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REPORT

Net Present Biodiversity Value and the Design of Biodiversity Offsets

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Abstract There is an urgent need to develop sound theory and practice for biodiversity offsets to provide a better basis for offset multipliers, to improve accounting for time delays in offset repayments, and to develop a common framework for evaluating in-kind and out-of-kind offsets. Here, we apply concepts and measures from systematic conservation planning and financial accounting to provide a basis for determining equity across type (of biodiversity), space, and time. We introduce net present biodiversity value (NPBV) as a theoretical and practical measure for defining the offset required to achieve no-net-loss. For evaluating equity in type and space we use measures of biodiversity value from systematic conservation planning. Time discount rates are used to address risk of non-repayment, and loss of utility. We illustrate these concepts and measures with two examples of biodiversity impact–offset transactions. Considerable further work is required to understand the characteristics of these approaches.

Keywords Net present value · Conservation planning · Time discounting · Benefit functions · No-net-loss

INTRODUCTION

Biodiversity offsets are being used to resolve tension between development and conservation. It is often claimed that offsets will maintain natural capital by achieving no-net-loss of biodiversity from development. Offsetting is usually advocated by developer interests as a 'win–win' solution that opens up greater access to natural capital, and is usually supported by environmental agencies. However, Salzman and Ruhl (2000) and Walker et al. (2009) provide theoretical arguments for difficulties with offsets. Walker et al. (2009) argue that for these reasons biodiversity offsets are likely to fail biodiversity and show that offsetting to date has generally facilitated development while perpetuating biodiversity loss. Indeed, biodiversity offsets usually fall short of what was pledged, and may not be implemented at all (Veltman 1995; Fox and Nino-Murcia 2005; Quigley and Harper 2005a, b; Walker et al. 2009). Nonetheless, biodiversity offsets are rapidly being implemented and there is an urgent need for a more defensible ecological basis. Their conceptual foundations, methods, and results are the subject of increasing scrutiny.

Here, we use the term biodiversity offsets in the sense of ten Kate et al. (2004), as compensation or correction for residual impacts on biodiversity that remain after following earlier steps in a mitigation sequence in which impacts have been avoided, minimized, and remedied. Conservation actions for offsetting must be strictly additional to conservation that would be done without the offset, i.e., they must not replace conservation actions that would have occurred without the offset. We focus on 'no-net-loss' offsets, in which each impact is fully offset to ensure no-net-loss of biodiversity occurs as a result of the development. We treat biodiversity offsets as biodiversity transactions, usually taking the form of a biodiversity loan, with immediate and relatively certain biodiversity impacts followed by delayed and more uncertain future biodiversity repayments. We refer to the exchange as an impact–offset transaction, and accept that equity in this transaction must be assessed across three dimensions (Salzman and Ruhl 2000): (1) type (of biodiversity), (2) time, and (3) space. The challenge is then to design impact–offset transactions to achieve the no-net-loss criterion.

Summaries of offset schemes (e.g., McKenney and Kiesecker 2010; Quetier and Lavorel 2011) and guides to their design (e.g., BBOP 2009) highlight the need for improvement in several aspects of theory and practice.

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First, multipliers are widely used to set ratios between impacts and offsets and account for diverse equity issues such as differences in biodiversity type, uncertainty, and time discounting. The magnitudes of multipliers (or exchange or compensation ratios) are generally determined by ambiguous procedures, reflecting a poorly formulated model of equity in biodiversity exchange across type and time. Second, offset schemes differ in whether they restrict the offsetting to the same type of biodiversity as the impact (in-kind) or allow offsetting with other types (out-of-kind). A more general approach that considered either type of offset, and allowed assessment of their relative ability to provide better biodiversity outcomes and ensure no-net-loss, would improve offset design. Third, time delays to full offsetting of the impact need more explicit consideration, and require an adequate basis for the treatment of equity through time.

Theoretical contributions to guidance on these matters are few. Salzman and Ruhl (2000) and Walker et al. (2009) identify interrelated ecological and non-ecological problems with the implementation of offsets, including the complexity of biodiversity and the imbalances of power, interest, and information between developers and biodiversity protection groups, and Walker et al. (2009) argue that these problems contribute to the failure of biodiversity offsets to protect biodiversity. Habitat equivalency analysis (Dunford et al. 2004) and landscape equivalency analysis (Bruggeman et al. 2005) provide methods for assessing equity of trades that include time discounting. Moilanen et al. (2009) consider the implications for offset design of uncertainty and spatial autocorrelation in project success and incorporate time discounting. Bekessy et al. (2010) argue that because of the problems with comparing equity across time, biodiversity offsets should be designed such that benefits from offsets precede the impact.

Systematic conservation planning (Margules and Pressey 2000; Moilanen et al. 2009) has a well-developed body of theory and practice to prioritize and choose the most efficient conservation actions throughout a region of interest, and thereby achieve most conservation for any given expenditure. The applicability of conservation planning tools to offset design has been noted (Kiesecker et al. 2009, 2010), and they have been used to address aspects of offset design (e.g., Gordon et al. 2011). Identification of priority sites that best contribute to biodiversity goals (e.g., persistence of species) has many parallels to the problem of designing out-of-kind offsets to achieve no-net-loss. The systematic conservation planning problem chooses among sets of actions with different benefits to diverse types of biodiversity in different places across a region or nation, and—equally important—chooses which types of biodiversity and places will not be protected and may therefore be lost. The rationale for biodiversity offsets is to enable economic gains without biodiversity loss (e.g., ten Kate et al. 2004) by choosing conservation projects that provide biodiversity at least equal to that lost to development. In both systematic conservation planning and out-of-kind biodiversity offsets, different types of biodiversity are being traded off across the landscape over time. This paper draws on the theory of systematic conservation planning to provide a basis for comparing biodiversity equity across type, time, and space.

We use net present biodiversity value (NPBV) as a fundamental measure of equity in biodiversity transactions across type, space, and time. This requires several components, including biodiversity value functions adapted from systematic conservation planning, together with the financial concepts of net present value (NPV) and time discounting. The use of biodiversity value or utility functions from conservation planning provides an explicit mechanism for the design of in-kind or out-of-kind offsets by allowing comparisons in type and space. The appropriate value function must capture the important characteristics of biodiversity and contain the inherent nonlinearities, appropriate scaling, and context-dependence exhibited by biodiversity. The use of NPV and time discounting provides a mechanism for addressing equity across time. We present versions in both continuous and discrete time and provide some illustrative examples.

APPROACH

Measures of Relative Biodiversity Value

Central to both systematic conservation planning and the design of biodiversity offsets is a robust measure to compare the value of different amounts and types of biodiversity at different locations. Comparison in time is generally not considered during the choice of conservation projects (but see Stephens et al. 2002), but is particularly important for offsets, where the preservation of equity is a prime concern. All systematic conservation planning approaches (e.g., Stephens et al. 2002; Moilanen 2007; Ball et al. 2009; Ferrier and Drielsma 2010; Overton et al., 2010) use a function to describe the value, benefit or utility derived from a given amount (e.g., area, abundance) of each component (e.g., species, community, ecosystem type) of biodiversity. The value function is then combined with other considerations, such as spatial fragmentation and costs, to develop an overall objective function for choosing between potential reserves or projects in order to optimize conservation expenditure. Fundamental to these approaches is the ability to account for nonlinearities in value and the influence of scaling and context, as captured in common measures such as irreplaceability or complementarity (Margules and Pressey 2000). The role of value functions (and the overall objective function) in systematic conservation planning is to allow comparisons of the value of different biodiversity components at different sites, rather than direct comparisons of the biodiversity features themselves. This provides a solution to the commensurability issues associated with out-of-kind offsets.

Here we denote the biodiversity value of a given amount of abundance as BV(A). The marginal biodiversity value (MBV) lost from a biodiversity impact A' is then:

$$\mathrm{MBV}(A') \quad \mathrm{BV}(A) \quad \mathrm{BV}(A \quad A') \tag{1}$$

This definition of marginal loss essentially calculates the instantaneous marginal value over a given interval. The marginal value for gains from an offset is calculated in a similar way. Note that if BV(A) is a nonlinear function of A, then the marginal value depends on the overall abundance, indicating that the biodiversity context is important in determining the marginal value of a given unit of abundance. A more general formulation would be to compare the biodiversity value of the overall biodiversity configuration with and without the impact to assess the marginal value of the loss due to the impact.

A value function that has been used in conservation planning tools (e.g., Moilanen 2007; Overton et al. 2010) is a simple power function of the occupancy of the species or habitat type. This occupancy of a species or habitat type is calculated from the area or abundance (A) as the proportion A/A_n of the natural abundance (A_n) remaining. The value of a given amount of abundance is given by:

$$\mathrm{BV}(A) \quad (A{=}A_n)^z \tag{2}$$

The MBV of a loss of biodiversity A_i from impacts is:

$$(A{=}A_n)^z \quad ((A \quad A_i){=}A_n)^z \tag{3}$$

Once a measure of MBV is derived, it can be used to assess planning of conservation action, reporting on conservation achievement, and other uses, such as the design of biodiversity offsets. These value functions provide the basis for designing both in-kind and out-of-kind offsets. It is important that the value function chosen is sufficiently powerful for a given application. In many cases, the use of abundance or area alone will not be a sufficient surrogate to capture biodiversity value. For instance, while abundance is one of the most important predictors of the probability of persistence of species, a range of other factors will also be important. Similarly, the use of area of habitat or occupancy remaining is known to be an imperfect surrogate for predicting species persistence (e.g., Rodrigues and Brooks 2007; Smith 2010).

The NPV–NPBV Analogy

Financial accountants use the concept of NPV to estimate equity in a stream of gains and losses over time (e.g., Bierman and Smidt 1966). We suggest the same method can be applied to biodiversity. Conceptually, biodiversity offsets can be considered in the same way a bank treats a loan. When a bank lends money, the borrower has use of the money while the bank will define a repayment schedule for which the NPV of the loan is sufficient for the bank to make a profit. The NPV of a financial transaction is simply the sum over the time period of the transaction of the discounted payments and debits. Time discounting has been used in for the design of biodiversity offsets and compensation (e.g., Dunford et al. 2004; Bruggeman et al. 2005; Moilanen et al. 2008).

Here, we define NPBV as a basic measure against which the no-net-loss criterion can be measured, and demonstrate the application to the design of biodiversity offsets. The NPBV measure requires specifying the relative value of biodiversity, discount functions or rates, and estimating the time profiles of both the biodiversity losses due to the impacts and the biodiversity benefits from the losses.

Discounting Biodiversity

Frequently, the time required to fully offset a biodiversity impact is substantial, necessitating consideration of time equity in the design of an impact–offset transaction. This requires exploration of reasons why the time profile of payments is important. The factors causing variation in equity over time include:

(1) Risk. Payments (or losses) in the future are often discounted because they may never happen.
(2) Lost opportunity cost of use of biodiversity. Opportunity cost is the loss of value due to the temporary biodiversity debt incurred during the impact–offset transaction. This is often included within the rate of return on investment, but might be considered separately for biodiversity.
(3) Rate of return on biodiversity capital. Biodiversity has the capacity to beget more biodiversity, through population growth or regeneration, and on longer time scales, evolutionary processes, if protected from factors causing decline. A temporary debit of biodiversity will mean a loss of future biodiversity amount (and therefore value).
(4) Change in marginal value of payments. In financial terms this is considered inflation. For biodiversity the situation is frequently deflation due to increased rarity. This component of changing value could also be accounted for in the MBV function.
(5) Pure-time preference. Even with the above effects removed, there may remain a preference for benefits or consumption sooner rather than later. This can be seen as a form of impatience.

These factors can mostly be reflected in a discount rate, or more generally via a discount function. A discount function, $D(t)$, provides the discount to apply to impacts or offsets that occur at time t into the future. Many types of discount functions could be used, the commonly used exponential discount functions with fixed discount rates will generally be the default choice for $D(t)$. Assuming the use of an exponential function and an annual discount rate d, the discrete and continuous time versions could be:

$$\text{Discrete}: \quad D(t) = (1 - d)^{t} \tag{4}$$

$$\text{Continuous}: \quad D(t) = \exp(-dt) \tag{5}$$

Some aspects of time equity may require other functions. For example, the risk of non-repayment might decline sharply upon successful completion of a difficult and high-risk offset milestone. In some cases, such as when temporary reductions result in the permanent loss of biodiversity elements from the system, it may be appropriate to account for time equity more directly in the biodiversity value function. The separation of the time aspects of biodiversity value from other aspects of biodiversity value is maintained in the following section mostly for conceptual convenience.

NET PRESENT BIODIVERSITY VALUE

NPBV is a general method to derive in-kind or out-of-kind offsets in which the impacts and offsets can occur at different times while meeting the no-net-loss criterion. The use of an appropriate value function is the basis for determining equity for in-kind offsets and, importantly, the relative value of impacts and offsets for out-of-kind offsets. NPBV is first defined below and then illustrated with several examples.

Definition

The no-net-loss criterion requires that the NPBV of a combined impact and offset be greater than or equal to zero. NPBV takes into account the future biodiversity gains and losses and applies a time discount to future changes. In the following formulation, we allow for a time constraint on the achievement of no-net-loss by stipulating a finite payback time.

Define: NPBV = net present biodiversity value, $MBV_{Impacts}(t)$ = marginal biodiversity value loss from impacts, $MBV_{OffsetGains}(t)$ = marginal biodiversity value gain from offsets, $D(t)$ = discount function, t = time (usually years), PBT = payback time, the time until the impact–offset transaction must achieve an NPBV of zero.

In discrete time, a simple version of the equation for NPBV is:

$$NPBV = \sum_{t=0}^{PBT} MBV_{OffsetGains}(t) \times D(t) + \sum_{t=0}^{\infty} MBV_{Impacts}(t) \times D(t) \tag{6}$$

In continuous time

$$NPBV = \int_{t=0}^{PBT} MBV_{OffsetGains}(t) \times D(t) + \int_{t=0}^{\infty} MBV_{Impacts}(t) \times D(t) \tag{7}$$

Note that the MBV from impacts is negative. In these equations, MBV can be acquired from an equation such as Eq. 1 or Eq. 3. $D(t)$ can be obtained from an equation such as Eq. 4 or Eq. 5, and it will usually be appropriate to apply different discount rates to the impacts and offset gains because of differences in both the risk profiles and other components of their respective discount rates.

The finite payback time specifies when an impact–offset transaction will achieve a non-negative NPBV, in the same way in which a home loan has a finite time to repayment of the loan. The application of a finite payback time will increase the offset required. Setting payback time to infinity is an interest-only (biodiversity) loan, and the repayment of the capital debt is not a part of the plan. Generally, this would not be seen as an equitable offset arrangement, but it is useful to consider as an easily solved limiting case. Even without a finite payback time, the size of an offset may still exceed the impact several- or many-fold.

The use of MBV accounts for changes in the biodiversity context in which the offset is operating. This provides a natural avenue to account for changes in the marginal value of biodiversity. Consequently, a properly designed value function will discourage continued cumulative loss of particular components of biodiversity.

Example 1: In-Kind Offsets—Averted Loss

Consider an impact–offset transaction for which an impact will be offset by adding additional protection elsewhere to the same ecosystem type to avert ongoing loss of that ecosystem type (Fig. 1). Note that while this example focuses on averted loss, the NPBV framework can also be applied to offsets that involve restoration. Specifications for a fair averted loss offset are not obvious, because an immediate loss associated with the project will be offset gradually by diminished loss of the same habitat in other

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areas. NPBV can be used to calculate the area to which additional protection must be applied so that the reduction of loss in other areas over time will offset the immediate impacts. In addition to knowing the biodiversity loss associated with the impact, we also require estimates of future background loss, the future loss rate under additional protection, and a discount rate. In this example, two important quantities change over time: (1) the process of loss of biodiversity, and the difference in loss made by the offset, and (2) the relative values of future impacts and offsets due to time discounting.

For this example, we assume that: (1) the ecosystem type is divided into protected and unprotected areas differing in their rates of biodiversity loss, (2) payback time is set to infinity (analogous to an interest-only biodiversity loan), and (3) the impact occurs at time $t = 0$.

Figure 1 depicts a situation where there is no loss in the protected area (i.e., $L_p = 0$), but the more general case is solved here, where the protection provides a different (and hopefully lower) rate of loss than the loss in unprotected areas.

Let $P =$ proportion of remaining habitat protected (N.B. not the proportion of original biodiversity protected), $A_0 =$ area of habitat/environment remaining in natural condition at $t = 0$, $L_p =$ loss rate of protected, $L_u =$ loss rate of unprotected.

Here we use area of an ecosystem type as the measure of biodiversity amount for assessing impacts, costs, and benefits. Species abundance or another measure of biodiversity amount could be substituted for area in the calculations below.

Let $A_b(t) =$ area of biodiversity at time t under the background scenario (no activity), $A_a(t) =$ area of biodiversity at time t with the activity (impact and offset), $A_i =$ area of impact (residual), $A_x =$ area to protect as an offset, $d =$ time discount rate applied to offset benefits.

Then $A_b(t) =$ area of protected 9 protected decay rate ? area unprotected 9 unprotected decay rate, or

$$A_b(t) = PA_0e^{-L_pt} + (1 - P)A_0e^{-L_ut} \tag{8}$$

With the impact and offset, we start with the background amount above and subtract A_x and A_i from the unprotected and add A_x to the protected, assuming that both remain constant

$$A_a(t) = (PA_0 + A_x)e^{-L_pt} + ((1 - P)A_0 - A_x - A_i)e^{-L_ut}. \tag{9}$$

We can apply a biodiversity value function here, $BV(t) = V(A(t))$. For the sake of analytical ease, we simplify by using just the area as the value, i.e., $V(A(t)) = A(t)$. This is reasonable under certain circumstances, For instance, when A_i and A_x are small relative to A_0, the value

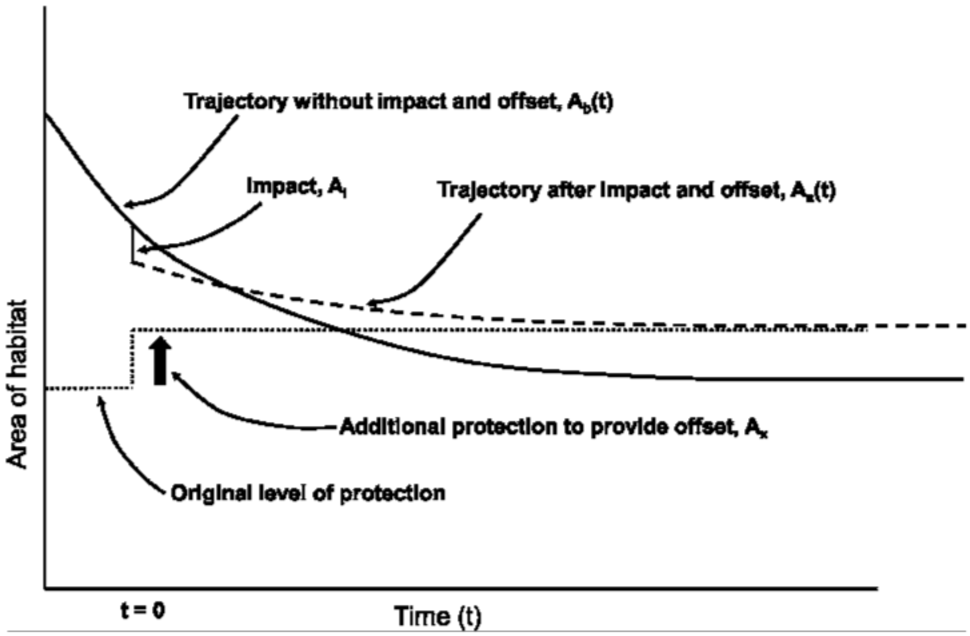

Fig. 1 An example of an averted loss offset. The solid line provides the expected trajectory of the area of habitat through time without the impact–offset transaction. This background extent is predicted to decline until only the habitat in the protected areas remains. The area of impact, A_i, is shown, and time is rescaled to define the impact at time $t = 0$. The offset consists of adding protection to an area A_x, which reduces the overall rate of loss of habitat and provides a higher expected amount of habitat over longer time periods, resulting in a trajectory shown by the dashed line. In this case, an immediate biodiversity debt due to the impact is repaid gradually over a number of years. Here we use NPBV to address the fair value of A_x that would provide equity in this exchange to provide for no-net-loss of biodiversity

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function will be roughly linear in the small region in which we will be operating. Under this simplification, P and A_0 do not appear in the final result. For the case in which A_i or A_x are substantial relative to A_0, and also for the more general case of out-of-kind offsets, a value function that accounts for the wider biodiversity context is required.

Using the continuous time version of NPBV (Eq. 7)

$$\mathrm{NPBV} \quad \int_{t\ 0}^{\mathrm{PBT}} \mathrm{MBV}_{\mathrm{OffsetGains}}(t) \times D(t) + \int_{t\ 0}^{\infty} \mathrm{MBV}_{\mathrm{Impacts}}(t) \times D(t);$$

we use a standard exponential continuous time discounting from Eq. 5. Assuming the impacts commence at time $t = 0$, then the term $\mathrm{MBV}_{\mathrm{Impacts}}(t)$ 9 $D(t)$ is simply - A_i. The offset gains, $\mathrm{MBV}_{\mathrm{OffsetGains}}(t)$, are the difference in loss rates between $A_b(t)$ and $A_u(t)$, or the difference between the time derivatives of Eqs. 8 and 9. Most of the terms cancel, leaving

$$dA_u(t)=dt \quad dA_b(t)=dt \quad L_u(A_x + A_i)e^{-L_u t} \quad L_p A_x e^{-L_p t}$$

$$\mathrm{NPBV} \quad A_i + \int_{t\ 0}^{\mathrm{PBT}} L_u(A_x + A_i)e^{-L_u t} \quad L_p A_x e^{-L_p t} \quad e^{-dt}$$

For an interest-only offset, we set PBT to infinity, and evaluate the integral,

$$\mathrm{NPBV} \quad A_i + L_u(A_x + A_i)=(L_u + d) \quad L_p A_x = L_p + d \tag{10}$$

To determine the size of the offset (A_x) that would provide an NPBV of zero, we set $\mathrm{NPBV} = 0$ and solve for A_x:

$$A_x \quad \frac{A_i \ L_p + d}{L_u \quad L_p}$$

Interestingly, a loss rate in the protected areas both adds to the discount rate and reduces the differential between the protected and unprotected areas. Assuming a loss rate for the protected area of zero

$$A_x \quad A_i \frac{d}{L_u}; \tag{11}$$

this result can also be rewritten as:

$$\frac{A_x}{A_i} \quad \frac{d}{L_u}$$

Indicating that for this no-payback impact–offset transaction, the ratio of the offset area and the impact area is equal to the ratio of the discount rate and the unprotected biodiversity loss rate.

Example 2: Out-of-Kind Offsets

In the examples of in-kind offsets above, MBV is compared only within a particular species or vegetation type. The application of NPBV to out-of-kind offsets differs only by including biodiversity measures that allow comparison between different types of biodiversity. The use of more complex biodiversity value functions or the use of a short-term payback time may preclude analytical solutions (e.g., Eq. 11) but numerical solutions can be implemented, as for optimization problems in conservation planning.

As an example of how applications to more complex and inclusive biodiversity value functions can be distilled to an easily understandable format, we adapt a simplified example from Stephens et al. (2002), who estimated the conservation merits and cost effectiveness of a range of conservation projects within a district of New Zealand. Each project under consideration has a well-defined spatial and temporal extent. The measure of conservation value of a project included a wide range of considerations from systematic conservation planning, including the complementarity of that project to other projects. Estimates of the conservation merit of each project combined conservation value with estimates of the feasibility, risk, and time to project completion to quantify overall net present merit for the conservation project. The NPBV of each project is the estimated value of the successful completed project, discounted by the risk of non-completion and time to completion (Stephens et al. 2002). For this example (Table 1), in the absence of offsets and within a budget of \$2 million, three conservation projects are chosen that provide a combined merit of 0.51. Since the projects are quite different from each other, the total conservation merit is the sum of the individual merits. The need for conservation far exceeds the budget, as illustrated by the large number of conservation projects that are not chosen.

In Table 1, development impacts were included by an equivalent listing of development projects, which have both negative conservation merits and negative costs reflecting money provided to offset impacts. The negative costs of development projects reflect the payment by the developer to fund enough conservation work to offset the impacts of the development. The amount of this payment can be set using at least two approaches. The default approach for offsets can be termed the cost method, where a developer chooses to pay the smallest amount that would fund a project sufficient to offset the biodiversity loss for the development. An alternative could be termed the value method (M. McGlone, pers. comm.) where developers would propose an offset payment that reflects the value to them that would be provided by incurring the residual biodiversity loss. In either case, if the payment is not sufficient to fund a conservation project that will offset the

Table 1 A combined process for choosing conservation projects and offsets

Project description	Biodiversity benefit	Project cost (k$)
Selected projects with no offsets		
Wilding pine control	0.3979	1037.5
Thar control	0.1015	711.8
Wallaby control	0.0084	156.7
Total of selected conservation projects	0.5078	1906[a]
Additional projects with offsets		
Predator control to benefit black stilt	0.0188	414.1
Pig control	0.0012	51.1
(Wind farm)	(- 0.0005)	(- 100)
(Coal mine)	(- 0.0010)	(- 500)
Total of selected combined projects	0.5263	1771.2[a]
Additional projects not selected		
Maintain existing stock fences	0.0371	1115.4
River recovery project	0.0168	1421.8
Rabbit control	0.0005	625.1
Property development	(- 0.005)	(- 50)

Conservation projects show the net present conservation merits (discounted by time to completion and risk of non-completion) and net present costs that are used to choose the most cost-effective set of projects (adapted from Stephens et al. 2002). Development projects are illustrative (not based on data) and show the estimated biodiversity impact and proposed monetary contribution to offset this impact. When combined, the development impacts and offset contributions (shown in parentheses) are treated as negative project benefits and negative costs

[a] We assume a conservation budget of 2000 k$

residual losses, the development impact cannot be offset or the payment must be increased. The entries of Table 1 use the value method for determining offset payments, and in this example the property development was not willing to fund a project of sufficient conservation worth to offset the impact from the development.

Since Stephens et al. (2002) incorporated both time discounting and risk of failure to estimate the net present MBV of proposed projects, the development projects and conservation projects can be compared directly—equivalent to the terms $\mathrm{MBV}(t)\ 9\ (1 - d_{\mathrm{off}})^t$ of the offset gains or impacts in Eqs. 6 and 7. In this context, out-of-kind offsets can be included to create a combined list of conservation projects (with positive conservation benefits and positive costs) and development projects (with conservation impacts and negative costs). This provides the opportunity for offsets to be considered in a standard systematic conservation planning approach. In the illustrative example shown in Table 1, the inclusion of development projects allows more conservation projects to proceed and increases total biodiversity value gained. Allowing the coal mine and wind farm (illustrative examples) to provide funding to achieve an out-of-kind offset for their impacts results in a net biodiversity merit (merits minus impacts) of 0.5251 with a conservation budget of 1.7 M$.

DISCUSSION

Biodiversity offsets are being implemented or contemplated in a number of countries, but have often performed poorly at protecting biodiversity in the past (Veltman 1995; Fox and Nino-Murcia 2005; Quigley and Harper 2005a, b; Walker et al. 2009). Poor biodiversity outcomes result from both ecological and non-ecological reasons, and without solutions to the administrative or institutional dynamics that undermine environmental protection, theoretical and technical improvements on the ecological side will not necessarily improve outcomes (Salzman and Ruhl 2000; Walker et al. 2009). Nevertheless, improved ecological metrics may provide both biodiversity protection agencies and project developers with greater confidence. Importantly, a more robust and transparent ecological basis for exchanges should reduce the information asymmetry which systematically favors development over protection (Walker et al. 2009). Improved offsetting measures could avoid (or at least reveal) the loss of significant biodiversity in exchanges currently justified by simple (but scientifically indefensible) metrics, and should increase accountability for biodiversity outcomes.

Drawing on systematic conservation planning and financial accounting, we have developed NPBV as a general and robust basis for designing impact–offset transactions. The use of NPBV provides a framework to assess these biodiversity transactions against the criterion of no-net-loss, by allowing comparisons of equity across time, space, and biodiversity type. It also provides an opportunity to improve offset design by replacing arbitrary multipliers with a more transparent theoretical foundation, by accounting for repayment schedules through time, and by providing the basis for both in-kind and out-of-kind offsets.

The NPBV approach provides a method for assessing the equity of impact–offset transactions in which both impacts and offsets, independently, may be spread across time. Temporal changes in the contribution of impacts and benefits to NPBV are accounted for in the discount functions. Example 1 (averted loss) provides an example of how NPBV can be used to assess a fair offset when the impact is immediate, but the benefits from additional protection are provided gradually through time (Fig. 1). In this case, the future repayments in the form of averted habitat loss are time discounted. While we recognize and do not dismiss problems with biodiversity lending (e.g., Walker et al. 2009; Bekessy et al. 2010), we demonstrate a general approach for assessing the equity of biodiversity loans.

A particular advantage of the NPBV framework is that it provides a general approach for the design of out-of-kind offsets, and the prospect of achieving better biodiversity outcomes by allowing the relative amounts of different biodiversity to change across the conservation landscape. The use of appropriate biodiversity value or benefit functions from conservation planning allows equity across different types of biodiversity to be assessed. This is a fundamental requirement for out-of-kind exchanges. In Example 2, the estimates of the conservation value of projects by Stephens et al. (2002) include time profiles and risk of failure. This results in a measure of the NPBV of the gains from the projects (Table 1). A similar approach can be taken for the development projects to characterize the (negative) NPBV from the residual impacts. The overall NPBV (Eqs. 6 or 7) of an impact–offset transaction in which a development paid for a conservation project is simply the sum of the (negative) NPBV from the impact, and the (positive) NPBV from the offsetting conservation project. This example highlights that a measure such as NPBV, which can be difficult to calculate, can be distilled into a simple format that allows impacts and offsets to be compared directly, and that conservation planning metrics and tools provide important components for biodiversity offset design.

The example from Table 1 also highlights the similarities between systematic conservation planning and biodiversity offset design. Conservation projects have positive conservation benefits and positive costs. The development projects have residual impacts with negative conservation benefits, but also negative costs in that they may provide money for other projects to proceed. In this light, biodiversity offsets have a number of parallels to approaches to the design of reserve systems that consider both biodiversity values as well as forgone economic opportunities (e.g., Faith et al. 1996; Faith and Walker 1996). An important caution with the approach to biodiversity offsets shown in Table 1 is that mechanisms must be used to ensure the funding provided by offsets is strictly additional to public allocation of funds to conservation. If governments see that conservation projects are being funded by industry, they may make larger decreases (or smaller increases) to conservation budgets, and so violate both the additionality principle and the no-net-loss criterion for biodiversity offsets.

While the NPBV framework advances the theory and practice of biodiversity offsets, many conceptual and practical issues remain (Table 2). Discount functions are provided as a general means of addressing the equity of transactions through time, but the development of the appropriate form of these functions, and the basis for setting discount rates will require considerable further development. The choice of discount rates for environmental issues is a topic of ongoing debate, exemplified by the Stern report on the economics of climate change (Stern et al. 2006) and discussions of the choice of discount rates and the impacts this has on the outcomes (Nordhaus 2007; Gollier 2010; Hampicke 2011). By extension, it is reasonable to consider other types of discount functions other than the standard exponential form, or for the discount rate to decrease further in the future (e.g., Weitzman 2001).

The detailed development of discount functions and rates is outside the scope of this paper (Table 2), but we provide some general guidance. A good default discount function is the usual exponential discount function (e.g. Eqs. 4 and 5). Discount rates (e.g., the parameter d of Eqs. 4 and 5) should reflect the various reasons why time profiles matter, including: risk of non-repayment; lost opportunity cost of the use of biodiversity; the rate of (biodiversity) return on biodiversity capital; the change in marginal value of biodiversity; and pure-time preferences. Values for each of these components should be added to arrive at the overall discount rate. Default positions would be zero rates for the components of changing marginal value and pure-time preference. Loss of use of biodiversity and rate of biodiversity return on biodiversity capital would each have rates of about 1–2 % in general, although this could be considerably higher if the biodiversity is providing benefits such as critical ecosystem services or cultural values. It is also reasonable to consider different discount

Table 2 A number of issues that need to be addressed for offset schemes, and the contribution of this paper to those issues

Issue	Discussed	Formulated	Addressed	Solved
Fundamental framework for offset equity in type, time and space	Yes	Yes	Yes	Yes
Robust biodiversity value functions	Yes	Yes	Yes	No
Choice of discount functions and rates	Yes	Yes	Yes	No
Problems with trading different types of biodiversity with different rates of increase and decrease	Yes	Yes	No	No
Practical demonstrations and tools for implementation	Yes	Yes	No	No
Social problems behind the effective implementation of offsets	Yes	No	No	No

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rates for impacts and offsets, with discount rates for offsets generally higher than impacts reflecting the certainty of loss relative to the uncertainty of gain. The largest component of the discount rate for an offset will reflect risks of non-repayment. Given the observed poor completion of offsets (e.g., Veltman 1995; Quigley and Harper 2005a, b; Walker et al. 2009), the risk component of discount rates might be quite high (e.g., 10–20 %). However, high discount rates for risk are not the best way to address risk, because if an offset is not implemented, then a large discount rate does not achieve NNL. Achieving NNL through high discount rates across a set of projects would penalize owners of projects who did complete their offset and benefit owners of those that did not. A better approach is to develop appropriate mechanisms (e.g., bonds, effective penalties, or sanctions) for non-completion, or the use of approaches such as 'robustly fair' offsets (Moilanen et al. 2008) that shift the burden of uncertainty towards those responsible for completing offsets. In general, it is probably best to treat risk separately from other components of the discount rate. Overall, this leads to non-risk related discount rates of 2–4 %, which might decline as time passes (e.g., Weitzman 2001). If non-delivery risk is not effectively managed using other mechanisms then a rate premium possibly exceeding 10 % should be added.

The implementation of the NPBV approach will also present challenges in practice. For instance, in Example 1, the prediction of time profiles of impacts and benefits is a potential difficulty. Estimating the magnitude and type of impacts and offset gains is challenging, and estimating relevant time profiles is even more difficult. The alternative is to ignore time profiles, which will not generally benefit biodiversity. At the very least, the use of NPBV allows the comparison of the effects of different time profiles and discount rates. Predictions of time to achieve specific milestones in the delivery of an offset also provide performance criteria for consent conditions.

The biodiversity value function is the main avenue for addressing non-temporal equity for both in-kind and out-of-kind offsets. We recognize the difficulties of developing robust measures for the relative biodiversity value of different types of biodiversity in different places and contexts. But the formulation used here serves to focus the equity and trading issues more generally and clearly, and also highlights the similarity of the conservation offset problem with familiar problems of systematic conservation planning. The development of robust biodiversity value or benefit functions is challenging, because of the complex, multi-level, hierarchical, and inherently non-additive nature of biodiversity. Care needs to be taken to choose an appropriate value function. For instance, the simple power value function shown in Eq. 2 may not be appropriate in many circumstances. Our use of area as the major determinant of biodiversity value in the averted loss offset of Example 1 is a decent approximation when adding additional protection to intact areas, but this would not apply to many other types of offsets. Our second example draws upon the work of Stephens et al. (2002) which uses a much more robust method for assessing the relative value of projects. An excellent example of a general and more inclusive value function or objective is biodiversity persistence as modeled by Ferrier and Drielsma (2010). The challenge of developing robust biodiversity value functions is important because the characteristics of the value function will determine how well it protects and maintains biodiversity when used in an offsets scheme. For example, equitable out-of-kind exchange must be based on nonlinear and context-based value functions that account for issues such as complementarity. However, the challenge is not unique to the design of biodiversity offsets, but is shared among the fields of reserve planning, identification of the most cost-effective conservation projects, reporting on conservation achievement, and the design of biodiversity offsets. Despite the central role that value, benefit or objective functions play in conservation planning, little work has been done to investigate the operational characteristics of these functions (but see Moilanen 2007; Overton et al. 2010) and the effects of different functions on conservation outcomes. In this light, more critical examination and development of these biodiversity value functions will benefit both fields.

Progress in better ways of addressing biodiversity equity through time developed for biodiversity offset design will also benefit systematic conservation planning. Temporal equity is not a critical issue for reserve network design, where the only conservation projects being considered are buying reserves in different locations. But as the systematic conservation planning problem is generalized to compare a wide range of different projects, with widely contrasting time profiles, accounting for temporal equity becomes much more important. As noted in Example 2, Stephens et al. (2002) incorporated NPV when comparing conservation projects. Hartig and Drechsler (2008) found that the choice of the time horizon for planning can strongly influence the choice of projects. As such, NPBV plays an important role in conservation planning, as it does for the design of biodiversity offsets.

We have emphasized similarities between the design of biodiversity offsets and systematic conservation planning, but important differences also exist. The likely harm to biodiversity through a poorly implemented conservation planning scheme is likely to be less than that incurred through a failed offsets scheme. The former reduces the conservation achieved for the available funding, while the latter facilitates biodiversity loss. The characteristics of the value function will determine the ability of the NPBV measure to protect biodiversity from loss during impact–offset transactions.

Another important difference between conservation planning and offsetting is that the asymmetry of interest discussed by Salzman and Ruhl (2000) and Walker et al. (2009) also leads to asymmetries in the errors associated with the characterization of biodiversity value. Uncertainties in comparing the equity in trades of very different types of biodiversity or over different time profiles (e.g., offsetting permanent loss with short-term gain) suggest a precautionary approach that favors offsetting with similar types or time profiles, as reflected in the restriction of many offset schemes to in-kind offsetting. We agree that some restrictions to in-kind offsets are more prudent and precautionary for biodiversity, but argue that these are better seen as restrictions of a more general approach that may include out-of-kind offsets and enable assessment of equity across different types of biodiversity.

We present this paper as an additional step in developing a more robust theory and practice of biodiversity offsetting. We raise some new issues and questions to address before the theory can be practically implemented. In particular, we recommend that out-of-kind offsets be explored carefully, with continued use of restrictions on the types of biodiversity that can be exchanged, particularly those with contrasting time profiles of loss and recovery. More explicit characterization of biodiversity value functions and their operating characteristics for their use in biodiversity exchanges is critical to the implementation of these ideas, because less adequate value functions (or currency) present greater potential for damage to biodiversity (Salzman and Ruhl 2000; Walker et al. 2009). Similarly, more careful characterization of the reasons why differences in time matter will better inform the use of discount functions. Ideally, this approach would be studied using simulated biodiversity exchanges and also trialed in the field to better understand the expected impacts on biodiversity of implementing such an approach.

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