A quantitative framework for evaluating the impact of biodiversity offset policies

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Abstract

We propose an impact evaluation framework for biodiversity offsetting that can be used to determine the impacts attributable to developments and their associated offsets under a range of assumptions. This framework is used in conjunction with two hypothetical models of the offsetting process to illustrate a number of issues that can arise when conducting impact evaluations of biodiversity offsetting, where the ‘intervention’ comprises a development and its associated offsets. We establish that including gains due to avoided losses (i.e. development that would have otherwise happened) in the intervention impact calculation results in a reduction in the offset requirements per unit of development. This occurs regardless of whether the biodiversity at the development or offset sites is declining, stable, or improving. We also show how including gains due to avoided loss requires the consideration of offsets that might otherwise have occurred. These ‘avoided offsets’ increase the offset requirements per unit of development regardless of the background site dynamics. Finally, we examine offsetting as part of a larger, spatially strategic scheme and show that when the development and offset regions are separated, including avoided loss in the impact calculations can result in a situation where the development impact goes to zero and a system that attains ‘net gain’ regardless of the development and offsetting activities. The proposed framework can be used to inform offset policy by providing a transparent and logical methodology for the determining the offset requirements for the impacts attributed to development.

1. Introduction

Over the past decade, biodiversity offset policies have emerged as an important tool for dealing with development impacts on biodiversity (Madsen et al., 2011). They aim to balance the negative biodiversity impacts of development with conservation gains elsewhere, and have been rapidly adopted in an increasing number of nations worldwide (Brownlie and Botha, 2009; Ives and Bekessy, 2015; Madsen et al., 2011; Saenz et al., 2013). In addition, a range of industries have adopted informal voluntary offsetting, in part as a social license to operate (Benabou, 2014; Madsen et al., 2011; Rainey et al., 2015).

Biodiversity offsets are unique among conservation interventions as the biodiversity gains attributed to a set of conservation actions are tied directly to biodiversity losses. Offsets involve counterbalancing a specified biodiversity loss after appropriate avoidance measures for the loss of biodiversity have been considered. When the gains attributed to the offset fully mitigate the losses attributed to the development, the offset is considered to have achieved "no net loss" (NNL) of biodiversity (Bull et al., 2014; Gibbons and Lindenmayer, 2007a). A "net gain" or "net positive impact" are also commonly cited as offset policy objectives (Bull and Brownlie, 2015; Gibbons and Lindenmayer, 2007b; McKenney and Kiesecker, 2009). However, the effectiveness of offset policies remains unclear as there have been few formal impact assessments undertaken, in part due to the time and expense of these assessments, and in addition, a lack of political will to enforce them (Gordon et al., 2015).

To understand if and when a biodiversity offset achieves NNL, a net gain, or fails in these objectives, it is necessary to measure and compare the change attributable to the development actions with the change attributable to the offset actions associated with that development. We refer to this change as the "impact" (which can be negative or positive) and apply this term to the measurement of both the development and offset interventions. An impact evaluation aims to measure the difference between what happened subsequent to the intervention (the 'outcome'), and what was likely to occur in the absence of the intervention (a 'counterfactual') (Baylis et al., 2016; Ferraro, 2009). Counterfactuals therefore play a critical role in the impact calculations as they provide the baselines that are used to quantify the change attributable to an intervention.

A meaningful impact calculation requires that the outcome and the counterfactual used in the impact calculation are both measured using the same metric. The specification of the metric is particularly important in offsets as the development and offset impacts need to be commensurate in order to calculate the net impact (Bull et al., 2014, 2013). There is therefore an implicit requirement that in order to determine the net impact, the outcomes of the development and offset sites, as well as their respective counterfactuals, are all measured according to the same metric. If this condition is not met, the development and offset impacts are assessed under a different set of assumptions and any subsequent evaluation of no net loss is invalidated.

A sound impact evaluation requires that the chosen counterfactual adequately capture the processes and events that are likely to influence the site in the absence of the intervention. For example, in the offsets policy used in New South Wales, Australia, if the biodiversity of a site is in decline due to background pressures such as invasive species or climate change, the counterfactual needs to capture this decline, yielding gains due to avoided declines when that site is appropriately managed (Office of Environment and Heritage for the NSW Government, 2017). Additional gains can be obtained if the site is protected using a 'security benefit score' for vegetation in good condition and without any existing conservation obligations. In this case there are effectively two distinct processes that need to be accounted for in the impact calculations, namely large scale background condition decline, and local scale processes such as vegetation clearing that are associated with the avoided clearing gains.

Despite the importance of counterfactuals in biodiversity offsets, guidance on the specification of the counterfactuals used in the impact calculations is often limited or lacking (Maron et al., 2016b). In the limited number of cases where counterfactuals are mentioned, the assumptions used in the specification of the counterfactual are rarely quantified and made explicit, and in some cases are demonstrably incorrect

(Maron, 2015; Maron et al., 2013). While impact assessments using counterfactuals that change through time have been previously discussed in the context of biodiversity offsetting (Bull et al., 2014, 2013; Gordon et al., 2015; Maron et al., 2015; Sonter et al., 2017, p. 2; Virah-Sawmy et al., 2014), these publications consider only a single counterfactual in a particular impact calculation. In real-world applications, there is nearly always uncertainty regarding what counterfactuals could or should be used in the impact calculations and many counterfactuals can be plausible choices. These cases require a systematic framework that can incorporate multiple processes and uncertainties in the impact calculations.

To address these issues, we present a quantitative framework that allows the impact of the development and offset to be calculated relative to particular counterfactuals, or relative to an aggregated set of counterfactuals via a 'weighted counterfactual'. Using this framework in conjunction with two hypothetical offsetting models we examine the components of potential loss and potential gain in both the development and offset sites. We determine the subsequent effect of including gains due to avoided loss in the offset and development impacts over a range of declining, stable and improving ecological states where consistent counterfactuals are enforced in both the development and offset impact calculations. We examine these impacts at the scale pertaining to a single development-offset pair, and compare these impacts to those obtained at the scale pertaining to larger offset schemes where multiple development impacts are offset in a spatially strategic manner.

2. Methods

Determining the impact of a development or offset requires the specification of a metric that is used to quantify both the absolute state of the site(s) and the impact(s) relative to a counterfactual. Throughout this paper it is assumed that the states and impacts of all sites and interventions are assessed using the same metric, i.e. the development and offsets are assessed on a like-for-like basis. For simplicity we present the results in this paper under the assumption that the biodiversity value can be quantified by a single component biodiversity surrogate that the offset intervention targets (Bull et al., 2016, 2013; Maron et al., 2012; Quétier and Lavorel, 2011). This metric can represent a quantity such as vegetation cover and condition, or a speciesbased metric such as species occupancy or abundance. We derive a set of results using equations with a general, analytic form, applicable to any function that can be used to describe a time-evolving ecological state, as well as presenting a set of examples that use the logistic function (Mace et al., 2008) to model the changing ecological state of the development and offset sites.

2.1 The state of the development and offset

The biodiversity state of the development site is assumed to initially evolve according to an arbitrary function, $C_D(t)$, that represents the condition change over time. We assume, for simplicity, that the development of a site immediately results in a complete and permanent loss of the biodiversity at that site. The biodiversity state, $B_D(t)$, of a site that is developed at time, t_1, can then be written as

$$B_D(t) = \begin{cases} C_D(t) & (t \leq t_1) \\ 0 & (t > t_1) \end{cases}. \quad (1)$$

To compensate for the loss of biodiversity attributed to the development, an offset is implemented at an alternate site. We assume that the offset involves a restoration, with a resulting state that is described by a function, $R(t)$. For simplicity, it is assumed the offset is also implemented at time t_1. The biodiversity state of the offset site, $B_O(t)$, can be written as

$$B_O(t) = \begin{cases} C_O(t) & (t \leq t_1) \\ R(t) & (t > t_1) \end{cases}. \quad (2)$$

In the absence of the development and offset, if it is assumed that the development and offset sites would continue to evolve according to $C_D(t)$ and $C_O(t)$ respectively, for the period defined by $t > t_1$, then these functions describe counterfactual states of the sites and can be used in the development and offset impact calculations.

Throughout this paper we present a series of time evolving states and impacts that are modeled using a logistic function, widely accepted to model ecological processes such as non-linear population dynamics, with the form,

$$C(t) = \frac{K}{1 + Ae^{-\alpha(t-t_0)}}. \tag{3}$$

The maximal, minimal, and initial states are determined by the parameters K and A. The parameter, α, governs the rate of change, and setting α to $\alpha < 0$, $\alpha = 0$, and $\alpha > 0$ results in a monotonically decreasing, stable, and monotonically increasing state respectively. A time-shift, t_0, can be included to ensure a continuous ecological state under the change of a management regime. In the examples presented here, the biodiversity state of each site prior to either an offset or development intervention is assumed to be in decline (i.e. $\alpha < 0$ for all sites) although the results are generalizable to include improving and stable states (see Supplementary Information). Example development and offset states, described by Eq. 1 and Eq. 2 respectively, and where $C_D(t)$ and $C_O(t)$ have the form in Eq. 3 are shown in Fig. 1 (a) and (b).

2.2 Calculating impacts

The impact of an intervention is defined as the difference between the state, $B(t)$, subsequent to the intervention and a counterfactual for the site, $C(t)$, i.e.

$$I(t) = B(t) - C(t). \tag{4}$$

The impact of a development relative to a counterfactual, $C_D(t)$, is, from Eq. 1 and Eq. 4,

$$I_D(t) = \begin{cases} 0 & (t \leq t_1) \\ -C_D(t) & (t > t_1) \end{cases}, \quad (5)$$

where the impact is by definition zero prior to the intervention and negative afterwards. The impact of the offset relative to a counterfactual, $C_O(t)$, is, from Eq. 2 and Eq. 4,

$$I_O(t) = \begin{cases} 0 & (t \leq t_1) \\ R(t) - C_O(t) & (t > t_1) \end{cases}. \quad (6)$$

The net impact is defined as the sum of the development-offset impact pair, i.e.

$$I_{NET}(t) = I_D(t) + I_O(t), \quad (7)$$

yielding, via Eq. 5 and Eq. 6,

$$I_{NET}(t) = \begin{cases} 0 & (t \leq t_1) \\ R(t) - C_O(t) - C_D(t) & (t > t_1) \end{cases}. \quad (8)$$

If the offset gains fully mitigate the losses attributed to the development at a time, t_{NNL}, the immediate loss associated with the development D_1, as well as the delay required to achieve NNL, results in a projected time-lag, $\tau = t_{NNL} - t_1$, prior to the development-offset pair achieving NNL. Eq. 8 results in a net gain relative to the counterfactuals, $C_O(t)$ and $C_D(t)$, when $I_{NET}(t) > 0$.

2.3 A 4-site development and offset model

A hypothetical 4-site model can be used to illustrate the issues that can arise under different assumptions regarding counterfactuals (Fig. 1). In this model, we assume that site, S_1, is developed at time, t_1, via a development, D_1 (Fig. 1). The biodiversity loss associated with D_1 is mitigated by an offset, O_1, that is implemented at an alternate site, S_i, at time, t_1, where $i \in 2, 3, 4$. A subsequent development, D_2, and offset, O_2, occur at time, t_2, resulting in the development or offset of all four sites subsequent to t_2 (Fig. 1).

Given the development, D_1, the three counterfactual states for the remaining sites, S_2, S_3, and S_4, are the selection for the initial offset, O_1, the subsequent development, D_2, at time, t_2, or the selection for offset, O_2, at time, t_2. Fig. 1 shows the actual state and all counterfactual states for the site, S_2 (black dashed lines). The offset, O_1, of the site, S_2, results in the states shown in Fig. 1 (b) and (c). The remaining states in Fig. 1 (d) - (g) represent all of the counterfactual states for the site S_2. We define "potential development" counterfactual states as the states where the site would be subsequently developed, (Fig. 1 (d), (f)), and likewise for "potential offset" states (Fig. 1(e), (g)). The impact of the offset relative to either of these states can be determined via Eq. 4.

Due to the symmetry of the 4-site model, the sites, S_3 and S_4, have the same set of counterfactual states as S_2. In addition, the system arrangements corresponding to the development, D_1, of the sites S_2, S_3, or S_4, yield an equivalent set of counterfactual states and are thus also effectively addressed in our analysis.

2.4 The impact of the offset

The impact of the offset, O_1, relative to a declining background counterfactual (Fig. 1 (h)-(i)), results in a positive, monotonically increasing impact for $t > t_1$. Calculating the offset impact relative to a development counterfactual (Fig. 1(d), (f)), results in an increase in the impact, ΔI_O^D, (Fig. 1(j), (l)), compared to the impact relative to the background counterfactual due to avoided losses. This gain applies to all offset impacts relative to a development counterfactual. Calculating the offset impact relative to a potential offset counterfactual (Fig. 1(e), (g)), results in a decrease in impact, ΔI_O^O (Fig. 1(k), (m)), compared to the impact relative to the background counterfactual. The reduction in the offset gains applies to all offset impacts relative to an offset counterfactual, with the proviso that the potential offset yields gains relative to the background counterfactual.

2.5 The impact of the development

The impact of the development, D_1, in the 4-site model, relative to a declining background counterfactual (Fig. 1 (a)), is negative and reduces in magnitude for $t > t_1$. The condition that the development and offset impacts are commensurate enforces the same set of assumptions on the counterfactuals used in the development and offset impact calculations. The use of potential development and/or potential offset counterfactuals in the offset impact calculation therefore requires that these potential states are also included in the development impact. If this condition is not met the development and offset impacts are assessed under a different set of assumptions and relative to a different type of counterfactual. In this case, the impacts are incommensurate and cannot be used to determine the net impact of the development and offset. For the 4-site model the impact of the development, D_1, of the site S_1, needs to be calculated relative to an equivalent set of counterfactuals as those discussed in Section 2.3 for the offset, O_1, of the site S_2.

In the absence of the development, D_1, occurring at the site, S_1, the development, D_1, is forced to occur in sites S_2, S_3, or S_4. The site, S_1, would therefore be either offset at time, t_1, via the offset, O_1, or subsequently developed via the development, D_2, or offset via the offset, O_2. The development counterfactuals for the development site corresponding to the potential development, D_2, are therefore equivalent to the development counterfactuals for the offset discussed in Section 2.3 and shown in Fig. 1(d), (f), with the distinction that the background counterfactual is replaced by the background counterfactual for the development site, $C_D(t)$. Similarly, the potential offset states are equivalent to the states represented in Fig. 1(e), (g), with the distinction that the potential restoration is replaced with the potential restoration for the development site, $R_D(t)$.

Many potential states can be incorporated into the impact calculations using a 'weighted counterfactual', that combines a set of counterfactuals weighted by their probability of occurrence via

$$C_O^W(t) = \sum_{j=1:J} p_j(t) \cdot C_j(t), \tag{9}$$

where $p_j(t)$ is the probability that the j^{th} state corresponding to the counterfactual, $C_j(t)$, occurs. This approach can be used to combine development and/or offset counterfactuals.

A full description (including analytic forms) of the development, offset, and net impacts relative to a range of counterfactuals, including weighted counterfactuals is provided in Supplementary Information sections S1 – S3.

2.6 Extension to many sites

It is not feasible to methodically determine all permutations of developments and offsets in a system with a large number of sites where many sites are developed or offset over time. However, as we show, a weighted counterfactual can be determined for a given site if the range of plausible potential states for that site, and their associated probabilities of occurrence, can be identified or estimated.

For an *N*-site system, where a site, S_j, is developed or offset at a time, t_j, and $j \in 1..N$, we assume that there are L subsequent developments, $D_l(t)$, at times, t_m, with M associated offsets, $O_m(t)$, where $l \in 1 ... L$ and $m \in 1..M$. In the absence of the development or offset interventions of the site, S_j, we assume there are three types of potential states that can be used as counterfactuals: the site could be subsequently developed, subsequently offset, or remain unused in the development/offset program. The expected loss due to subsequent potential developments for either intervention can be written as the weighted mean over all development counterfactual states, yielding the expected loss via Eq. 9 as

$$D^*(t) = \sum_{l=1:L} p_D(t_l) \cdot B(t_l), \tag{10}$$

where $B(t_l)$ has the form in Eq. 1, $p_D(t_l)$ is the probability that the site is subsequently developed at time, t_l, and there are L subsequent developments.

Similarly, the expected gains due to potential offsets (where the site is used to offset a potential development of another site in the system) for both the development and offset interventions intervention can be written as the sum of all offset counterfactual states,

$$O^*(t) = \sum_{m=1:M} p_O(t_m) \cdot R_i(t_m), \tag{11}$$

where $p_O(t_m)$ is the probability that the site is offset at time, t_m, and $R_i(t_m)$ is a particular restoration state. The expected background decline subsequent to either intervention can be written as

$$\begin{aligned} C^*(t) &= \sum_{k=1:(N-M-L)} C(t) p_C(t_k) \\ &= C(t) \cdot \left(1 - \sum_{k=1:(N-M-L)} [p_D(t_k) + p_O(t_k)] \right), \end{aligned} \tag{12}$$

where $p_C(t_k) = 1 - p_D(t_k) - p_O(t_k)$ is the probability that the site is not selected for a development or offset and continues to decline according to Eq. 3. The net weighted counterfactual that includes potential developments, potential offsets, and potential condition decline is (from Eqs. 9-12)

$$B^*(t) = C^*(t) + O^*(t) + D^*(t). \tag{13}$$

2.7 An example many-site model

We modeled the ecological value of a development and offset in an N-site system through time using Eq. 3, where the parameters, K and A, were set to yield an initial ecological value of 40 for the offset site and 50 for the development site, and a minimum and a maximum (asymptotic) value of 0 and 100 respectively, for both sites. We assumed that the system had a total of $N = 1000$ sites, where 250 sites were developed and each development was offset with a single restoration offset site (i.e. there were 250 offsets) that was implemented simultaneously to the particular development it offsets. The number of developments per year was sampled from a random normal distribution with a mean, $\mu = 5$, and standard deviation $\sigma = 1$. The potential development/offset states in Fig. 2 were modeled using Eq. 3, with $\alpha = -0.05$.

3. Results

3.1 Evaluating the development and offset impacts

The ecological states and counterfactuals, including the counterfactuals associated with potential developments, potential offsets, and the net weighted counterfactual, for the development and offset sites are shown in Fig. 2 (a) and (b) respectively. The background decline counterfactuals in Fig. 2 represents the potential states where the site was not selected for any developments or offsets and subsequently declined according to the background counterfactual. The development and offset impacts relative to the weighted counterfactual including decline and potential developments, decline and potential offsets, and the net weighted counterfactual are shown in Fig. 2 (c) and (d) respectively.

The impact of the development relative to a declining background counterfactual (Fig. 2 (c)), results in a negative impact that reduces in magnitude subsequent to the intervention. The impact of the offset, O_1, relative to a declining background counterfactual (Fig. 2 (d)), is positive and monotonically increases subsequent to the intervention. The net impact relative to the background counterfactual is shown in Fig. 2 (e). In this case the net impact is negative for the period defined by $t_1 < t < t_{NNL}$, gradually increasing until the net impact switches from net loss to a net gain for the period defined by $t > t_{NNL}$.

If the impacts are calculated using a weighted counterfactual that, in addition to the background decline counterfactual, includes potential developments, the magnitude of the development impact is decreased (Fig. 2 (c)), the magnitude of the offset impact is increased (Fig. 2 (d)), and the net impact is increased (Fig. 2 (e)), compared to the impacts relative to the background decline counterfactual. The development-offset pair therefore delivers a net gain prior to t_{NNL}, i.e. to achieve the same net impact as the net impact relative to the background decline counterfactual the offset requirements need to be decreased. If the impact is calculated using counterfactuals using a weighted counterfactual that, in addition to the background decline counterfactual, includes potential offsets, the magnitude of the development impact is increased, the magnitude of the offset impact is decreased, and the net impact is decreased (Fig. 2 (c)-(e)). Calculating the impact relative to a weighted counterfactual that includes potential offsets results in smaller gains due to avoid gains from other offsets, and in this case the system does not achieve NNL, i.e. the offset requirements therefore need to be increased. The net impact relative to the weighted counterfactual (shown in Fig 2 (c)) must lie between the bounds imposed by the weighted potential impact including offsets and the weighted potential impact including developments. Whether the net impact relative to the weighted counterfactual is greater or less than the net impact relative to the background decline counterfactual is dependent on the probabilities of the potential states and the characteristics of the ecological dynamics of the development and offset.

A sensitivity test on the impacts relative to a background counterfactual that includes potential developments, potential offsets, and all states, for declining, stable, and improving, development and offset site states is provided in the Supplementary Information (Section S4, Fig. S1-3). The sensitivity analysis shows that including potential developments in the impact calculations resulted in the decrease of the offset requirements to achieve NNL for a particular development, regardless of whether declining, stable, or improving ecological states were assumed. Including potential offsets in the impact calculations increased the offset requirements to achieve NNL for a particular development under all assumptions of ecological change. Including both potential developments and offsets in the counterfactual resulted in an increasing impact where the offset and development sites were both improving, a decreasing impact where both sites were in decline, and a result between these bounds when one site was improving and the other declining.

3.2 Perverse consequences when separating offset and development regions

Constraining offsets to occur within a strategically selected region in compensation for development zoned to occur elsewhere is increasingly common in spatially strategic development planning (Kiesecker et al., 2009; Kujala et al., 2015; Whitehead et al., 2017). In these cases, the development occurs within a specified development region where offsetting does not occur, and vice versa. The separation of the development and offset sites into disjoint regions has implications for the selection of the counterfactuals used in the impact assessments, as the offset region has no development occurring in it, and therefore a zero probability of any site being cleared, and similarly development has a zero probability of any site being offset. The counterfactuals for sites within the development/offset region are therefore restricted to either the background decline state, or a set of states where the site would be subsequently developed/offset respectively. An example set of potential states for sites in the development and offset zones are shown in Fig. 3 (a) and (b) respectively.

A weighted counterfactual for sites in the development and offset regions can be obtained via Eq. 9, where the probabilities of the potential offsets/developments, $P_O(t_m)$/ $P_D(t_m)$, are set to zero depending on whether the site is in the development/offset region. The separation of the development and offsets results in a decrease in the expected loss for sites in the development zone and a decrease in the expected gains for all sites in the offset region. The magnitude of the offset and development impacts are therefore both reduced compared to their impacts relative to the background counterfactual. The change in the net impact is dependent on both the probabilities of each potential state and the background ecological dynamics for each site.

Fig. 3 (a) also shows the case where all sites within the separated development region are developed, under the assumption that each site is equally likely to be developed. Critically, as shown in Fig. 3 (c) (black line), the separation of the development and offset regions ultimately results in a zero impact for all sites in the development region, as all sites are to be developed. Therefore the net development-offset impact ultimately attains NNL regardless of how small the offset gains are. An example set of potential states and the associated weighted counterfactual for a site within an offset region is shown in Fig. 3 (b), under the assumption that the offset states have the form in Eq. 3 ($\alpha = 0.05$) and that all states are equally likely. This results in a weighted counterfactual that approaches the state of the offset site (Fig 3(b)). The offset impact relative to the weighted counterfactual, shown in Fig. 3 (c), is therefore small and positive. When the offsets and developments are separated, the impact relative to counterfactuals that include potential developments and potential offsets therefore guarantees a system that inevitably attains NNL. Including these states in the impact calculations therefore results in a system where the 'offsets' are simply a mechanism for funding the implementation of a spatial conservation plan (Kiesecker et al., 2009; Whitehead et al., 2017), which we argue is a use removed from the original intent of offsets (Maron et al., 2016a).

4. Discussion

We have presented a generalized framework that can be used to evaluate the biodiversity impact attributable to developments and offsets. To simplify our arguments we have limited the discussion to a single component measure of "biodiversity" that can be a range of ecological metrics such as species population abundance, or aggregate measures such as vegetation cover or vegetation condition. Although we recognize this simplification, the arguments presented here also apply to the case where a multiple component metric is used to evaluate the biodiversity value of the sites.

In order to measure the change attributable to the development and offset it is necessary to estimate what would have happened in the absence of these interventions. Using a hypothetical model, we have shown that there can be many potential states that could be used as counterfactuals in the development and offset impacts. We have also shown that the choice of counterfactual can yield profoundly different, and sometime non-sensible impact calculations for both the development and the offset. In real world cases, such as those where the offsets target a threatened species population (to compensate for losses in that population from development), the assumptions regarding what counterfactuals should be used in the impact calculations can be critical for the survival of the species—especially if they are implemented over multiple developments and offsets.

The framework we have presented allows the impact of the development or offset to be calculated relative to a particular potential state, or relative to a group of states via a weighted counterfactual, enabling an impact evaluation that can incorporate multiple processes and uncertainties in both the development and offset impact calculations. However, to use this approach it is necessary to assign a probability to each counterfactual and in many real-world cases this information is highly uncertain and may often be unavailable. In these cases, the framework proposed in this paper can be used to obtain the bounds in which the weighted counterfactual is likely to lie, given an explicit set of assumptions regarding the counterfactuals used to determine the weighted counterfactual (Miller et al., 2015). If the probabilities of the counterfactuals cannot be estimated but are given instead as plausible ranges, Eq. 13 can be used to obtain a weighted band where the exclusion of the potential offset counterfactuals yields a lower bound, and the exclusion of the potential development counterfactuals yields an upper bound.

To ensure the impacts of the development and offset are commensurate and can be summed to assess the net impact (and subsequently determine whether the system has achieved no-net-loss), consistent sets of assumptions need to be applied in estimating counterfactuals for each development-offset pair, e.g. if the gains due to avoided development are included in the offset impact calculation, then avoided development also needs to be included the development impact calculation when there is a plausible risk that a subsequent development could occur on both sites. Where these potential losses also require potential offsets, we have shown that in order to be logically consistent, a set of potential offset counterfactuals also needs to be included in both the offset and development impacts. If these potential developments and/or potential offsets are included in either the development or the offset impact calculation (but not both), the impacts cannot be summed and any subsequent evaluation of No Net Loss is therefore invalidated.

We found that when the impact calculation included potential developments, the offset impact was increased and the development impact was decreased, compared to the impacts calculated relative to the background counterfactuals. The offset requirements for a given development were therefore reduced compared to the offset requirements when using the background counterfactual. However, if the impact is calculated using counterfactuals that include potential offsets, the offset requirements were increased. These findings were independent of assumptions regarding whether the background counterfactual was static, declining or increasing (see Supplementary Information S4).

At larger, strategic scales, where the developments and offsets are directed into pre-determined and separate regions, we have demonstrated that when the losses due to potential development are included in the development impact calculations, the impact is decreased for all development sites and ultimately results in zero development impact if all sites are earmarked for future development. Similarly, when potential offsets are used in the counterfactual to determine offset impact, the gains are reduced for all offset sites and ultimately approach zero when all sites within the offset region are used to offset a development in the development region. To address this issue, we argue that the assessment of strategically directed developments and associated offsets into spatially separated regions requires that the development and offset impacts are considered as cumulative sets. In this case the entire region set aside for development should be regarded as a single "site" where the biodiversity is lost over time as development occurs. Similarly, the set of strategically planned offsets also should be considered as a single cumulative offset "site". There are no potential development or potential offset states in this two-site system and subsequently there are no counterfactuals for the development and offset regions that include potential developments or offsets. We therefore assert that strategic planning at larger scales requires that development and offset impacts should be assessed relative to counterfactuals that do not include losses that themselves generate offsets.

We conclude by arguing that only processes that are independent of the development and offsetting process should be included in the counterfactuals used in the impact calculations (Maron et al., 2018). These might include 'background' biodiversity decline or improvement, but also local scale events such as illegal clearing (Gordon, 2015), or the impacts of natural events such as fires. If, in the absence of the interventions associated with the offset policy, there is an alternate or additional conservation policy in place that is likely to yield biodiversity gains, for example the implementation of new conservation areas (Maron, 2015; Maron et al., 2016a), the expected biodiversity states resulting from these policies should also be included in the counterfactuals. The framework proposed in this paper allows these processes and their associated uncertainties to be included in the impact calculations.

5. Conclusion

We presented a framework that enables a transparent and consistent impact evaluation of both the development and its associated offsets at the site scale and at larger strategic scales. The framework was used in conjunction with a hypothetical model to illustrate a number of issues that can arise in the impact calculations, and we have shown why these pitfalls occur, and how to avoid them. The framework can be used to inform offset policy by providing a logical and transparent way to deal with multiple counterfactuals in both the development and offset impact calculations.

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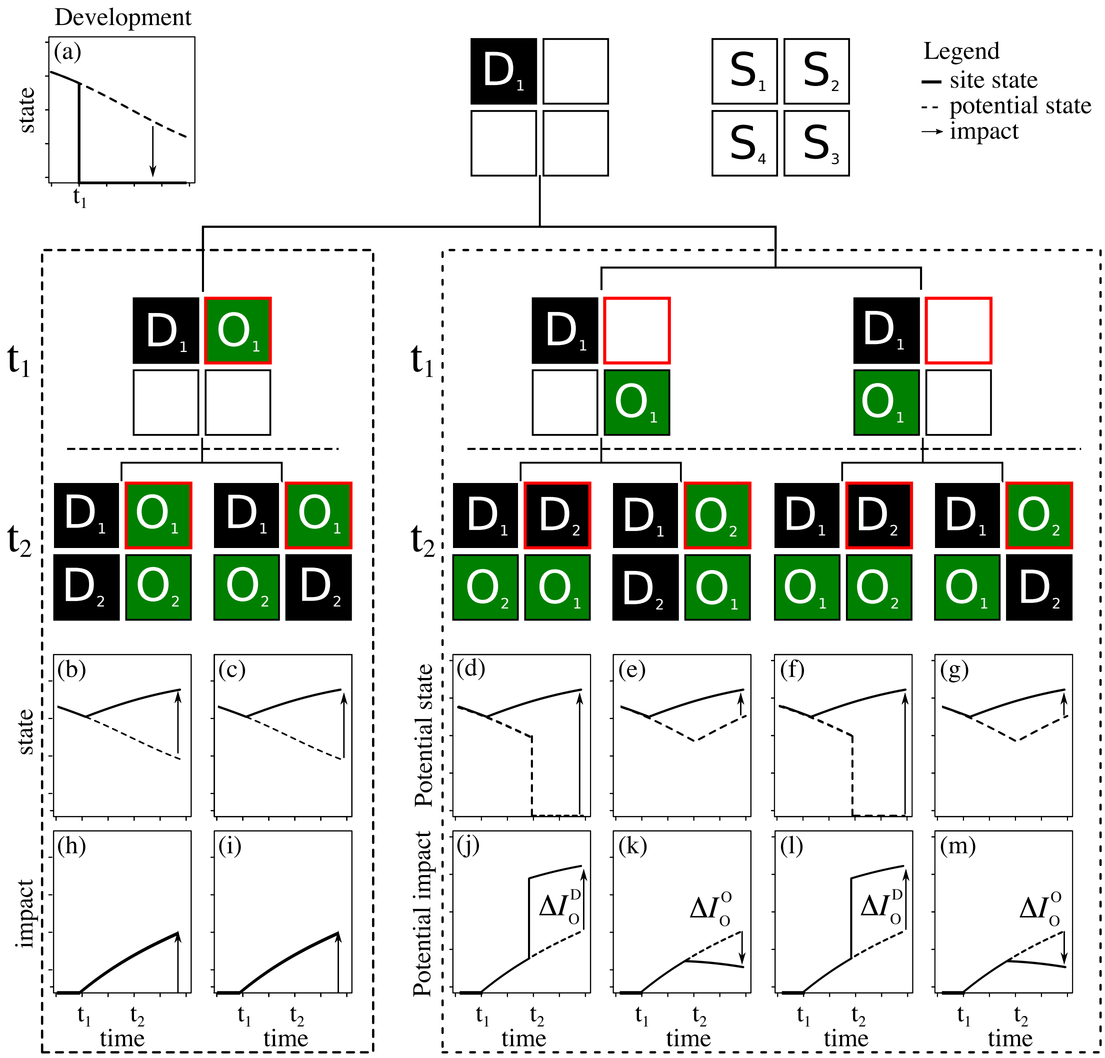

Figure 1. A hypothetical 4-site offset model. (a) A site, S_1, with a declining biodiversity state is developed via an initial development, D_1, at time, t_1, resulting in the total loss of biodiversity at the development site for the period $t > t_1$. The development, D_1, generates a restoration offset, O_1, that is implemented on S_2 at time t_1. The subsequent development, D_2, and its offset, O_2, can occur in either sites S_3 or S_4, resulting in the two system arrangements shown in (b) and (c). The impact of the offset, O_1, on the site, S_2, relative to the background decline counterfactual is positive and increases over time as shown in (h) and (i). The counterfactual states for the site, S_2, that could occur if the offset, O_1, did not occur on S_2, are shown as the dashed lines in the potential states panel in (d) - (g). Measuring the impact of the offset, O_1, on the site, S_2, relative to the counterfactual states in (d) – (g) yields the series of potential impacts and changes in the potential impacts denoted by ΔI_O^O, ΔI_O^D, in (j) – (m).

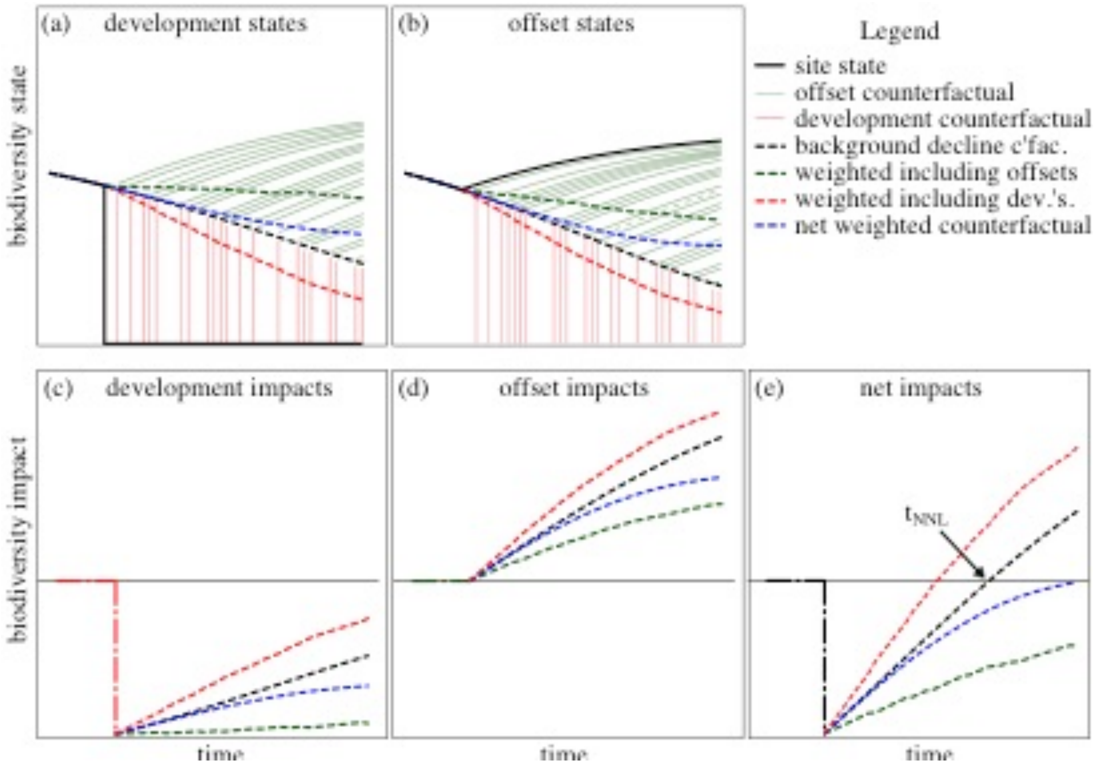

Figure 2: A hypothetical impact evaluation in a system with many developments and offsets. (a) The development site state (solid black line), the background decline counterfactual (black dashed line), and the set of potential development counterfactuals (thin red lines) and potential offset counterfactuals (thin green lines), result in a weighted counterfactual including developments (bold red dashed line), a weighted counterfactual including offsets (bold green dashed line), and the net weighted counterfactual (blue dashed line). The offset site state and corresponding weighted potential states for an offset site are shown in (b). The development impacts relative to each of the weighted counterfactuals in (a) are shown in (c). The corresponding offset impacts are shown in (d). The net impacts corresponding to each of the offset and development impacts are shown in (e). The net impact relative to the background counterfactual (dashed black line) shows that the offset gains relative to the background counterfactual are equal to the development losses at the time, t_{NNL}, when no-net-loss occurs, with the offset attaining a net gain subsequent to this time. Calculating the impact relative to either of the weighted counterfactuals yields an increase or decrease in the time required to achieve NNL, as shown in (e).

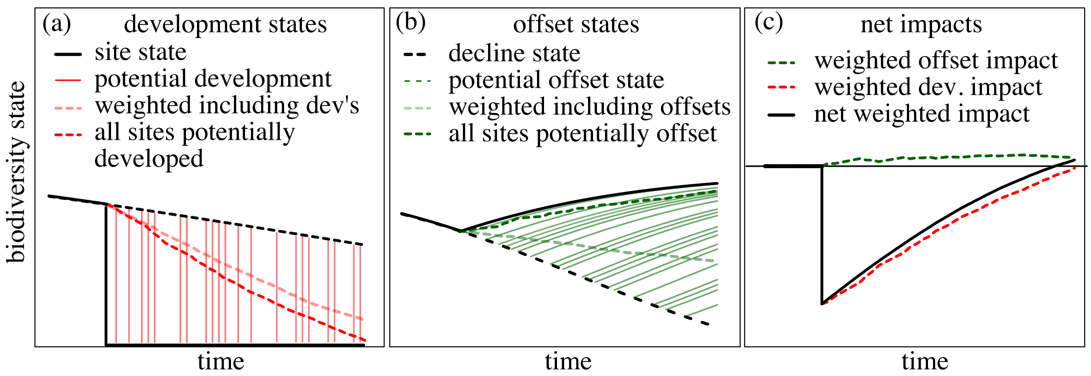

Figure 3: A hypothetical impact evaluation in a spatially strategic offset program where the development and offset regions are separated. The separation of the development and offset regions results in only potential development and background decline states for all development site, and only potential offset states and background decline states for the offset sites, shown in (a) and (b) respectively. The weighted potential state for the development site (light red dashed line) is therefore decreased, resulting in a decrease in the magnitude of the development impact compared to the impact relative to the background counterfactual (black dashed line). The weighted potential state for the offset site (light green dashed line) is increased, resulting in a decrease in the magnitude of the offset impact. The net impact is therefore decreased compared to the net impact relative to the background counterfactual (black dashed line). In the case where all sites in the development region are developed, the weighted potential state decreases to zero shown in (a) (bold red dashed line). The restoration of all sites in the offset region results in a potential state that approaches the offset state as shown in (b) (bold green dashed line). The resulting development, offset and net impacts relative to the weighted counterfactual are shown in (c).

Supplementary Information

S1.1 Impacts relative to background counterfactuals

The impact of the development, D_1, in the 4-site model, relative to a declining background counterfactual is shown in Fig. S1 (a), yielding a negative impact that reduces in magnitude for $t > t_1$. The impact of the offset, O_1, relative to a declining background counterfactual is shown in Fig. S1 (b), yielding a positive, monotonic increasing impact for $t > t_1$. The development and offset impact relative to background counterfactuals yields the net impact shown in Fig. S1 (c). In this case the net impact remains negative for the period defined by $t > t_1$, gradually reducing in magnitude according to the rates determined by the background decline counterfactuals for the development and offset, but does not achieve NNL for the period shown.

S1.2 The development impact relative to potential state counterfactuals

The impact of the development, D_1, relative to a potential development counterfactual of the type in Fig. 1 (c) and (e), is shown in Fig. S1 (d). The impact relative to a counterfactual including potential development results in a development impact of zero for the period defined by $t > t_2$ and subsequently there is no offset mitigation required for this period. The zero-development impact is independent of the function used to describe the background development counterfactual. The development impact relative to a potential development counterfactual yields a decrease in the magnitude of the impact by ΔI_D^D, compared to the loss relative to the background counterfactual. This decrease applies to all development impacts relative to a potential development counterfactual.

The impact of D_1 relative to a potential offset counterfactual of the type in Fig. 1 (e) and (g), is shown in Fig. S1 (g). The development impact relative to a potential offset counterfactual yields an increase the magnitude of the impact by ΔI_D^O, compared to the development impact relative to the background counterfactual. Provided the potential restoration offset would yield a gain relative to the background counterfactual this increase applies to all development impacts relative to a potential offset counterfactual.

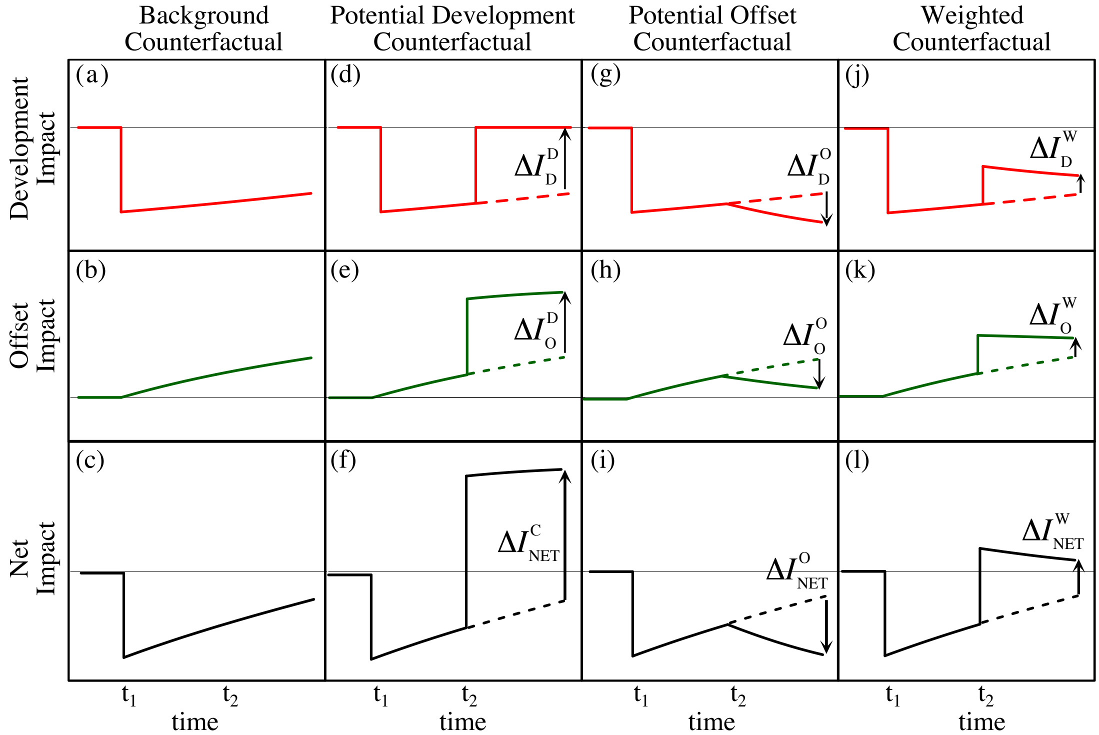

Figure S1. The impacts for the offset, development and net impacts for the site S_2 in the 4-site model, calculated using a series of counterfactuals that arise in the absence of the offset and development interventions. The offset impact relative to a background decline counterfactual, a counterfactual including decline and potential development, a counterfactual including decline and potential offset restoration, and a weighted counterfactual that combines all three counterfactual types is shown in (a)-(d) respectively. The corresponding impacts for the development site are shown in (e) – (h). The net impacts of both the development and offsets sites are shown in (i) – (l), respectively, yielding the gains or losses in the net impact of ΔI_c, ΔI_O, and ΔI_W relative to the net impact calculated using a background decline counterfactual (i).

The impact of D_1 relative to a weighted counterfactual, with the assumption of equal likelihood for potential development and potential offset states, is shown in Fig. S1 (j). The change, ΔI_D^W, is dependent on the relative probabilities and magnitudes of the potential development and offsets states. In the example presented here this change is a small increase, ΔI_D^W, in the calculated impact compared to the offset impact relative to the background counterfactual.

S1.3 The offset impact relative to potential state counterfactuals

The impact of the offset, O_1, relative to a potential development counterfactual is shown in Fig. S1 (e). The offset impact relative to a potential development counterfactual yields the gain, ΔI_O^D, compared to the gains relative to the background counterfactual shown in Fig. S1 (a). This additional gain due to avoided loss applies to all offset impacts relative to a potential development counterfactual.

The offset impact relative to a potential offset counterfactual is shown in Fig. S1 (h). The offset impact relative to a potential offset counterfactual yields the loss, ΔI_O^O, in the calculated offset impact compared to the impact relative to the background counterfactual. The reduction in the offset gains applies to all offset impacts relative to a potential offset counterfactual, with the proviso that the potential offset yields gains relative to the background counterfactual.

The offset impact relative to a weighted counterfactual, under the assumption of equal likelihood for the counterfactuals corresponding to potential development and potential offset states in Fig. S1 (e) and Fig. S1 (h), is shown in Fig. S1 (k). The offset impact relative to a weighted counterfactual yields a change, ΔI_O^W, that is dependent on the relative probabilities and magnitude of the potential development and offset states. In the example presented here this change is a small increase, ΔI_O^W, in the calculated impact compared to the offset impact relative to the background counterfactual.

S1.4 The net impact relative to potential state counterfactuals

The net impact for the development and offset impacts relative to the potential development counterfactuals in Fig. S1 (d), and (e) respectively, is shown in Fig. S1 (f). Including the potential development states into the impact calculation yields an increase in the evaluated net impact of the offset and development, ΔI_{NET}^D, compared to the impact calculated relative to the background decline counterfactual. This increase in the net impact applies to all development and offset impacts relative to a potential development counterfactual. It also implies a corresponding reduction in the offset activities required to achieve the same net impact. In the example presented in

Fig. S1 (f) this increase results in NNL occurring at $t = t_2$, and a net gain impact evaluation relative to the potential development counterfactual for the period subsequent to this.

The net impact for the development and offset impacts relative to potential offset counterfactuals in Fig. S1 (g), and (h) respectively, is shown in Fig. S1 (i). Calculating the offset and development impact relative to potential offset states yields the decrease in the net impact, by ΔI_{NET}^{D}, shown in Fig. S1 (i). The reduction in the net impact applies to all development and offset impacts relative to a potential offset counterfactual, provided that the potential offsets would yield an improvement relative to the background counterfactuals. The reduction in the net impact implies a corresponding increase in the offset activities required to achieve NNL for a given development impact when compared to the impact relative to the background decline counterfactual.

The offset, development, and net impact relative to weighted counterfactuals are shown in Fig. S1 (j), (k) and (l) respectively. Calculating the impact relative to the weighted counterfactual can yield an increase or decrease (compared impacts relative to the background counterfactual) that depends on the expected decline states, the expected restoration states, and the estimated probabilities of each of the potential states. In the example presented here the net impact relative to the weighted counterfactual yields a small increase in the magnitude of the net impact by ΔI_{NET}^{W}.

S2. Impacts in analytic form

S2.1 The development impact relative to potential state counterfactuals

The impact of the development, D_1, of the site, S_1, at time, t_1, relative to a potential development counterfactual, $I_D^D(t)$, is (from Eq. 1 and Eq. 4)

$$I_D^D(t) = B_D(t) - C_D^D(t) = \begin{cases} 0 & (t \le t_1) \\ -C_D(t) & (t_1 < t < t_2). \\ 0 & (t_2 \le t) \end{cases} \quad (14)$$

The impact of the development relative to a potential development counterfactual is therefore zero for the period defined by $t \ge t_2$. The development impact relative to a potential development counterfactual yields a gain, ΔI_D^D, compared to the gains relative to the background counterfactual of (via Eq. 5 and Eq. 14)

$$\Delta I_D^D = I_D(t) - I_D^D(t) = \begin{cases} 0 & (t < t_2) \\ C_D(t) & (t \ge t_2) \end{cases}. \quad (15)$$

The development impact relative to a potential offset counterfactual, $I_D^O(t)$, is (from Eq. 1, Eq. 2 and Eq. 4)

$$I_D^O(t) = B_D(t) - C_D^O(t) = \begin{cases} 0 & (t \le t_1) \\ -C_D(t) & (t_1 < t < t_2) \\ -R_D(t) & (t_2 \le t) \end{cases}. \quad (16)$$

Given a monotonic increasing restoration function, $R_D(t)$, the development impact relative to a potential offset counterfactual is therefore negative and increases over time for the period defined by $t \ge t_2$. The development impact relative to a potential offset counterfactual yields a loss, ΔI_D^O, in the calculated impact compared to the impact relative to the background counterfactual of (via Eq. 5 and Eq. 16)

$$\Delta I_D^O = I_D(t) - I_D^O(t) = \begin{cases} 0 & (t < t_2) \\ C_D(t) - R_D(t) & (t \ge t_2) \end{cases}. \quad (17)$$

The development impact relative to the weighted counterfactual is, via Eq. 1, Eq. 4, and Eq. 9,

$$I_D^W(t) = B_D(t) - C_D^W(t) = \begin{cases} 0 & (t \le t_1) \\ -C_D(t) & (t_1 < t < t_2), \\ -(1-p) \cdot R_D(t) & (t_2 \le t) \end{cases} \tag{18}$$

where p is the probability that in the absence of the development D_1, of the site, S_1, a potential development state subsequently occurs on that site. The development impact relative to a weighted counterfactual yields an increase or decrease increase, ΔI_D^W, in the calculated impact compared to the offset impact relative to the background counterfactual of (via Eq. 5 and Eq. 18)

$$\Delta I_D^W = I_D(t) - I_O^W(t) = \begin{cases} 0 & (t < t_2) \\ (2p-1) \cdot C_D(t) - p \cdot R_D(t) & (t \ge t_2) \end{cases}. \tag{19}$$

S2.2 The offset impact relative to potential state counterfactuals

The impact of the offset, O_1, on the site, S_2, relative to a potential development counterfactual, $C_O^D(t)$ is, via Eq. 1, Eq. 2, and Eq. 4,

$$I_O^D(t) = B_O(t) - C_O^D(t) = \begin{cases} 0 & (t \le t_1) \\ R_O(t) - C_O(t) & (t_1 < t < t_2), \\ R_O(t) & (t \ge t_2) \end{cases} \tag{20}$$

where t_2 is the time of the subsequent potential development. The offset impact relative to a potential development counterfactual yields a gain, ΔI_O^D, compared to the gains relative to the background counterfactual of (via Eq. 6 and Eq. 20)

$$\Delta I_O^D = I_O(t) - I_O^D(t)$$
$$= \begin{cases} 0 & (t < t_2) \\ C_O(t) & (t \geq t_2) \end{cases} . \tag{21}$$

The offset impact relative to a potential offset counterfactual, $I_O^O(t)$, where the development D_2, at an alternate site, caused the site, S_2, to be offset at time, t_2, is, from Eq. 2 and Eq. 4,

$$I_O^O(t) = B_O(t) - C_O^O(t)$$
$$= \begin{cases} 0 & (t \leq t_1) \\ R_1(t) - C_O(t) & (t_1 < t < t_2), \\ R_1(t) - R_2(t) & (t_2 \leq t) \end{cases} \tag{22}$$

where $R_1(t)$ describes the restored state and $R_2(t)$ describes the potential restored state associated with the offset O_2. The offset impact relative to a potential offset counterfactual yields a loss, ΔI_O^O, in the calculated offset impact compared to the impact relative to the background counterfactual of (via Eq. 6 and Eq. 22)

$$\Delta I_O^O = I_O(t) - I_O^O(t)$$
$$= \begin{cases} 0 & (t < t_2) \\ C_O(t) - R_2(t) & (t \geq t_2) \end{cases} . \tag{23}$$

The impact of the offset, O_1, on the site, S_2, relative to a weighted counterfactual is, from Eq. 2, and Eq. 4 and Eq. 9,

$$I_O^W(t) = B_O(t) - C_O^W(t)$$
$$= p \cdot I_O^D(t) + (1-p) \cdot I_O^O(t)$$
$$= \begin{cases} 0 & (t \leq t_1) \\ R_1(t) - C_O(t) & (t_1 < t < t_2). \\ R_1(t) - (1-p) \cdot R_2(t) & (t_2 \leq t) \end{cases} \quad (24)$$

The offset impact relative to a weighted counterfactual yields a change, ΔI_O^W, in the calculated impact compared to the offset impact relative to the background counterfactual of (via Eq. 6 and Eq. 24)

$$\Delta I_O^W = I_O(t) - I_O^W(t)$$
$$= \begin{cases} 0 & (t < t_2) \\ C_O(t) - (1-p) \cdot R_2(t) & (t \geq t_2) \end{cases}. \quad (25)$$

S2.3 The net impact relative to potential state counterfactuals

The net impact of the development-offset pair relative to potential development counterfactuals, $I_{NET}^D(t)$, can be calculated from Eq. 7, Eq. 14 and Eq. 20

$$I_{NET}^D(t) = \begin{cases} 0 & (t \leq t_1) \\ R_1(t) - C_O(t) - C_D(t) & (t_1 < t < t_2). \\ R_1(t) & (t \geq t_2) \end{cases} \quad (26)$$

Including the potential development states into the impact calculation yields an increase in the evaluated net impact of the offset and development, ΔI_{NET}^D, compared to the impact calculated relative to the background decline counterfactual of

$$\Delta I_{NET}^D = \begin{cases} 0 & (t < t_2) \\ C_O(t) + C_D(t) & (t \geq t_2). \end{cases} \quad (27)$$

The net impact relative to a potential offset counterfactual, $I_{NET}^{O}(t)$, is, from Eq. 7, Eq. 16 and Eq. 22

$$I_{NET}^{O}(t) = I_{O}^{O}(t) + I_{D}^{O}(t) \tag{28}$$
$$= \begin{cases} 0 & (t \leq t_1) \\ R_1(t) - C_O(t) - C_D(t) & (t_1 < t < t_2) \\ R_1(t) - R_2(t) - R_D(t) & (t \geq t_2) \end{cases}$$

Calculating the offset and development impact relative to potential offset counterfactuals yields a decrease in the net impact of

$$\Delta I_{NET}^{O} = \begin{cases} 0 & (t < t_2) \\ C_O(t) + C_D(t) - R_2(t) - R_D(t) & (t \geq t_2). \end{cases} \tag{29}$$

The net impact relative to the weighted counterfactual is, from Eq. 7, Eq. 18 and Eq. 24

$$I_{NET}^{W}(t) = I_{O}^{W}(t) + I_{D}^{W}(t) \tag{30}$$
$$= \begin{cases} 0 & (t \leq t_1) \\ R_1(t) - C_O(t) - C_D(t) & (t_1 < t < t_2) \\ R_1(t) - p \cdot R_2(t) - (1-p) \cdot R_D(t) & (t \geq t_2). \end{cases}$$

The change in the net impact relative to weighted counterfactuals compared to the net impact relative to the background counterfactual is

$$\Delta I_{NET}^{W} = \begin{cases} 0 & (t < t_2) \\ C_O(t) + C_D(t) - p \cdot R_O(t) - (1-p) \cdot R_D(t) & (t \geq t_2) \end{cases} \tag{31}$$

The impacts relative to the weighted counterfactual can yield an increase or decrease in the net impact compared to the impact relative to the background decline counterfactual depending on the expected decline states, $C_O(t)$ and $C_D(t)$, and the expected restoration states, $R_O(t)$ and $R_D(t)$.

S3. Sensitivity test of the development, offset and net impacts relative to counterfactuals including potential states.

We modeled the ecological states of a development and offset site using Eq. 3, where the parameters, K, and A in were set to yield a minimum (asymptotic) value of 0 and a maximum (asymptotic) value of 100 for both sites, and an initial ecological value of 40 for the offset site and 50 for the development site. The parameter, α, was tested over the range (-0.1, 0.9) in steps of 0.01, for both sites, yielding the sets of ecological state curves with declining, stable, and improving states for both the development and offset sites shown in Fig. S2 (a) and (b) respectively. The restoration rate was set to 0.1 for all states and potential states, i.e. it is assumed a potential restoration yields a higher value than the potential background states. The weighted potential states were determined under the assumption that the development and offset sites are part of a larger offset program where 250 sites are developed and each development is offset by a single offset site, in a region with 1000 sites in total. The weighted potential states including clearing were determined using Eq. 9 for the potential background states and are shown in Fig. S2 (a) and (b) for the development and offset sites respectively. The impacts corresponding to these potential states are shown in Fig. S2 (c) and (d). The net impact relative to the background counterfactual including clearing was determined for all combinations of the development and offset impacts and compared with the corresponding net impacts relative to the background counterfactual.

Although there was considerable variation in the magnitude of the calculated impacts (the magnitude of the impacts is dependent on the particular parameters used in the logistic equations for the development-offset pair), including potential developments yielded a decrease in the development impact, an increase in the offset impact, and an increase in the net impact (Fig. S2 (e)) for all assumptions of declining, stable, or improving ecological states. The required offset gains for a particular development were therefore reduced for all assumptions of ecological change. The greatest increase in the net impact occurred when the ecological states of the development and offset sites were improving, the least increase when the sites were in decline, and an intermediate increase when the one site was improving and another in decline.

The potential states including offsets were determined for the sets of declining, stable, and improving ecological states for both the development and offset sites and are shown in shown in Fig. S3 (a) and (b) respectively. Including potential offsets in the impact calculations yielded an increase in the development impact (Fig. S3 (c)), a decrease in the calculated offset impact (Fig. S3 (d)), and subsequently a decrease in the net impact (Fig. S3 (e)), i.e. the offset requirements for a particular development were increased for all assumptions of ecological change. The greatest decrease in the net impact occurred when the ecological states of the development and offset sites were in decline, the least decrease when the sites were both improving, and an intermediate decrease when the one site was improving and another in decline.

The net weighted potential states including potential developments and potential offsets were determined for declining, stable, and improving ecological states for both the development and offset sites, and are shown in shown in Fig. S4 (a) and (b) respectively. Using both sets of potential states yielded a decrease in development impact for sites that were improving and an increase in the impact for sits that were declining. The impact in the offset sites yielded a decrease in the offset impact for sites that were improving, and an increase in the offset impact for sites that were in decline (Fig. S4(d)). The change in the net impact was positive where the sites were both improving, negative where both sites were in decline, and between the bounds associated with either of these conditions when one site was improving and the other declining (Fig. S4 (e)).

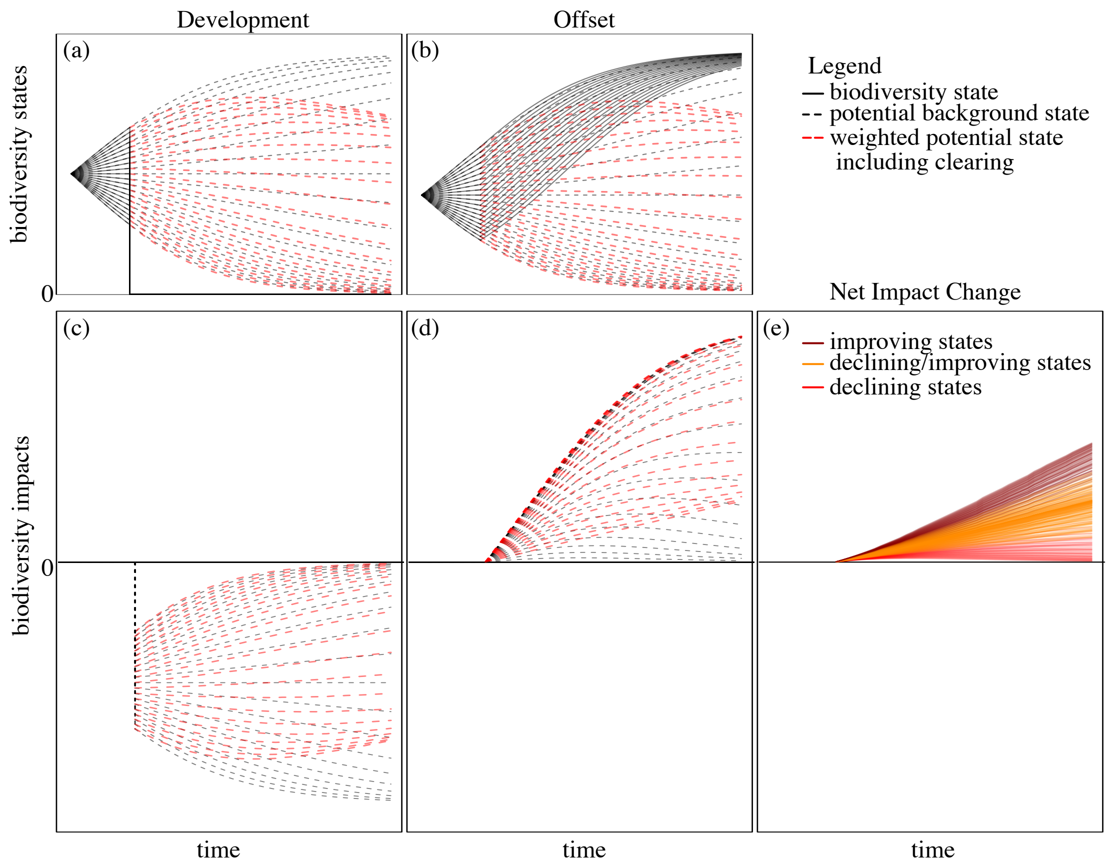

Figure S2: Sensitivity test for the impact relative to counterfactuals including potential developments for development and offset sites with declining, stable and improving ecological states. (a) A set of development site states (solid black lines), where a development at a time, t_1, results in the total loss of biodiversity for all states. These states are associated with a set of background counterfactuals (black dashed lines) and a set of weighted counterfactuals including potential developments (red dashed lines). The offset site states, background counterfactuals, and corresponding weighted potential states including clearing are shown in (b). The development impacts relative each of the weighted counterfactuals in (a) are shown in (c). The corresponding offset impacts are shown in (d). The increase in the net impacts compared to the net impacts relative to the background counterfactuals for all combinations of improving, stable, and declining states are shown in (e), yielding a positive change for all combinations when using the weighted counterfactual including potential developments.

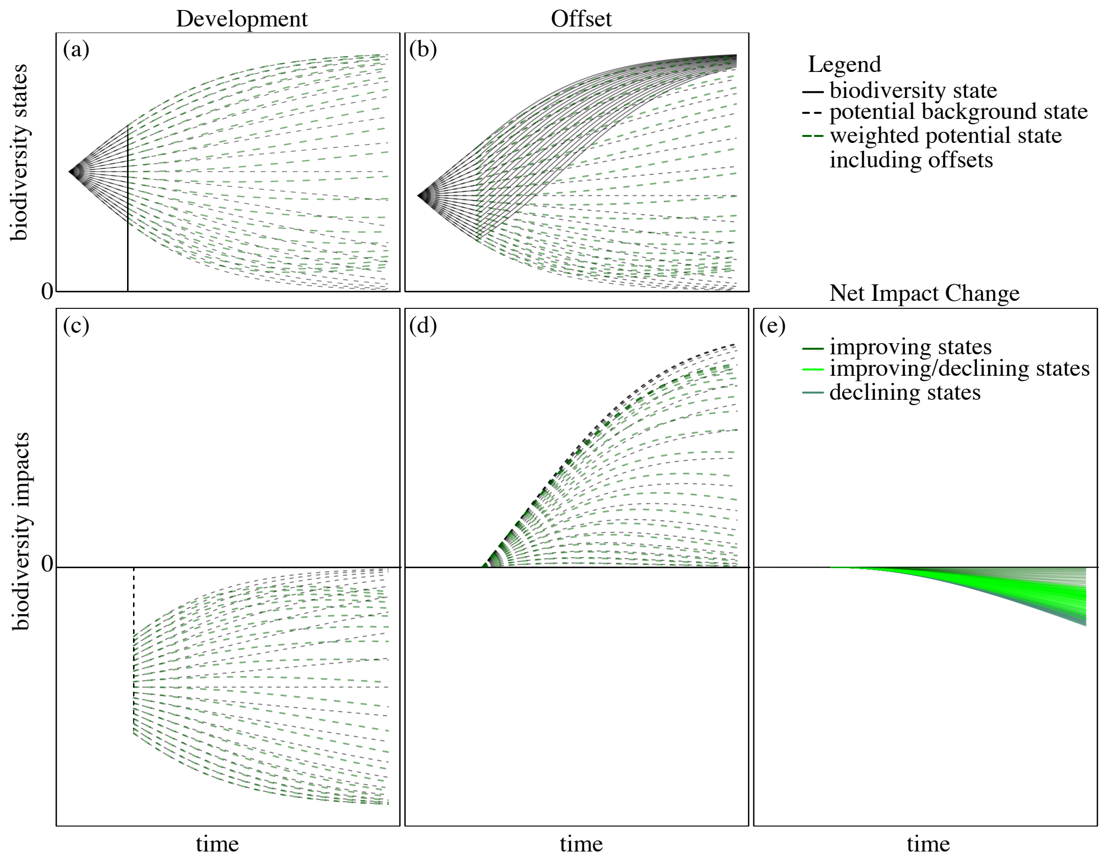

Figure S3: Sensitivity test for the impact relative to potential offset counterfactuals for development and offset sites with declining, stable and improving ecological states. The development site states (solid black lines), the background decline counterfactuals (black dashed lines) associated with these states, and the weighted counterfactuals including offsets (green dashed lines) associated with these states are shown in (a). The offset site states and corresponding weighted potential states for an offset site are shown in (b). The development impacts relative each of the weighted counterfactuals in (a) are shown in (c). The corresponding offset impacts are shown in (d). The increase in the net impacts compared to the net impacts relative to the background counterfactuals for all combinations of the states corresponding to each of the offset and development impacts are shown in (e), yielding a negative change for all combinations when using the weighted counterfactual including potential offsets.

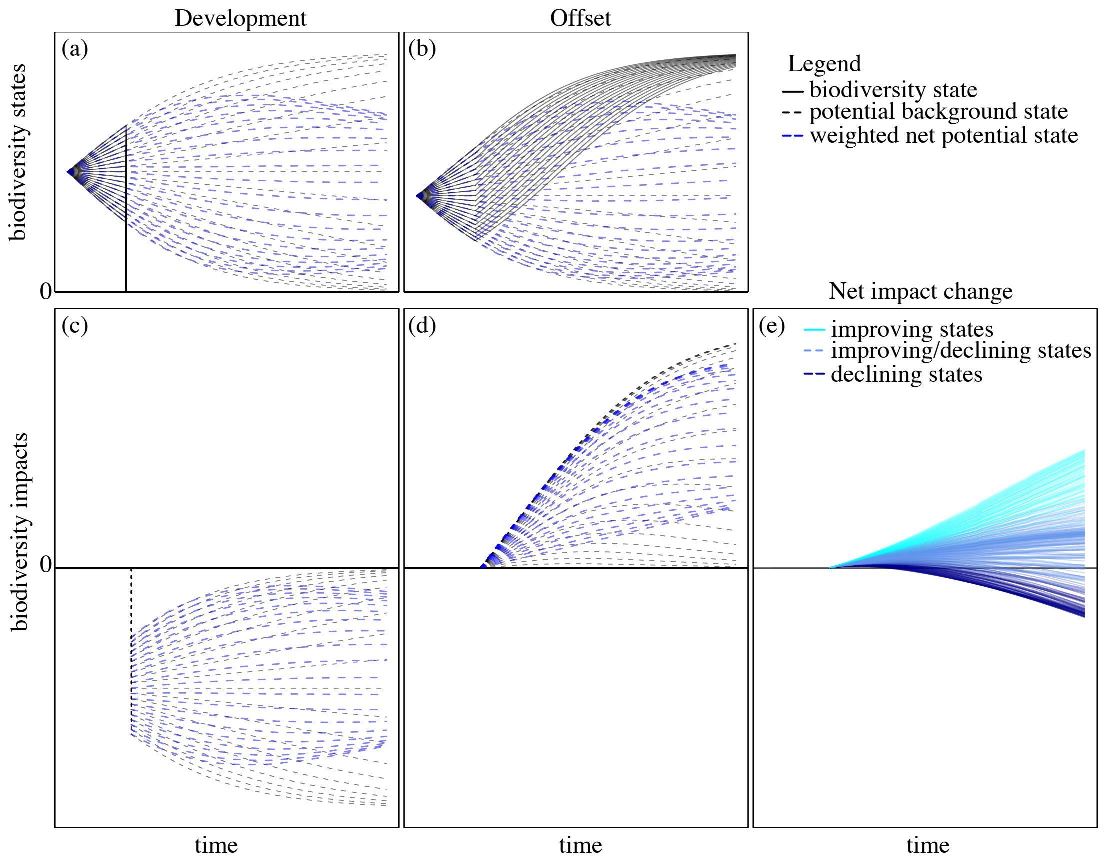

Figure S4: Sensitivity test for the impact relative to weighted counterfactual including potential offset and potential development counterfactuals for development and offset sites with declining, stable and improving ecological states. (a) The development site states (solid black lines), the background decline counterfactuals (black dashed lines), the weighted counterfactuals including offsets (blue dashed lines). The offset site states and corresponding weighted potential states for an offset site are shown in (b). The development impacts relative each of the weighted counterfactuals in (a) are shown in (c). The corresponding offset impacts are shown in (d). The increase in the net impacts compared to the net impacts relative to the background counterfactuals for all combinations of the states corresponding to each of the offset and development impacts are shown in (e), yielding a range of changes across all combinations when using the weighted counterfactual including potential offsets and potential developments.