 0$.\(^2\) Note that the particular specifications for the equations comprising the population

\(^2\) Our system equations differ somewhat from Wilman in that she indicated a negative relationship between the livestock population and the pest population ($e < 0$), which seems unusual, and included pest control as an additional control variable. In the former case, we assume the relationship is positive, i.e. that more livestock, as prey of the
dynamics imply logistic growth for each species in the absence of the other. Thus, the pest is not an obligate predator. In modeling this system, Wilman found that under deterministic conditions there existed an interior equilibrium that was either a stable focus or a stable node, depending upon the values of the parameters.\(^3\)

The livestock operator’s management problem is to maximize the discounted value of (1), subject to the population dynamics in (2). The current value Hamiltonian for this problem is:

\[
\tilde{H} = (p'S - h)X + \lambda(a - S - bX - cB)X + \gamma(d + eX - fB)B
\]  

where \(\lambda\) and \(\gamma\) are the current value shadow prices of livestock \(X\) and pest stock \(B\), respectively. It is relatively straightforward to solve this problem for the optimal time path of offtake, \(S\). In this formulation, the livestock enterprise takes the biodiversity of the grazing and nearby freshwater environment as given. We have assumed so far that there is no disruption to the biodiversity of this environment, although a certain degree of natural variability is understood to be inevitable.

To capture the role of the broad range of ecosystem processes and species in supporting this livestock enterprise we now consider the potential for economic damages stemming from a reduction in biodiversity, where the latter depends on a driver subject to management. For example, since blackfly populations in South Africa are regulated by freshwater flows, \(z\), modifications in these flows that increase the suitability of the freshwater environment for pest, leads to more pests, and ignore control costs since these compete with natural pest control and, therefore, are not relevant here.

\(^3\) The condition for a stable focus was found to be \((bX - fB)^2 < 4ecBX\) and otherwise the equilibrium was a stable node (Wilman, 1996; 141).
blackfly can reduce livestock productivity. In the process, the biodiversity of the freshwater system is altered, assuming biodiversity is defined broadly. This occurs because changes in the freshwater flow regime improve conditions for blackfly, so that this species now constitutes a much greater proportion of the biotic community (measured as individuals or biomass). As a result, a biodiversity index measuring “evenness”, such as the Shannon-Weiner index, would decline even if numbers of species did not. Thus, there is a reduction in measured biodiversity associated with the change in a management driver; here this driver is the freshwater flow regime.

These changes are often subject to thresholds, rather than being characterized by graduated effects (Perrings and Pearce, 1994). In the case of blackfly, this would be manifested in relatively little variation in the blackfly population as freshwater flows are altered until the threshold is met, here denoted as $Z$. Above this threshold, the blackfly population is subject to a new and more virulent growth function. This synopsis describes the experience in South Africa with blackfly quite well and may well characterize other similar systems. In this case, the increased regularity in flows, $z$, increases the likelihood that this threshold will be met.\footnote{4}{Taking the Shannon-Weiner index ($I$) as our measure of biodiversity, we can characterize this situation as follows:}

$$I = \begin{cases} 
- \sum_{j=1}^{N} m_j \ln(m_j) = R_1 & Z > z \\
- \sum_{k=1}^{M} m_k \ln(m_k) = R_2 & Z < z
\end{cases}$$

where $R_i$ refers to the value of the biodiversity index under the two possible states of the world. For $i = 1$, the threshold level of flows has not been met, $Z > z$, so that the value of the biodiversity index is $R_1$. If $i = 2$, and the threshold has been surpassed, $Z < z$, then the biodiversity index is $R_2$. Note that by our assumptions, $R_1 > R_2$.\footnote{4}{Taking the Shannon-Weiner index ($I$) as our measure of biodiversity, we can characterize this situation as follows:}
formulating the problem in this way we are able to link biodiversity with ecosystem services and subsequently with the associated economic values of interest.

Following Cropper (1976), a stochastic version of the pest population dynamics in (2) that captures this formulation of the problem can be written as:

\[
\begin{align*}
\dot{X} &= F_i(X, B, S) = (a - S - bX - c_i B)X \\
\dot{B} &= G_i(X, B) = (d_i + eX - fB)B
\end{align*}
\]

where \(F_i(X, B, S)\) and \(G_i(X, B)\) refer to livestock and pest population dynamics, respectively, under state of the world \(i\). Either the livestock-pest system has not been modified so that natural growth in the pest population is regulated by natural conditions (e.g. seasonality in freshwater flows), which gives \(i = 1\), or due to modifications (e.g. enhanced flows and reduced drought periods) the system now provides an ideally suited environment for the pest, leading to much enhanced population growth \((i = 2)\). Growth in the pest stock under \(i = 1\) exceeds that of \(i = 2\), over the entire domains of \(X\) and \(B\) for any given values of these two variables. The possibility of recovery of the system, once it has shifted to more suitable conditions for the pest \((i = 2)\), is not considered here. Clearly, this could involve complex dynamics, including hysteresis and other non-linear phenomena.

The stochastic variable in the analysis is the unknown threshold \(Z\) at time \(t\) that triggers a jump in the growth relationship governing the pest stock from one variant in (4) to the other. This random variable is assumed to be distributed over the interval \([0,4]\) with a probability density function \(f(Z)\), and is identically and independently distributed over time. Given these
assumptions, the following expression describes the cumulative density function governing the population dynamics of the livestock-pest system:

\[
\begin{align*}
\Pr \left[ F_i(X, B, S) = F_1(X, B, S) \right] &= \Pr[Z > z] = \int_z^\infty f(Z) dZ \\
\Pr \left[ F_i(X, B, S) = F_2(X, B, S) \right] &= \Pr[Z < z] = \int_0^z f(Z) dZ \\
\end{align*}
\]

(5)

with \( \int_0^\infty f(Z) dZ = 1 \)

The first line in (5) shows the probability of increased pest productivity not occurring, which assumes that the threshold \( Z \) lies within the interval \( z \) to 4; that is, it lies above the current level of the environmental driver \( z \) (e.g. freshwater flows). The second line indicates the probability of increased pest productivity occurring on the assumption that the threshold lies within the interval 0 to \( z \) and, therefore, will be encountered in the current time period, \( t \). The c.d.f. in (5) implies that growth in the blackfly stock is determined jointly by the stock of livestock \( X \), the current pest population \( B \), the current environmental driver regime \( z \) and the random variable \( Z \). Denoting the first expression in (5) as \( \Lambda(z) \) and the second as \( \Phi(z) \), it follows that \( \Lambda(z) = 1 - \Phi(z) \), \( d\Phi/dz = f(Z) > 0 \) and \( d\Lambda/dz = -f(Z) < 0 \).

The expected Hamiltonian for this new problem is found by substituting (4) into (3). Taking this expectation yields:

\[
\tilde{H} = (p'S - h)X + \lambda[a - S - bX - \Lambda(z)c_1 + \Phi(z)c_2]B + \gamma([\Lambda(z)d_1 + \Phi(z)d_2] + eX - fB)B
\]
Solution of the problem involving the above Hamiltonian follows in a straightforward manner. Given appropriate parameters, the steady state solutions can be found for offtake rate, $S^*$, livestock population, $X^*$, and pest population, $B^*$.

3. **Two approaches for valuing biodiversity**

   In this section we present a general approach for valuing biodiversity in the class of models described above and then show how the Brock-Xepapadeas approach can be derived from the more general model. Given an environmental driver subject to management, we are interested in the impact that changes in this driver have on the value of agricultural production, operating via the possibility of shifts in the biodiversity “state”. In economic welfare terms the valuation problem requires measuring the impact of a marginal change in the environmental driver, $z$, on discounted profits in the livestock enterprise, calculated at the steady state solution. In our model, $z$ is a parameter so that determining what impact a small change will have on the objective functional requires the use of comparative dynamics techniques (La France & Barney, 1991).

   Accordingly, we can state the maximized value function in terms of the initial value of the parameter $z$ as:

   $$ J^*(z) = \int_0^\infty \pi[S^*(z), X^*(z)] e^{-rt} dt $$

Applying the dynamic envelope theorem and adjusting to present values:
\[
\frac{\partial J^* (z)}{\partial z} = \int_{0}^{\infty} \frac{\partial \tilde{H}[S^*(z), X^*(z), B^*(z)]}{\partial z} e^{-\alpha t} dt
\]  

Taking this derivative and rearranging, we obtain the following expression for the value of a marginal change in the environmental driver, \( z \):

\[
\frac{\partial J^* (z)}{\partial z} = \int_{0}^{\infty} \left\{ p'(c_1 - c_2) X^* - \gamma(d_2 - d_1) \right\} B^* f(Z) e^{-\beta t} dt
\]  

(9)

The terms on the right-hand side of (9) constitute an indirect stochastic effect arising from a marginal change in the environmental driver (e.g. freshwater flows), when seen from an \textit{ex ante} perspective. The first term in the bracketed expression represents the value of livestock lost from a more virulent pest effect under a jump to the modified pest population dynamics \((i = 2)\), expressed per unit of the pest population at the steady state, \( B^* \). The second expression within brackets is the shadow value of increased damages per unit of pest population associated with modified versus unmodified conditions. As with the first expression in brackets, this effect is measured as the difference in the affected parameters of the population growth function for the two states of the world, multiplied by the shadow price \( \gamma \). This component of the marginal value constitutes the damages from a jump to more productive pest population growth at a given level of the environmental driver, \( z \).

The entire bracketed expression in (9) is multiplied by the probability density function \( f(Z) \), which measures the increased risk of encountering the threshold nutrient level \( Z \) when the environmental driver regime is altered slightly. Thus, the stochastic formulation incorporates the \textit{ex ante} uncertainty about the position of the random threshold \( Z \) and allows for the possibility of encountering it as the environmental driver is altered (e.g. increased freshwater flows). The aggregate effect of a marginal change in environmental conditions is negative, since \( \gamma < 0 \),
One objective of this paper is to demonstrate the importance of establishing the appropriate stance in attempting to value biodiversity. The analysis presented above involves a marginal and *ex ante* perspective, where the ecosystem is characterized by threshold effects linking ecosystem functioning (e.g. freshwater flow regime) and the ecosystem services of interest (e.g. pest control). However, this model can be modified to suit the approach suggested by Brock and Xepapadeas (2003), where the value of alternative biodiversity states is assessed as the difference in the value of the integrated ecological-economic system in each of these states. It is presumably an *ex post* (or non-stochastic) perspective, and involves discrete biodiversity states.

Under this latter approach to the value of biodiversity, the maximized value functions for each of the two states of the world, unmodified environmental conditions \((i = 1)\) and modified conditions \((i = 2)\), are expressed as \(J_1^*(S^*)\) and \(J_2^*(S^*)\), respectively. Brock and Xepapadeas (2003) show that the value of the change in biodiversity from state 1 to state 2 is simply \(J_1^*(S^*) - J_2^*(S^*)\). This result is obtained from our modelling by employing (6) and setting the probabilities alternatively at 1 and 0. Note that there is no reference to the environmental driver, \(z\), in this formulation. Here we have assessed the value of biodiversity as the change in maximized enterprise profits under alternative biodiversity states. No allowance is made for drivers of biodiversity change since these are ignored or biodiversity is manipulated directly. While the latter is true of the case examined by Brock and Xepapadeas (e.g. crop mixes), it is generally not true of biodiversity loss more generally, e.g. habitat loss, freshwater flows, invasive alien species, etc.

4. Application of the model to the blackfly-livestock system of South Africa

In this section we apply our modeling to the case of the blackfly and livestock system in South Africa. The situation in the Orange, Great Fish and other rivers provides a good
illustration of the conditions modelled in the previous section. In recent decades the region has been plagued by frequent outbreaks of a particularly virulent blackfly species (*S. chutteri*) that feeds on nearby livestock, resulting in reduced lambing rates and higher lamb mortalities (O’Keeffe and Moor, 1988). Apparently, the situation has arisen because of the construction of dams and tunnels for interbasin transfers to supply water for irrigation use (Myburgh and Nevill, 2003). These projects have resulted in enhanced flows during the normal dry season when most rivers have no flow at all for extended periods (up to four months). As flows have been enhanced there has been a marked jump in productivity of blackfly, since the natural regime of extended dry spells normally limits productivity for blackfly. Thus, we would anticipate that a natural break in flow of approximately four months results in a relatively lower number of blackfly, As this dry period is reduced, and flow enhancement approaches year round, the likelihood of this jump in blackfly productivity increases commensurately.

We used a cost-benefit analysis by Connagarth Economists (2005) and other literature sources to parameterize our model. The Cononagarth study shows that livestock abundance decreases by 23%, including both suckling lamb mortality and reduction in lambing, as a result of blackfly outbreaks. O’Keeffe and de Moor (1988) report that peak blackfly larval densities more than doubled on one occasion following a flood on the Orange river. However, they report this statistic with uncertainty, since it was based on relatively little data. Zhang et al. (1998) conducted a study of blackfly abundance at 51 rapids in rivers with and without dam-related disruptions in Sweden. These authors found a 25% to 50% increase in blackfly larval abundance at sites with reduced flow due to dams. This latter study included many sites, accounted for a large number of driving variables, and the results are presented with less uncertainty. In order to use the best data available while accounting for the findings of Moor and O’Keefe, which concern the area of study, we assumed that black fly abundance increases by 50% as a result of once freshwater flow enhancement crosses the random threshold described in the previous section.
Using the above data, we parameterized the system of equations in (4) such that the livestock and black fly biomasses under non-outbreak conditions \((i = 1)\) were indexed to 1.0. Under outbreak conditions, the black fly biomass increases to 1.5, and the livestock biomass decreases to 0.77 \((i = 2)\). We programmed the equations in (4) into Mathcad, and integrated them over a time series using an adaptive Runge-Kutta algorithm commonly used to solve interdependent systems of differential equations (Conrad and Clark, 1987). Blackfly and livestock biomasses were given initial starting values of 1.0, and the parameters were first adjusted so that the values stayed at 1.0 for the full time series. Next, we increased the \(c_2\) and \(d_2\) parameters until index values of 1.5 and 0.77 resulted for blackfly and livestock biomass, respectively.

Finally, we needed to adopt a probability distribution governing the behaviour of the random threshold at which the blackfly population dynamics jumped from non-outbreak to outbreak conditions. Engineers and hydrologists familiar with the situation are confident that stopping the flow in the immediate vicinity for a week would almost certainly reduce the overwintering population of juvenile blackflies sufficiently to prevent a spring outbreak of adults. The uncertainty arises with how long you would have to close a dam at the top end of the river to ensure cessation of flow as much as 400 km downstream. It might take several weeks of no supply before the flows stopped, because of the return flows and groundwater seepage. We used a beta distribution to model the random stoppage time needed to obtain at least a one week cessation of flow in the lower river. We set the finite interval for the beta distribution at 120 days, beginning from zero. The beta distribution requires two parameters; experimentation led to the use of three parameter sets, for sensitivity purposes. These resulted in mean values for the distribution of 80 to 90 days. Recall these periods represent the threshold at which enhanced freshwater flow triggers an outbreak of adult blackflies. Values used for the beta distribution and other parameters are summarized in Table 1.

The results of our empirical modeling consist of steady state values for the main system variables and estimates of the value of steady state profits and the comparative dynamics associated with changes in the freshwater flow regime (Table 2). Results are presented for a
variety of cases involving differing assumptions about the parameters of the beta distribution (describing the blackfly outbreak threshold) and the current length of enhanced freshwater flows, \( z \), as well as social discount rates of 5% and 10%. Not surprisingly, the offtake rate, livestock population and livestock enterprise profits all decline as enhanced freshwater flows increase from 0 to 120 days. As the likelihood of an outbreak increases, this is reflected in a greater weighting of the outbreak parameters \( i = 2 \), since these are associated with lower optimal values associated with the livestock enterprise.\(^5\)

The value of biodiversity concept advanced in this paper is captured in the sixth and eleventh columns of Table 2. These figures represent the present value of a permanent marginal change in freshwater flow, as described in (9). Since the marginal change increases the flow, it nudges the livestock-blackfly system closer to the random threshold at which biodiversity shifts to a blackfly dominated state and, as a result, the derivative has a negative sign (a loss). However, the marginal value varies dramatically, depending on the current state of the flow regime, increasing by a factor of more than 10 when the current enhanced flow increases from 30 to 90 days. There is no estimate for marginal value for the end points of the interval (0 and 120 days). At these extremes, the system becomes deterministic, with either no possibility of a blackfly outbreak (0 days) or certainty of an outbreak (120 days). The above result involving extreme values of the probability distribution has interesting implications for calculating the value of biodiversity using the Brock-Xepapadeas approach, as discussed in the next section.

\(^5\) Noteworthy are the low optimal livestock population values \( (X^*) \), especially in comparison to the current estimate of 264,000 units reported in Connigarth Economists (2003). These lower values may result from non optimal management of current livestock operations, perhaps stemming from transfers that cause profitability to diverge from socially optimal values.
5. Discussion

As discussed earlier, the modeling of biodiversity value associated with a particular ecosystem service can be formulated using (at least) two approaches. The approach favored in this paper involves extending the calculus to include the drivers of biodiversity change and then ensuring this is further linked to the ecosystem services flowing from a given biodiversity state. Direct marginal valuation of biodiversity is possible when a continuously varying driver influences the biodiversity state, as described in the previous section (Table 2). Alternatively, Brock and Xepapadeas argue for a measure of biodiversity value that is derived by solving the optimization problem for the production system under the varying biodiversity states. The difference in the maximized value functions associated with each state represents the value attributable to the difference in biodiversity.

The Brock-Xepapadeas value of biodiversity can be obtained directly from our calculations as the difference in the extreme values of the present value of profits (see Table 2). These extreme values are common across all sets of parameters for the beta distribution; since there is no account taken of the drivers of biodiversity change (unless biodiversity is directly manipulated) the choice of distribution and accompanying parameters is irrelevant. However, their measure does vary by discount rate. For a 5% discount rate, the value is \( R \, 247,860,332 - R \, 130,819,808 = R \, 117,040,524 \), in present value terms. At a 10% discount rate, the equivalent value is \( R \, 122,362,684 - R \, 63,842,441 = R \, 58,520,243 \). It is instructive that these values are substantially larger than the marginal values given in Table 2. But this should come as no surprise, since we are comparing marginal and non-marginal values. Indeed, the two measures are directly related, since the Brock and Xepapadeas measure is simply integration of the marginal value we derive over the entire range of values for the environmental driver (e.g. freshwater flows), as shown below:

\[
\text{Marginal value of biodiversity: } \frac{\partial J^*(z)}{\partial z}
\]
Brock-Xepapadeas measure: \[
\int_0^{120} \frac{\partial J^* (z)}{\partial z} dz
\]

So which measure of the value of biodiversity is correct? It seems to us that both may have their appropriate uses. However, the approach suggested by Brock and Xepapadeas may be more limited. For example, it is not particularly useful to concentrate on the value of alternative states if we do not directly manipulate these states through management. While Brock and Xepapadeas refer to an exception -- the case of crop mix in a managed agricultural ecosystem -- we would argue that it is more usual for management to have an indirect and perhaps stochastic influence on biodiversity. Clearly, the Brock-Xepapadeas measure is not appropriate when we adopt an \textit{ex ante} and marginal value stance. Indeed, biodiversity is an attribute of the ecological and economic system but not the driver of change. Instead, it is the manipulation of ecosystem characteristics (in-stream flows) that drives the change, while the stochastic nature of the problem ensures that attention devoted narrowly to changes in biodiversity ignores the more subtle valuation problem. Even though a standard measure of biodiversity may not change much until a threshold is met, there is a cost associated with driving the ecosystem in this direction, one that is not manifested in valuation of the current biodiversity state itself.
5. References


Table 1. Parameters used to Model the Blackfly-Livestock System of the Upper Great Fish River, South Africa

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.965</td>
<td>Livestock growth rate</td>
</tr>
<tr>
<td>b</td>
<td>0.9</td>
<td>Density-dependant feedback in livestock</td>
</tr>
<tr>
<td>c₁</td>
<td>0.06</td>
<td>Impact of black fly on livestock, non-outbreak level</td>
</tr>
<tr>
<td>c₂</td>
<td>0.18</td>
<td>Impact of black fly on livestock, outbreak level</td>
</tr>
<tr>
<td>d₁</td>
<td>0.182</td>
<td>Blackfly growth rate, non-outbreak level</td>
</tr>
<tr>
<td>d₂</td>
<td>0.273</td>
<td>Blackfly growth rate, outbreak level</td>
</tr>
<tr>
<td>e</td>
<td>0.00001</td>
<td>Impact of livestock on blackfly population</td>
</tr>
<tr>
<td>f</td>
<td>0.182</td>
<td>Density-dependant feedback in black fly</td>
</tr>
<tr>
<td>p</td>
<td>380</td>
<td>Gross livestock (lamb) price for offtake</td>
</tr>
<tr>
<td>m</td>
<td>0.25p</td>
<td>Marketing margin for offtake</td>
</tr>
<tr>
<td>h</td>
<td>0.10p</td>
<td>Holding cost of livestock</td>
</tr>
<tr>
<td>f(Z)</td>
<td>-</td>
<td>pdf of beta distribution governing random threshold at which blackfly productivity jumps from non-outbreak to outbreak parameter values; parameters are (4,2), (5,2) and (6,2) with A = 0 and B = 120 days</td>
</tr>
<tr>
<td>r</td>
<td>5%, 10%</td>
<td>Social discount rate</td>
</tr>
</tbody>
</table>

Note: to convert values for the livestock population from an index to actual magnitudes, the b and e parameters were divided by the current livestock population of 264,000 units (Connigarth Economists, 2003).
Table 2. Optimal Solutions for the Blackfly-Livestock System in the Orange River Region, South Africa

<table>
<thead>
<tr>
<th>Period of Enhanced Freshwater Flows</th>
<th>Beta (4,2)</th>
<th>r = 5%</th>
<th>B*</th>
<th>X* (units)</th>
<th>S* (units)</th>
<th>(\partial J(z) / \partial S)</th>
<th>(\partial J(z) / \partial B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 days</td>
<td>.542</td>
<td>105844</td>
<td>1.0000</td>
<td>247806332</td>
<td>-5.692</td>
<td>98511</td>
<td>1.0000</td>
</tr>
<tr>
<td>30 days</td>
<td>.5430</td>
<td>105498</td>
<td>1.0078</td>
<td>246341200</td>
<td>-5.680</td>
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<tr>
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<td>75044</td>
<td>1.5000</td>
<td>130819808</td>
<td>-4.642</td>
<td>67710</td>
<td>1.5000</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Period of Enhanced Freshwater Flows</th>
<th>Beta (5,2)</th>
<th>r = 10%</th>
<th>B*</th>
<th>X* (units)</th>
<th>S* (units)</th>
<th>(\partial J(z) / \partial S)</th>
<th>(\partial J(z) / \partial B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 days</td>
<td>.542</td>
<td>105844</td>
<td>1.0000</td>
<td>247806332</td>
<td>-5.692</td>
<td>98511</td>
<td>1.0000</td>
</tr>
<tr>
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<td>1.0023</td>
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<tr>
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<td>103333</td>
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<td>95999</td>
<td>1.0547</td>
</tr>
<tr>
<td>90 days</td>
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<td>91588</td>
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<td>-238453</td>
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<td>1.2670</td>
</tr>
<tr>
<td>120 days</td>
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<td>130819808</td>
<td>-4.642</td>
<td>67710</td>
<td>1.5000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Period of Enhanced Freshwater Flows</th>
<th>Beta (6,2)</th>
<th>r = 10%</th>
<th>B*</th>
<th>X* (units)</th>
<th>S* (units)</th>
<th>(\partial J(z) / \partial S)</th>
<th>(\partial J(z) / \partial B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 days</td>
<td>.542</td>
<td>105844</td>
<td>1.0000</td>
<td>247806332</td>
<td>-5.692</td>
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<td>1.0000</td>
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<td>60 days</td>
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<td>130819808</td>
<td>-4.642</td>
<td>67710</td>
<td>1.5000</td>
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</tbody>
</table>