A method for calculating minimum biodiversity offset multipliers accounting for time discounting, additionality and permanence

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Summary

1. Biodiversity offsetting, which means compensation for ecological and environmental damage caused by development activity, has recently been gaining strong political support around the world. One common criticism levelled at offsets is that they exchange certain and almost immediate losses for uncertain future gains. In the case of restoration offsets, gains may be realized after a time delay of decades, and with considerable uncertainty.

2. Here we focus on offset multipliers, which are ratios between damaged and compensated amounts (areas) of biodiversity. Multipliers have the attraction of being an easily understandable way of deciding the amount of offsetting needed. On the other hand, exact values of multipliers are very difficult to compute in practice if at all possible.

3. We introduce a mathematical method for deriving minimum levels for offset multipliers under the assumption that offsetting gains must compensate for the losses (no net loss offsetting). We calculate absolute minimum multipliers that arise from time discounting and delayed emergence of offsetting gains for a one-dimensional measure of biodiversity. Despite the highly simplified model, we show that even the absolute minimum multipliers may easily be quite large, in the order of dozens, and theoretically arbitrarily large, contradicting the relatively low multipliers found in literature and in practice.

4. While our results inform policy makers about realistic minimal offsetting requirements, they also challenge many current policies and show the importance of rigorous models for computing (minimum) offset multipliers. The strength of the presented method is that it requires minimal underlying information. We include a supplementary spreadsheet tool for calculating multipliers to facilitate application.

Key-words: compensation ratio, decision support tool, mitigation ratio, no net loss, offset ratio, offsetability, replacement ratio, time discounting

Introduction

Biodiversity offsetting is compensation for ecological and environmental damage caused by development activities (ten Kate, Bishop & Bayon 2004; Bekessy *et al.* 2010; BBOP 2013; Bull *et al.* 2013). Recently, offsetting has been gaining political acceptance and support all around the world (Kiesecker *et al.* 2009; Palmer & Filoso 2009; Madsen, Carroll & Moore Brands 2010). In this work, we concentrate on the ratio between the amounts of area (negatively) impacted and the area compensated. This ratio has been called a multiplier (Dunford, Ginn & Desvousges 2004; Bruggeman *et al.* 2005; Moilanen *et al.* 2009), mitigation ratio (Bendor 2009), offset ratio (Moilanen *et al.* 2009), compensation ratio (McKenney & Kiesecker 2010; Vaissiere *et al.* 2013) and replacement ratio (Dalang & Hersperger 2010; McKenney & Kiesecker 2010). We adopt the term multiplier for the present work. Multipliers are a superficially easily understandable way forward with offsetting,

answering the question 'how much biodiversity needs to be managed, protected or restored so as to compensate for the environmental damage that development activities have caused'. Nevertheless, it is generally unknown how large multipliers should be to achieve the key requirement of no net loss (Dunford, Ginn & Desvousges 2004; Harper & Quigley 2005; Gibbons & Lindenmayer 2007).

Several studies have analysed offsets empirically, often finding relatively low multipliers (of size <10). Some examples from the literature are summarized in Table 1. In many such cases, no net loss offsetting is unlikely. For example, Quigley & Harper (2006a,b) found that while official requirements resulted in offset ratios that should be on average 6·8:1 (area gained: area lost), the mean realized offset ratio was only 1·5:1, thereby failing legal requirements for no net loss. There are also some examples of relatively large offset ratios in the empirical literature (see Table 1). For example, Pickett *et al.* (2013) investigate offsetting for frogs in ponds that were lost due to the construction of the Sydney Olympic Park. In this rare example of confirmed successful offsetting, they found that losses of natural habitat for frogs could be robustly offset by a 19-fold

Table 1. Examples of offset multipliers (offset ratios, compensation ratios or replacement ratios) from the literature

Multiplier	Reference	Application
Between 2 and 6	Cameron, Cohen & Morrison (2012)	Solar energy development in Mojave Desert, USA
4	Vaissiere *et al.* (2013)	Compensation of damaged ecosystem services, Bay of Brest, France
Between 1·5 and 8	Dalang & Hersperger (2010)	Replacement ratio estimates for Swiss dry grassland biotopes
1·5 (average realized multiplier); 6·8 (average multiplier that would meet the official requirements)	Quigley & Harper (2006a,b)	Habitat compensation projects in Canada, where the NNL requirement was not achieved for all projects.
Between 1 and 10	Environmental Law Institute (2002)	Legal requirements for wetland compensation in the USA
1 or less	Zedler (1996)	Minimum replacement ratio allowed by regulatory agencies for certain areas in the USA
19	Pickett *et al.* (2013)	Habitat offsetting of a threatened frog in Sydney Olympic Park
30	DEADP (2007)	South Africa's Western Cape policy for critically endangered habitats

increase in pond area via the construction of compensating artificial ponds.

In this work, we investigate multipliers in the context of time. One of the most common criticisms levelled at biodiversity offsets is that they exchange certain losses for uncertain gains: if offsets are implemented via habitat restoration, the compensation may only become realized after a long time delay (up to many decades or even centuries in the case of forests), and often only with partial success (Stokstad 2008; Suding 2011). In some cases, it is implausible that losses truly can be recovered (Moilanen *et al.* 2009; Maron *et al.* 2010). Another relevant temporal component included in the present work is permanence (offset duration): how long are the offsets guaranteed to remain (Dargusch *et al.* 2010; McKenney & Kiesecker 2010; van Oosterzee, Blignaut & Bradshaw 2012)?

We develop a mathematical model to understand how large the multipliers should at least be under time discounting. Time discounting is widely used in economics to model the expected return on interest: future gains are given less value than immediate gains (Philibert 2003; Green & Myerson 2004). It can also be used in conservation to fairly balance immediate losses (due to development) with hypothetical future gains that follow habitat restoration, management or protection (Laibson 1997; Moilanen *et al.* 2009). Time discounting leads to the concept of net present value: what is the value of future income, or gained environmental value in this case, when discounted into the present day (Di Minin *et al.* 2013; Overton, Stephens & Ferrier 2013).

Specifically, we analytically derive minimum multipliers for offsetting conditional on the method of time discounting, linear additionality and permanence of gains. By additionality, it is meant that gains must be obtained by offset actions and not by other factors. We present numerical values for minimum multipliers for a wide range of parameter combinations and include a 'recipe' for easy reading of these results. As a supplement, we also include a simple spreadsheet application which allows straightforward application of the proposed methods in specific planning situations. While the present treatment is purposefully simplified and mathematical, we emphasize that our results have direct operational relevance for empirical offsetting cases and discussion about adequate offset multipliers in them.

Materials and methods

We present a method for deriving minimum levels for offsetting, given time delay in and duration of the offsetting action. We analyse the case in which effectively immediate losses are to be compensated by delayed future gains. The conceptual components included are the produced environmental value (biodiversity value or condition) and its response to damage and offsetting, time discounting, which accounts for delayed and uncertain offsetting responses, additionality, which requires that gains must be obtained by offset actions and not by other factors (in the business-as-usual scenario), and permanence, which measures how long the offsetting benefits are guaranteed to persist in the landscape (IUCN 2013). We refer to Table 2 for the definition of the above concepts and to Table 3 for mathematical notation.

We define the (offset) multiplier as the ratio of the area offset A_1 and the area damaged A_0 when no net loss is required (Dunford, Ginn & Desvousges 2004; Bruggeman *et al.* 2005; Moilanen *et al.* 2009):

$$M = \frac{A_1}{A_0}. \qquad \text{eqn 1}$$

When the size of the damaged area is assumed to be known, the size of the offset area A_1 can be calculated from Eqn 1 based on biodiversity lost from damage and gained from offsetting relative to the estimated business-as-usual (counterfactual) scenarios. The business-as-usual scenarios can include factors other than offsetting actions, such as active and passive management. For example, if compensation increases the condition of area as much as the impact decreases it, and both actions take place simultaneously, then the compensated area should be as large as the damaged area, yielding an offset multiplier equal to one; $M = 1$. In reality, the gain of condition from offsetting can be smaller than the initial damage: it is easy to completely destroy habitat but the converse action, restoration from a destroyed to a fully natural state, is practically impossible for most environments (Maron *et al.* 2012). Moreover, the offsetting action can take place after a time delay. In such situations, the area compensated should be (much) larger, yielding an offset multiplier (much) larger than one; $M > 1$.

Before presenting a general method for computing a minimum M, we illustrate the process by a simple example (see Fig. 1). Assume that every year t any area A yields a proportional environmental value $V(A, t) = q(t) A$, where $q(t)$ describes the condition of area A and takes its values between zero and one [a type of proportional environmental value is considered, for example, in the habitat hectares approach

Table 2. Definitions of some central terms

Term	Explanation
Additionality	A requirement that offsetting gains must be higher than those in the expected business-as-usual scenario (IUCN 2013)
Minimum multiplier	A minimum bound for no net loss multipliers (typically calculated using simplified methods)
Multiplier (offset multiplier, offset ratio, compensation ratio, replacement ratio)	The ratio of the area offset and the area damaged when the principle of no net loss is required (e.g. Dunford, Ginn & Desvousges 2004; Bruggeman *et al.* 2005; Moilanen *et al.* 2009)
No net loss	A requirement that offsetting gains must be at least as large as losses, when compared to the expected business-as-usual scenario (Dunford, Ginn & Desvousges 2004; Harper & Quigley 2005; Gibbons & Lindenmayer 2007; BBOP 2013; IUCN 2013)
Permanence	A requirement that offsetting gains must last at least as long as the impacts are expected to persist (IUCN 2013)
Time discounting (time preference)	Relative valuation of future value. Typically gains or losses in the far future are valued less than those in the near future (e.g. Philibert 2003; Green & Myerson 2004).
Present value	Future value which has been time discounted to reflect its current value (Di Minin *et al.* 2013; Overton, Stephens & Ferrier 2013)

Table 3. Mathematical symbols

Symbol	Explanation
M	Offset multiplier
A_0, A_1	Damaged area, offset area
q	Condition of an area
$V(A, t)$	Environmental value produced in area A at time t. In the examples this is specified as $V(A, t) = q(t) A$
t_1	Start of the offsetting period
T_0, T_1	End of the period when damage has effect, end of the offsetting period
$Loss(A, t), Gain(A, t)$	Loss of value in area A at time t, gain of value in area A at time t
D, r	Discount factor, discount rate
$\delta_{loss}, \delta_{gain}$	Relative loss of condition q in area A_0, relative gain in condition q in area A_1

(Parkes, Newell & Cheal 2003)]. We assume that an area A_0 of pristine quality ($q = 1$) is damaged by development activity in the present year ($t = 0$), lowering its condition from 1 to 0. The drop of condition is permanent, and it is estimated that without development activity, the condition would have stayed at the level $q = 1$. Hence, at each year, the environmental value loss in A_0 is $(1 \times A_0) - (0 \times A_0) = A_0$ (Fig. 1a). Next, an offsetting action starts in area A_1 at time $t = t_1$, increasing its condition from 0 to 1. Assuming that without offsetting q would stay zero, the yearly environmental value gain in A_1 is $(0 \times A_1) + (1 \times A_1) = A_1$ (Fig. 1b). The offsetting action ends at time $t = T_1$ at which point permanence is no longer guaranteed and, in this example, q falls back to zero. Future losses and gains are made comparable with present losses and gains by discounting methods (which bear relation to the computation of compound interest), so that future losses and gains are typically given less weight than those close to the present time. A basic discounting model is the exponential model which corresponds to a constant rate of discounting, that is having a fixed discount rate for loss and gain for each year (Fig. 1c,d). Assuming, for example, a discount rate of 5%, the present value of the biodiversity loss in A_0 amounts to the sum of discounted losses for every year in the future, which equals $21 \cdot 0 \times A_0$ (sum of the bars in panel Fig 1c, when extended over the infinite time interval, is 21). Similarly, if the offsetting action starts at the year $t_1 = 5$ and ends at $T_1 = 20$, the present value of the biodiversity gain in A_1 is $8 \cdot 9 \times A_1$ (sum of the bars in panel Fig. 1d

is $8 \cdot 9$). Hence, in order for A_1 to be large enough for no net loss offsetting, A_1 must be at least $M = 21 \cdot 0/8 \cdot 9 = 2 \cdot 4$ times as large as A_0.

We next derive a general formula for computing minimum multipliers. Consider points in time (years) $t = 0, 1, 2, \ldots$, where $t = 0$ corresponds to the present time. Suppose that any area A produces value, measured by a function $V(A, t)$. This value may be interpreted, for example in terms of the change in intrinsic biodiversity value or the value of ecosystem services generated by the area. The loss from damage at time t is then given by the differences of the produced value in the damaged area, $V_{dmg}(A_0, t)$, and the value in the estimated business-as-usual scenario (where no damage occurred), $V_{bau}(A_0, t)$, and similarly in the case of gain in the offset area A_1:

$$Loss(A_0, t) = V_{bau}(A_0, t) - V_{dmg}(A_0, t);$$
$$Gain(A_1, t) = V_{off}(A_1, t) - V_{bau}(A_1, t).$$

To capture temporal preferences and uncertainty about the future, losses and gains are discounted to present time (Moilanen *et al.* 2009; Pouzols, Burgman & Moilanen 2012; Overton, Stephens & Ferrier 2013);

$$Loss(A_0) = \sum_{t=0}^{T_0} Loss(A_0, t)D(t);$$
$$Gain(A_1) = \sum_{t=0}^{T_1} Gain(A_1, t)D(t),$$

where $D(t)$ is a discount factor (see Table 4 for the exponential and quasi-hyperbolic models of time discounting). The most common form is discounting at constant rate r, in which $D(t) = 1/(1 + r)^t$. The numbers T_0 and T_1 denote the ends of the time intervals during which the damage has effect or offsetting actions are completed, respectively. (Both of these time intervals may also be infinite). It follows from the no net loss principle that gains must compensate losses, $Gain(A_1) \geq Loss(A_0)$, implying a minimum requirement that

$$Gain(A_1) = Loss(A_0). \qquad \text{eqn 2}$$

As the damaged area A_0 is assumed to be known, Eqn 2 implicitly defines the size of the required offset area A_1, and the offset multiplier can be solved from Eqns 1 and 2.

In the case where the environmental value is proportional to the area, the multiplier is easy to solve, as was seen in the example above. For example, let us assume that the destruction is immediate (occurring at $t = 0$) and permanent ($T_0 = \infty$) and that it results in a relative loss of condition δ_{loss}, so that $Loss(A_0, t) = \delta_{loss} A_0$ for all t. Assume
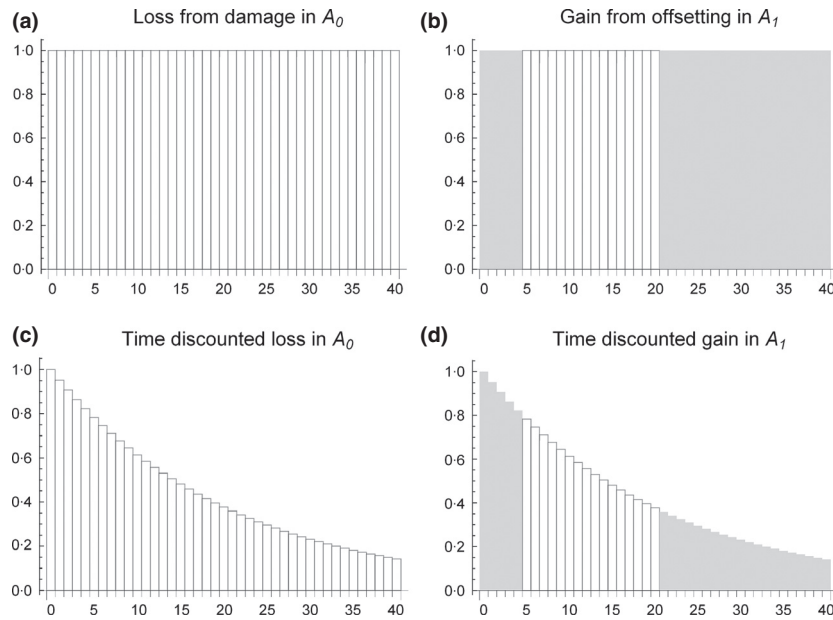
Fig. 1. An example of biodiversity loss and gain in a damaged area A_0 and the offset area A_1 where damage is permanent and the temporary offsetting action takes place between the years $t = 5$ and $t = 20$: The actual loss of biodiversity value in area A_0 (panel a) and gain of biodiversity value in the offset area A_1 (panel b) are higher than the discounted loss (panel c) and discounted gain (panel d). The grey areas in panels b and d indicate differences between loss and gain. The present value of loss is the sum of bars in panel c, and the present value of gain is the sum of bars in panel d. Although the graphs end at $t = 40$, positive loss exists indefinitely, because the damage was assumed to be permanent. Offset multiplier is the ratio A_1/A_0 where A_1 is large enough so that the present values of gain and loss are equal. A constant discount rate of $r = 5\%$ is applied.

further that an offsetting action increases the condition of area A_1 by the fraction δ_{gain} between t_1 and T_1 ($0 \leq t_1 < T_1 \leq \infty$), where Gain $(A_1, t) = \delta_{gain} A_1$. Then from the requirement of no net loss (Eqn 2), we get

$$\sum_{t=t_1}^{T_1} \delta_{gain} A_1 D(t) = \sum_{t=0}^{\infty} \delta_{loss} A_0 D(t).$$

Using Eqn 1, we solve

$$M = \frac{A_1}{A_0} = \frac{\delta_{loss} \sum_{t=0}^{\infty} D(t)}{\delta_{gain} \sum_{t=t_1}^{T_1} D(t)}.$$

In case exponential discounting is applied with rate r, this simplifies to

$$M = \frac{A_1}{A_0} = \frac{\delta_{loss}}{\delta_{gain}(R^{t_1} - R^{T_1+1})} \qquad \text{eqn 3}$$

where $R = 1/(1 + r)$. If $T_1 = \infty$, then the term R^{T_1+1} should be replaced by zero; see Table 4 for variants of this formula.

Note that while we have above formulated all values in discrete time (often years), these quantities could just as well be derived in continuous time, as is often performed in theoretical analyses. Calculations described here have also been implemented in a simple Excel application to facilitate easy application by practitioners (Supporting Information).

Results

Using the method presented above, we have analysed minimum multipliers for different parameter combinations to cover a large range of cases which show that realistic multipliers may be much larger than many multipliers reported in the literature. Here we have made the following additional technical assumptions, which generalize the simple example from the previous section (Fig. 1): (i) the produced environmental value is proportional to area; $V(A, t) = q(t)A$, (ii) damage in area A_0 is immediate (occurring at $t = 0$) and permanent ($T_0 = \infty$), (iii)

Table 4. Minimum multipliers for commonly used discount factors. The most common model for discrete time discounting is the exponential model, which corresponds to a constant discount rate r. Quasi-hyperbolic discounting is another commonly used model: it prefers immediate payment to delayed payments and its rate depends on two parameters β and γ between zero and one (Frederick, Loewenstein & O'Donoghue 2002). Some studies have proposed discount rates which prefer future payments instead (Gollier 2010; Kula & Evans 2011). We have abbreviated $R = 1/(1 + r)$

Time discounting model	Discount factor $D(t)$	Minimum multiplier; immediate loss of δ_{loss} units, delayed permanent gain of δ_{gain} units ($t_1 > 0$)	Minimum multiplier; immediate loss of δ_{loss} units, delayed temporary gain of δ_{gain} units ($t_1 > 0$)
Exponential	$D(t) = R^t$	$\frac{\delta_{loss}}{\delta_{gain} R^{t_1}}$	$\frac{\delta_{loss}}{\delta_{gain}(R^{t_1} - R^{T_1+1})}$
Quasi-hyperbolic	$D(0) = 1;$ $D(t) = \beta\gamma^t$ for $t > 0$	$\frac{\delta_{loss}(1+\beta-\gamma)}{\delta_{gain}\beta\gamma^{t_1}}$	$\frac{\delta_{loss}(1+\beta-\gamma)}{\delta_{gain}\beta(\gamma^{t_1} - \gamma^{T_1+1})}$

loss is complete; Loss $(A_0, t) = A_0$ for all t, (iv) offsetting action takes place between years t_1 and T_1 ($t_1 \leq T_1$), (v) offsetting action fully compensates for the local environmental losses; *Gain* $(A_1, t) = A_1$ for all t between t_1 and T_1, (vi) in the business-as-usual scenarios, loss and gain are both zero and (vii) exponential discounting with rate r is applied (We below explain how to calculate the correct multiplier when per area unit gains are smaller than per area unit losses).

Figures 2 and 3 show such minimum multipliers for a wide range of parameters. In the plot range of Fig. 2, the multipliers vary between zero and over 100, but can well be even higher than that. A zero multiplier represents the theoretical special case where no damage has occurred. In Fig. 2, it is assumed that the offsets will be permanent ($T_1 = \infty$) and multipliers are plotted for a range of offsetting delays t_1 and discount rates r. As Eqn 3 shows, the multipliers increase with both of these parameters; in fact, a multiplier with delayed offsetting is $1/R^{t_1} = (1 + r)^{t_1}$ times higher than a multiplier with immediate offsetting. As Fig. 3 shows, if a finite offsetting period is assumed, the multiplier increases the shorter the offsetting period $(T_1 - t_1)$ gets, eventually approaching infinity as T_1 approaches t_1. On the other hand, due to exponential discounting model, if the offsetting period is sufficiently long, multipliers from non-permanent offsetting approach those from permanent offsetting.

All the presented multipliers assume that $\delta_{loss} = 1$ and $\delta_{gain} = 1$. In general, these parameters can be anything between zero and one. For general δ_{loss} and δ_{gain}, a minimum multiplier can be computed simply with further multiplication by the relative loss ratio $\delta_{loss}/\delta_{gain}$ (by Eqn 3). We illustrate these observations by an example: if $\delta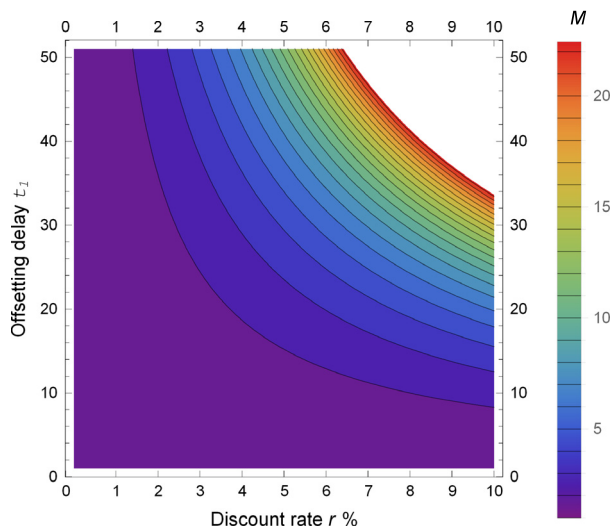_{loss}/\delta_{gain} = 1$, then with an offsetting delay of 10 years and a discount rate of 5%, the multiplier is 1·6. If, in addition, offsetting is expected to last only 10 years, the multiplier is 3·9. If, in addition, offsetting is estimated to be less efficient, so that $\delta_{gain} = 0·2$, the multiplier is $1/0·2 = 5$ times 3·9, that is, 19·6.

For readers' convenience, we include a recipe for calculating a minimum multiplier M using only the plots in Figs 2 and 3 when the necessary parameters are known. Note that this recipe is only meant as an easy first step in estimating the size of a minimum multiplier – the estimation of exact no net loss multipliers is instead a demanding task.

1. Assume that the parameters t_1, T_1, δ_{loss}, δ_{gain} and r are known. If offsetting is not permanent (T_1 is finite), assume also that r takes one of the values 1%, 3%, 5% or 7%.
2. If offsetting is permanent (T_1 is infinite), then Fig. 2 gives a multiplier M_0 which corresponds to r and t_1. If offsetting is not permanent, then depending on r, a multiplier M_0 which corresponds to t_1 and T_1 can be picked from one of the panels in Fig. 3. We call M_0 a reference multiplier.
3. The reference multiplier M_0 has been computed under the (optimistic) assumption that the ratio of relative loss and gain equals one. Hence, by Eqn 3, the sought minimum multiplier M is given by $M = M_0 \, \delta_{loss}/\delta_{gain}$.

Discussion

We have developed policy-relevant theory for biodiversity offsetting, focusing on multipliers while considering time discounting and delayed compensation – which is commonly the case when habitat restoration is involved (Maron *et al.* 2012). Main components included in the present analysis are additionality, permanence and time discounting. Here, we modelled additionality via a simple linear effect: the higher the gain achieved by offsetting action the lower the area multiplier needed for no net loss offsetting. When offset duration shortens (lower permanence), the minimum multiplier increases but not linearly, as the effects of permanence interact with time discounting. The multiplier is strongly influenced by time discounting and the delay in achieving offsetting gains, leading to high, exponentially increasing multipliers when development of compensation is much delayed. These computations could be considered, for example, together with other considerations at the initial offsetability determination stage of the hierarchy of impact avoidance, mitigation and offsetting (Pilgrim *et al.* 2013). Although the values of individual minimum multipliers vary depending on the model parameters, our results show that minimum multipliers can be large compared to those previously presented in the literature. Thus, the analysis demonstrates the importance of rigorous models for computing (minimum or exact) offset multipliers.

Time discounting is a critical component of the present analysis. We use time discounting in the sense of equitability: first, a yearly return on investment is expected from economic investment (implying time discounting for future gains). If this investment is enabled via ecological damage, it is fair that the
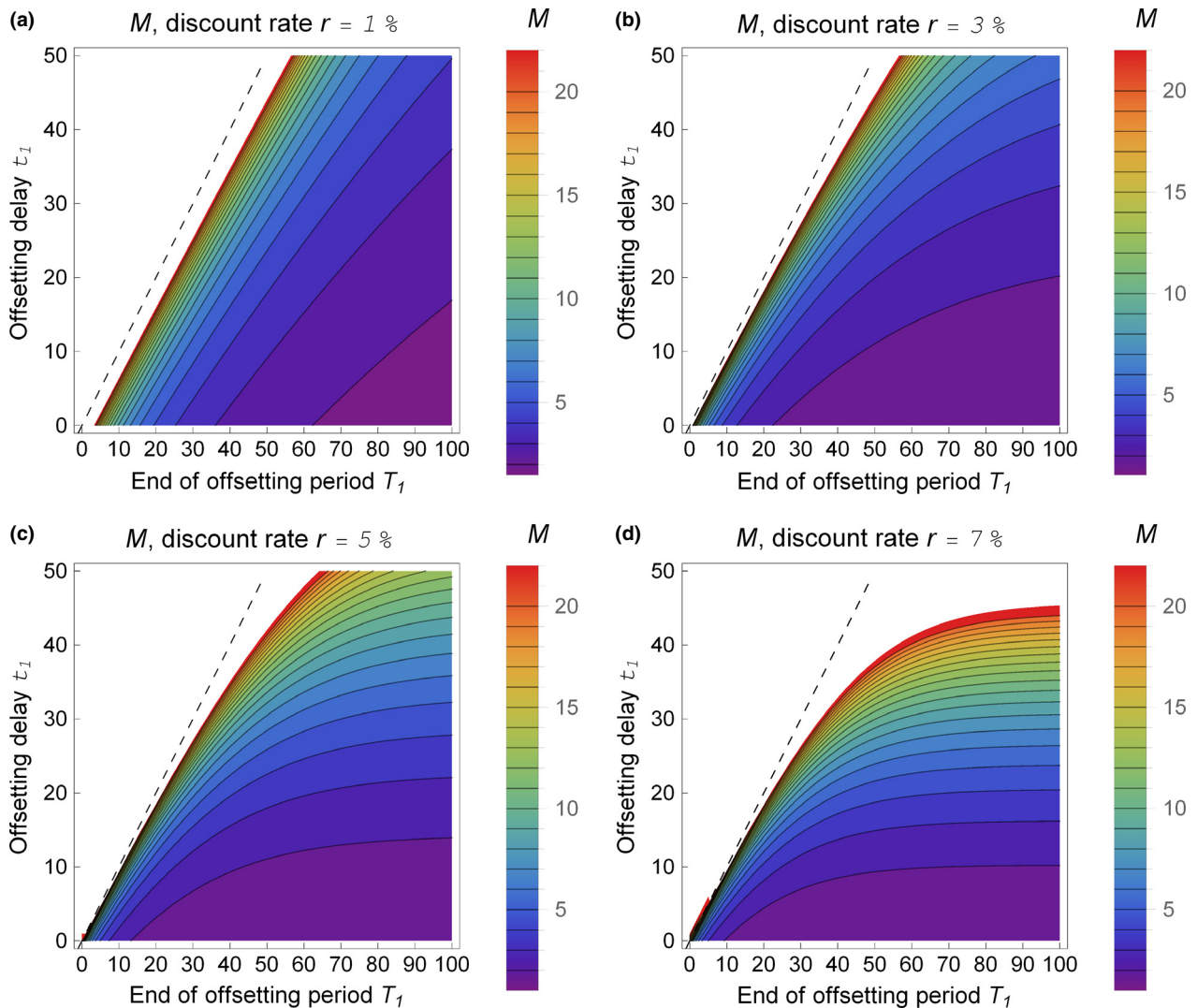

Fig. 2. Minimum multiplier M as a function of exponential time discount rate r and offsetting delay t_1. The figure has been computed assuming a relative decrease of 1 in condition of site A_0 at $t = 0$ and a relative improvement of 1 in condition at site A_1 at time t_1. Biodiversity value is proportional to the area, as in Fig. 1 and Table 4. In the white area, the multipliers quickly increase with r and t_1, having a value of 117 in the upper right-hand corner. The minimum multiplier in the lower left-hand corner is 1.

Fig. 3. Minimum multiplier M as a function of the offsetting delay t_1 and the end of offsetting period $T_1 \geq t_1$. The assumptions are same as in Fig. 2, and additionally, a relative increase of 1 in condition of area A_1 is assumed at time T_1. The four panels include minimum multipliers for exponential time discounting of rate (a) r = 1%, (b) $r = 2 \cdot 0$%, (c) $r = 5 \cdot 0$% and (d) $r = 7 \cdot 0$%. The values are only shown for the cases where $T_1 \geq t_1$, leaving empty the part of the graph where $T_1 < t_1$ (left-hand side of the dashed line). On the right-hand side of the dashed line, the values increase and can be much higher than 20, the closer they are to the dashed line and the higher they are in the y-axis.

same or higher time discounting should be applied to ecological compensation – it is not fair if immediate losses are only compensated by far future hypothetical gains. The discount rate can also model the offsetting risk, as an immediate certain gain may be preferable to a risky delayed gain. Some studies have proposed that the future could be valued equally or even higher than present (Gollier 2010; Kula & Evans 2011); we nevertheless adopt the equitability perspective in the present analysis. While we have explicitly discussed two discounting models, the exponential and the quasi-hyperbolic model, the methods presented in this paper can be formulated for any preferred model of time discounting and it is easy to see that the loss and gain functions can be defined using different discount factors to allow more detailed analysis of time discounting.

We have calculated minimum bounds for offset multipliers: this is a key concept that is not defined explicitly in otherwise exhaustive and robust frameworks for offsetting

(Pilgrim *et al.* 2013). The analysis was based on a simple one-dimensional response of habitat to habitat management or restoration, implying that the multipliers we calculate are almost certainly an underestimation of what is truly needed for no net loss offsetting. In reality, biodiversity is a highly multidimensional entity. Therefore, while we find high multipliers in the one-dimensional case (Figs 2 and 3), even higher multipliers would be needed if several different components of loss needed to be compensated with different actions in different areas. On the other hand, multidimensional measures of environmental value should be preferred in applications as one-dimensional measures may lead to different sizes of multipliers depending on the measure selected (cf. Table 1). Due to its simplicity, our method can nevertheless be operationally useful, and quick to apply starting point, compared to a possibly very difficult task of exact estimation of exact no net loss multipliers.

Other limitations and simplifications applied in the present work include that the work is non-spatial, environmental value on the left axis may be difficult to define, and costs are not included. We have further assumed a constant counterfactual (business-as-usual) scenario, although other scenarios would obviously affect the sizes of multipliers (Bull *et al.* 2014). In fact, the model is intentionally simple and aims to derive minimum multipliers under minimal conditions. Even with (optimistic) minimal assumptions, we find that large multipliers may be needed. Including spatiality would not decrease these multipliers. Costs are not relevant for the analysis of the multiplier for a specific offsetting action. Further accounting for uncertainty would increase, not decrease, multipliers: if responses are uncertain, robustly guaranteeing no net loss needs a large multiplier instead of a smaller one (Moilanen *et al.* 2009; Pouzols, Burgman & Moilanen 2012; Pilgrim *et al.* 2013). In the present case, uncertainty could be partially included by making a conservative estimate of the response function, the amount of gain in the function and delay in the development of compensation. Using more sophisticated frameworks, such as RobOff (Pouzols, Burgman & Moilanen 2012; Pouzols & Moilanen 2013), it is possible to explore the implications of many interacting factors such as multiple biodiversity components, different uncertainty models, alternative models of sustainability and varying planning horizons. As a final consideration, the present analysis applies to the two major classes of offsets that can be distinguished depending on the type of offset or compensation action: restoration and averted loss offsets (BBOP 2013; IUCN 2013). There is no need to make such distinction in the analysis above.

In conclusion, if multipliers smaller than suggested by the present analysis are used, it is unlikely that no net loss will be achieved in biodiversity offsetting.

Acknowledgements

Data accessibility

Excel spreadsheet tool: uploaded as online supporting information.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Data S1. Excel spreadsheet tool for calculating minimum offset multipliers.