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RESEARCH ARTICLE

How Much Compensation is Enough? A Framework for Incorporating Uncertainty and Time Discounting When Calculating Offset Ratios for Impacted Habitat

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Abstract

Biodiversity offset areas may compensate for ecological damage caused by human activity elsewhere. One way of determining the offset ratio, or the compensation area needed, is to divide the present conservation value of the development site by the predicted future conservation value of a compensation area of the same size. Matching mean expected utility in this way is deficient because it ignores uncertainty and time lags in the growth of conservation value in compensation areas. Instead, we propose an uncertainty analytic framework for calculating what we call robustly fair offset ratios, which guarantee a high enough probability of the exchange producing at least as much conservation value in the offset areas than is lost from the development site. In particular, we analyze how the fair offset ratio is influenced by uncertainty in the effectiveness of restoration action, correlation between success of different compensation areas, and time discounting. We find that very high offset ratios may be needed to guarantee a robustly fair exchange, compared to simply matching mean expected utilities. These results demonstrate that considerations of uncertainty, correlated success/failure, and time discounting should be included in the determination of the offset ratio to avoid a significant risk that the exchange is unfavorable for conservation in the long run. This is essential because the immediate loss is certain, whereas future gain is uncertain. The proposed framework is also applicable to the case when offset areas already hold conservation value and do not require restoration action, in which case uncertainty about the conservation outcome will be lower.

Key words: habitat banking, habitat equivalency analysis, information-gap decision theory, mitigation, no net loss principle, offsets, strong sustainability, time discounting, uncertainty analysis.

Introduction

Several countries have adopted policy to regulate the impact of economic development on natural habitats. After estimating the expected damage that a particular development project will do to existing habitat and associated species, a hierarchy of measures can be employed to alleviate the impact (Cuperus et al. 2001; ten Kate et al. 2004). The first step in this hierarchy aims at avoidance of the impact, e.g., by looking for alternative locations for development, where impact will be less severe. Once the development location is chosen, the second step concerns minimizing the impact. In the European context, this step is often referred to as mitigation, whereas in North America, the term mitigation often refers to the third step, the use of compensation measures for unavoidable damage to natural areas (Race & Fonseca 1996; ten Kate et al. 2004). Here, we use the term biodiversity offsets to indicate ecological compensation for unavoidable damage.

Biodiversity offsets involve the designation of compensation areas, which either hold significant conservation value already or where habitat creation, recreation, or restoration practices are carried out in order to balance for biodiversity loss elsewhere. Typically, loss is caused by direct anthropogenic action (urban expansion, etc.), but offsets could also be used to compensate for the slow degradation of biodiversity from present reserve areas (Sinclair et al. 1995). As ten Kate et al. (2004) emphasize in their review, quantitative guidelines for determining offset ratios and types are generally lacking. Typically, rules of thumb are used to describe offset requirements in terms of the location and habitat type; compensation areas near the development site and of a similar habitat type are preferred. Although the size of the affected areas is a quantitative measure, determining the conservation value of habitat remains difficult (ten Kate et al. 2004).

A similar concept, No Net Loss (NNL), has been developed for wetlands under the Fisheries Act in Canada and the Clean Water Act in the United States. Under these regulations, permits for development often require offsets

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to compensate for damaged wetlands. Harper and Quigley (2005) evaluate this approach for Canada (Harper & Quigley 2005; Quigley & Harper 2006*a*, 2006*b*). Quigley & Harper (2006*b*) report that although compensation requirements did determine required offset ratios to be on average 6.8:1 (area gained: area lost), the mean offset ratio that was actually implemented was only 1.5:1, resulting in 10 out of 16 cases not reaching NNL in terms of habitat productivity. Poor compliance to offset agreements was also found to be a problem in Australia by Gibbons and Lindenmayer (2007). The principle of NNL is similar to the concept of strong sustainability in capital theory, which requires that each form of capital, such as conservation value, is kept constant (Cowdy & Carbonell, 1999; Figge & Hahn 2004). A related concept, weak sustainability, allows that different forms of capital can be substituted for each other (Figge & Hahn 2004).

Habitat banking and Habitat Equivalency Analysis (HEA) are yet another two concepts used in the context of habitat compensation measures. Habitat banking, also referred to as "mitigation banking" or "conservation banking," aims at conservation practices which generate "biodiversity credits" that can be traded for later habitat destruction elsewhere by development practices (Bruggeman et al. 2005; Morris et al. 2006). An explicit feature of banking is that credits are generated before damage is undertaken. In contrast, with offsets, damage and credits are generated at best simultaneously. Due to inevitable delays in the growth of conservation value in restoration areas, credits can be realized after a substantial time delay (Morris et al. 2006).

HEA aims to compensate injured natural resources and has, in particular, been applied to coastal and marine habitats (National Oceanic and Atmospheric Administration 2000). Although HEA is widely applied in practice (particularly in the United States), very little has been published in peer-reviewed literature (Race & Fonseca 1996; Dunford et al. 2004). HEA involves quantitative measures to determine the amount of compensation required, potentially accounting for time delays in the process. Dunford et al. (2004) provide a thorough demonstration of the use of HEA in the context of oil spills. Framed in the context of conservation banking, Bruggeman et al. (2005) extended the concept of HEA to terrestrial habitats and coined the term Landscape Equivalency Analysis. They incorporate spatial and population genetic aspects quantitatively into the valuation of habitats and species.

In this study, we are interested in determining the offset ratio needed to achieve a fair exchange of areas. Fair could be defined in many ways. Most simply, one could use a criterion we call "matching mean expected utilities"; utility that is gained (eventually) from the compensation areas is estimated to exactly compensate for the immediate loss of utility from the development site. This criterion is deficient in that it ignores the time lag before the full value of compensation areas is realized, as well as uncertainty in the extent to which the expected conservation value at the compensation areas will be realized (Hilderbrand et al. 2005). Heuristically, matching mean expected utilities is like making a zero interest rate (biodiversity) loan to someone who is known to be unreliable and might pay back decades later.

We compare matching mean expected utility to a strategy that we call robustly fair offsets. We specify that compensation should be fair in the sense that net loss of conservation value is unlikely even when various uncertainties are accounted for. We investigate at a theoretical level what influence the following components have on the estimate of a fair offset ratio: (1) uncertainty in the amount of compensation gained; (2) correlation between (restoration) success of different compensation areas; and (3) time discounting. We develop a framework for the calculation of robustly fair offsets. Using a mathematically simple example, we demonstrate that assumptions about these components make a huge difference for the amount of compensation (offset ratio) that should be perceived as adequate.

Methods

The Conceptual Framework of Robustly Fair Offsets

Our goal of offsetting is consistent with NNL in the sense that present loss is compensated by future gains, accounting for uncertainty and time lags in the development of these gains. We specify that the probability of incurring net loss must be small, thereby ensuring what we call "robustly fair offsets." The uncertainty is a critical component when the aim is to avoid net loss due to unfavorable growth of conservation value at the restoration areas.

We assume three components of uncertainty. (1) Future value could be less than estimated, which could, e.g., represent the case that an area of forest develops fewer nesting holes than expected or that forest understory develops a community which is less species rich than expected. Outcome could be uncertain even when it is practically immediate, e.g., if compensation sites do not require restoration but the areas are poorly surveyed so that what is gained by the exchange is not accurately known. (2) Some feature of conservation value might completely fail to be established, e.g., a focal species may fail to colonize the area. (3) We also allow for the possibility that success and failure could be correlated between different restoration areas. The uncertainties in our analysis are most relevant where restoration action is applied at compensation areas. However, the proposed framework is equally applicable when compensation areas are such that they already hold substantial conservation value and some form of protection is applied rather than restoration action. In this case, uncertainties are smaller (or even zero), but the structure of the proposed calculations need not be changed.

We account for uncertainty by adopting a decision-theoretic approach to the calculation of offsets. If statistical models are available for the components above, one could use a statistical approach for identifying an offset ratio, which has, e.g., less than 5% chance of resulting in net loss. However, our formulation includes parameters, such as long-term success of restoration effort, for which it may be difficult to obtain reliable distributional information. In such a case, information-gap decision theory (Ben-Haim 2006; hereafter info-gap theory), which we employ here, provides a straightforward way of analyzing the influence of uncertainty on the offset ratio.

Time discounting (Carpenter et al. 2007) of the offset ratio is included because it is not fair to compensate immediate loss by hypothetical distant future gain. Presumably, the conversion of the development site would produce a relatively immediate economic return in the order of some percents per year. This revenue could plausibly be used for further environmentally harmful activity either directly or indirectly. On the other hand, conservation benefits arising from restoration effort may take a very long time to materialize fully, e.g., if one needs to wait for forest to grow. Consequently, we find it reasonable that the offset ratio should be calculated as a time-discounted weighted average across the planning frame. Omitting time discounting could place nature conservation efforts at an overall disadvantage.

These components have been noted in prior work: The outcome of restoration is often different from expected, for instance, due to existence of alternative equilibria and differences in ecological dynamics between degraded and less-impacted systems (Zedler & Callaway 1999; Folke et al. 2004; Suding et al. 2004; Hilderbrand et al. 2005). Following restoration, ecosystems can recover into different states from the same initial condition (Folke et al. 2004). Restoration action can fail despite the correct management action if, for instance, rainfall does not occur (Vesk & Dorrough 2006). Several authors note that there is uncertainty associated with the expected outcome of restoration (Cuperus et al. 2001; Bruggeman et al. 2005; Morris et al. 2006; Gibbons & Lindenmayer 2007) but do not explicitly account for it in their analyses. Keagy et al. (2005) investigate the feasibility of compensation for maintaining overall population abundance in the study area, when the compensation areas are of inferior quality compared to the lost habitat. Gibbons and Lindenmayer (2007) conclude that offsets will only contribute to NNL if (1) clearing is restricted to vegetation that is simplified enough so that its functions can be restored elsewhere; (2) any temporary loss in habitat between clearing and maturation of an offset does not represent significant risk to a species, population, or ecosystem process; and (3) offsets are substantial enough and they are complied to. HEA explicitly includes time discounting as an option (Dunford et al. 2004; Bruggeman et al. 2005). Morris et al. (2006) and Roach and Wade (2006) both mention that there is a time lag between impact and compensation, although they do not present methods that explicitly take that into account in analysis. Here we combine all these factors together into the same quantitative theoretical analysis.

Evaluating Offset Solutions Using an Uncertainty-Analytic Approach

We use info-gap theory (Ben-Haim 2006) to analyze the consequences of uncertainty for establishing a fair offset ratio. The main components of the info-gap theory are the goal (performance aspiration), the performance function, the nominal model, the uncertainty model, and the robustness function.

Our goal is to robustly achieve NNL. The nominal model is our best estimate for the expected conservation value in the development area and compensation areas (thick lines in Fig. 1). We indicate nominal models by $\tilde{V}_0(t)$ and $\tilde{V}_i(t)$ for conservation value at time t at the development area and compensation area i, respectively. The nominal model represents our best understanding of how conservation value will change in these areas over time. However, this information may be quite uncertain, which is modeled by the second central component of info-gap analysis, the uncertainty model (thin lines in Fig. 1). Note that instead of staying stable, conservation value at the development site could be declining, which would lead to smaller offset ratios.

The info-gap uncertainty model does not simply place bounds around the nominal estimate, as it might appear from Figure 1 because worst-case bounds are at best poorly known. Rather, the robustness of solution candidates are analyzed in terms of an uncertainty parameter, the horizon of uncertainty α. When this parameter is zero, it indicates full confidence in our nominal model and the nominal model is accepted as the true model. Higher values for α indicate less confidence in the

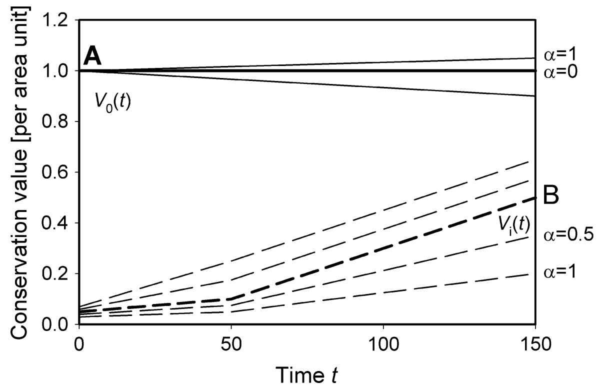

Figure 1. The assumed per unit area change in conservation value at the development area (thick solid line) and at the restoration areas (thick dashed line). Thin lines represent uncertainty bounds around these estimates; the relative uncertainty about the growth of conservation value at the restoration area is in our example higher compared to uncertainty about maintenance of value at the development site. The width of the uncertainty bounds would depend on the info-gap horizon of uncertainty parameter, α. When α is zero, the estimate (thick line) is taken as certain. With increasing α, the range of values possible for conservation value widens. Points A and B are used when calculating a naïve offset ratio based on mean expected value. Note that the conservation value of the development site is our estimate of what it would be if it was not developed. We assume that as a consequence of development, all conservation value is lost.

nominal model: the true model is somewhere within an expanding bound around the nominal model. In our example of Figure 1, the uncertainty model is represented by the thin lines around the nominal model. When $\alpha = 0$, the thick line is taken as the truth, and increasing α implies expanding bounds of possible outcome. Importantly, different areas and restoration actions could have different nominal estimates as well as different levels of uncertainty (often called error weights). For example, smallest error weights could be associated with a presently high-quality area that has been well surveyed. A relatively higher error would go for an area that is apparently valuable but is poorly surveyed. Highest error weights would be associated with areas where there is substantial lack of knowledge concerning the growth of conservation value there, e.g., as a consequence of trying out a completely new restoration technique. Technically, when evaluating a solution at any given level of α, the solution is evaluated according to the most adverse choice of the model inside the uncertainty bounds. However, since the horizon of uncertainty, α, is unknown, a solution is evaluated according to the greatest α up to which that solution yields adequate outcomes.

The aim of our uncertainty analytic approach is to identify solutions that are robust in the sense that they achieve our performance aspiration even when allowing for high uncertainty. In the typical info-gap formulation, the robustness of a solution, α^*, is the highest α at which it is guaranteed to meet the performance target (Fig. 2a). A solution is not robust if it may fail to achieve the goal even at low α, indicating that a small deviation from expected restoration outcome might miss the target of NNL.

Each offset candidate solution would be examined in terms of its performance under increasing uncertainty. This is illustrated in Figure 2. Assuming that offset candidates A, B, and C have equal cost, then A is the best option because it achieves goals while allowing for highest uncertainty (Fig. 2a). Candidate C is the second best option assuming nominal models are correct. However, candidate B is more robust to increasing uncertainty than C.

The robust optimal solution is the one solution that achieves the planners specified goals while allowing for highest possible errors in the nominal models. If only a few scenarios need to be compared, then solution performance and robustness can be evaluated for all candidates. If, however, the robust optimal solution needs to be identified from a large set of options (such as selecting 100 out of 1,000 sites), then some optimization method is needed. Below, we calculate the offset ratio that is sufficient for guaranteeing NNL while accounting for the modeled uncertainties (Fig. 2b).

A Simple Example of the Method

We illustrate the proposed method for the simple case where one unit area of land with relatively high conservation value is offset by a number of units of less valuable land that is restored. In this example, conservation value is treated as a one-dimensional construct. Table 1 gives a summary of symbols used in the equations.

Assuming that all conservation value of the high-quality development area will be lost following the land exchange, a naive solution using matching of mean expected utility for the offset ratio is as follows:

$$N_{\text{simple}} = \frac{\tilde{V}_0(0)}{\tilde{V}_i(t_p)}, \qquad (1)$$

where $\tilde{V}_0(0)$ is the best estimate for the conservation value of the development area presently (at time 0) and $\tilde{V}_i(t_p)$ is the best estimate for the final conservation value of the restoration area at the end of the planning period at time t_p. This is the ratio A/B in Figure 1. N_{simple} units of

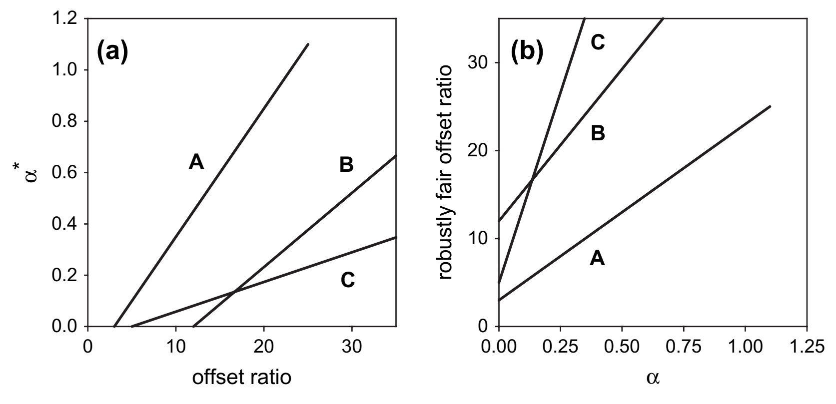

Figure 2. An illustration of how offset solutions would be compared in the info-gap approach. Panel (a) is the typical info-gap representation, in which solutions are graphed in terms of the level of uncertainty they can allow while still guaranteeing the performance goal (NNL). Panel (b) shows the offset ratio needed to guarantee NNL at given level of uncertainty. Each line is for one candidate solution, when uncertainty, α, increases. Of the three candidates, solution A is always best because it produces highest conservation value. Candidate C is better than B with low uncertainty, but with high uncertainty, B guarantees better outcome. Preference between B and C would depend of the level of confidence required for the solution. These curves can be graphed in two alternative ways.

Table 1. Explanation of symbols used.

t_p	Length of planning period
β	Reliability requirement, the probability of net loss should be less than $(1-\beta)$
p	Failure probability of restoration action at an area
ρ	Correlation coefficient for failure of restoration action between areas
d	Time discounting rate
α	Info-gap robustness parameter, horizon of uncertainty
$\tilde{V}_0(t)$	Best estimate for per unit area conservation value of the development site at time t (per unit area)
$\tilde{V}_i(t)$	Best estimate for per unit area value of compensation area option i at time t
$w_0(t)$	Size of error envelope (weight) of $\tilde{V}_0(t)$
$w_i(t)$	Error weight of $\tilde{V}_i(t)$; with restoration $w_i(t) >> w_0(t)$
$N_{\mathrm{method}}(\alpha, t)$	Number of equal-sized offset areas needed according to an offset calculation using the method indicated by subscript, N_{simple}, N_{IG}, N_{prob}, N_{corr}, and $N_{\mathrm{discounted}}$, for Equations 1, 2, 3, 5, and 7, respectively. This quantity depends on both α and t via Equation 2

restoration land are eventually predicted to hold the same conservation value as the development area.

We extend this solution to consider two sources of uncertainty: (1) that the conservation value achieved at the restoration areas could be less than expected and (2) that the conservation value of the development area could be even better than is thought. In the simplest version, to calculate the robustly fair offset ratio, $N_{\mathrm{IG}}(\alpha, t)$, the info-gap formulation only requires that $\tilde{V}_0(t)$ is replaced by $\tilde{V}_0(t) + \alpha w_0(t)$ and $\tilde{V}_i(t)$ by $\tilde{V}_i(t) - \alpha w_i(t)$ in Equation 1:

$$N_{\mathrm{IG}}(\alpha, t) = \frac{\tilde{V}_0(t) + \alpha w_0(t)}{\tilde{V}_i(t) - \alpha w_i(t)} \tag{2}$$

Here, $w_0(t)$ and $w_i(t)$ are relative error weights for conservation value at the development area and compensation areas at time t in the future. For instance, these envelope functions may derive from statistical modeling and/or expert opinion. Because other experts may have yet other opinions, or differently framed questions may elicit different expert responses, the uncertainty envelopes are multiplied by the unknown horizon of uncertainty, α. In our example $w_0(t)$ and $w_i(t)$ were calculated as the difference between the nominal estimate and the hypothetical error bounds of Figure 1, indicating that at $\alpha = 1$, the uncertainty envelope has expanded to the outer thin lines.

In the next level of sophistication, we allow for the possibility that conservation action in any one land unit could also fail altogether with a probability p. It is then logical to require that the even exchange would be achieved with a given reliability level β, say $\beta = 0.95$. The number of unit areas where conservation action would succeed, N_S, is now distributed binomially as $N_S \sim \mathrm{Bin}(N, p)$. To satisfy the reliability requirement, we need $\mathrm{Prob}[N_S < N_{\mathrm{IG}}(\alpha, t)] < (1-\beta)$. Denoting by $N_{\mathrm{prob}}(\alpha, t)$, the minimum number of unit areas needed, this number can be determined by finding smallest $N_{\mathrm{prob}}(\alpha, t) > N_{\mathrm{IG}}(\alpha, t)$ for which

$$\sum_{k=0}^{N_{\mathrm{IG}}(\alpha,t)-1} \binom{N_{\mathrm{prob}}(\alpha, t)}{k} (1-p)^{N_{\mathrm{prob}}(\alpha,t)-k} p^k < (1-\beta) \tag{3}$$

Equation 3 assumes statistical independence in success of restoration effort between different sites when calculating $N_{\mathrm{prob}}(\alpha, t)$. The assumption of independence is a strong one, and in general restoration, success between distinct restoration sites would be correlated to some degree (Fig. 3 illustrates effects of correlation). Ovaskainen and Hanski (2003) give a formula for the effective number of independent units, N_{eff}, when there is an uniform level of pairwise correlation, ρ, between N_{corr} sites,

$$N_{\mathrm{eff}} = \frac{N_{\mathrm{corr}}}{1 + \rho(N_{\mathrm{corr}} - 1)} \tag{4}$$

This equation essentially states that if the correlation is ρ, then there can be at most $1/\rho$ independent units irrespective of how many sites there are. Note that Equation 4 ignores higher-order correlations but, even so, it provides useful insight into the influence of correlation on the fair offset ratio.

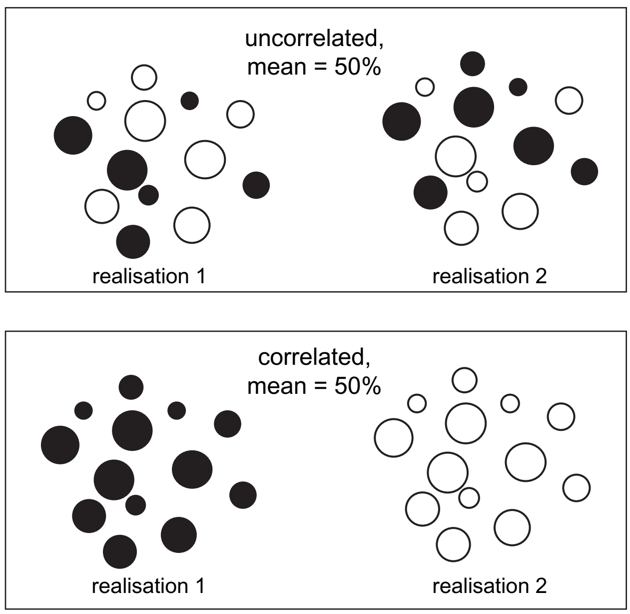

Figure 3. Illustrating effects of correlation. In both the uncorrelated and the correlated cases, the a priori chance of restoration success is 50% per site but the realized patterns are very different. Black and empty circles indicate sites with restoration success and failure, respectively.

Assuming N_{corr} correlated sites, we have only N_{eff} effective independent units, each of average size $S = N_{corr}/N_{eff}$. We then require that unit-size times the minimum number of units that succeed with reliability greater than β must be greater than $N_{IG}(\alpha, t)$. The number of effective units where conservation action would succeed, N_S, is now distributed $N_S \sim \mathrm{Bin}(N_{eff}, p)$. To satisfy the reliability requirement, we need $\mathrm{Prob}[SN_S < N_{IG}(\alpha, t)] < (1 - \beta)$. The minimum number of real units needed for this relation to be true can be determined numerically by finding smallest $N_{corr}(\alpha, t)$, for which

$$\frac{N_{corr}(\alpha, t)}{N_{eff}} N_{min} > N_{IG}(\alpha, t), \quad (5)$$

where N_{eff} comes from Equation 4 and N_{min} is the smallest number of units (out of N_{eff}) that succeed with a probability of at least β. N_{min} can be determined by inspecting the tail of the binomial distribution for the effective number of successful independent units. It is the largest number such that, out of N_{eff} units, at most $N_{min} - 1$ can fail with probability $(1 - \beta)$ or less, which implies that N_{min} or more units will succeed with probability greater than β:

$$\sum_{k=0}^{N_{min}-1} \binom{N_{eff}}{k} (1-p)^{Neff-k} p^k < (1 - \beta). \quad (6)$$

Note that Equation 6 cannot always be satisfied. For example, with $\rho = 0.25$, there can be at most four effective independent units. Then, if the failure probability of a unit is 0.5, a 95% reliability can never be achieved because $0.5^4 = 0.0625 > (1 - 0.95)$ meaning that the chance of all units failing is greater than the 5% allowed.

We add one final component, time discounting, to our analysis. A time-discounted offset ratio can be obtained simply as follows:

$$N_{discounted}(\alpha, t) = \frac{\sum_{t=0}^{t_p} (1 - d)^t N_{method}(\alpha, t)}{\sum_{t=0}^{t_p} (1 - d)^t}, \quad (7)$$

in which d is the time-discounting coefficient and $N_{method}(\alpha, t)$ represents any of the offset ratios from Equations 1, 2, 3, or 5, where the offset calculations have been done at time t using given horizon of uncertainty α. For practical purposes, this means that the offset ratio is weighted most heavily by the early years when the quality of the restoration areas is worst.

Results

We use our simple model to analyze the effects of uncertainty, correlation, and time discounting on the offset ratio. In our example, matching of mean expected utilities gives $N_{simple} = 2$, implying that an exchange could indeed be feasible—that is, by restoring an area twice the size of that lost to development. Figure 4 shows the effects of info-gap uncertainty analysis on the offset ratio (solid line). With $\alpha = 0$, the ratio $N_{IG}(\alpha, t_p) = N_{simple}$, but when α increases, the ratio increases substantially. In the present case, $N_{IG}(1, t_p) = 1.05/0.2 = 5.25$. Hence, accounting for uncertainty in the growth of conservation value makes a large difference to the offset ratio.

Next, we allow for the additional possibility that restoration fails completely in some of the restoration areas, e.g., because the most important focal species fail to migrate/establish there (Suding et al. 2004). We assume that each area has a 0.5 probability of complete failure, $p = 0.5$ in Equations 3 and 6. The number of restoration unit areas needed for replacing the conservation value of the development site with 95% reliability is given by the dashed line in Figure 4. This ratio grows from 1:8 ($\alpha = 0$) to 1:18 ($\alpha = 1$). Allowing uncertainty has thus changed our perception of the number of unit areas needed from 2 to 18. Note that with 18 units, the expected utility is $18 \times 0.5 \times 0.5 = 4.5$, where the halves account for predicted restoration value and the chance of failure. In fact, the expected utility is one quarter of the number of restoration unit areas in all our subsequent analyses.

The solid lines in Figure 5 show the offset ratios we obtain using time discounting (Equation 7; assuming 50% chance of failure per unit area and a 95% reliability requirement). With 1, 3, and 5% time-discounting coefficients, the $\alpha = 1$ offset ratios are now 1:59, 1:82, and 1:95, respectively. Even using no time discounting (0%) but calculating the ratio as an average over the 150-year planning horizon gives a ratio of 1:45 for $\alpha = 1$.

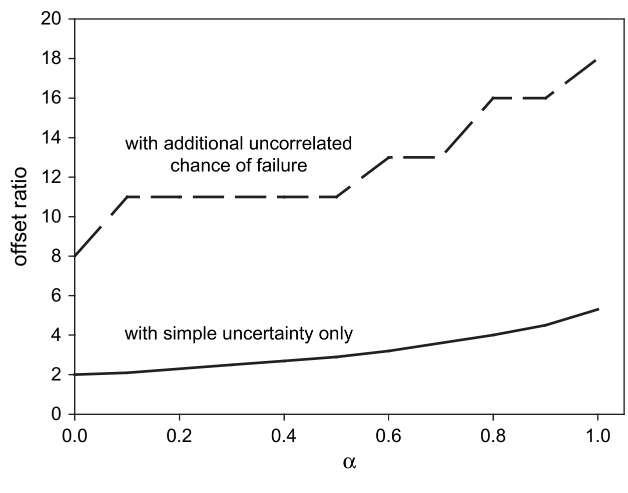

Figure 4. Offset ratio required to get "a fair even exchange" when exchanging one unit area of high conservation value with initially poor-quality restoration compensation areas. The solid line shows the ratio with simple effects of uncertainty ($N_{IG}(\alpha, t)$, with $t = t_p$; Equation 2) and the dashed line shows the respective result, assuming there is an additional uncorrelated per unit area chance of complete failure of restoration activity (N_{prob} assuming $p = 0.5$; Equation 3). (Steps in the dashed line are due to rounding down to integer values when calculating the number of areas needed.)

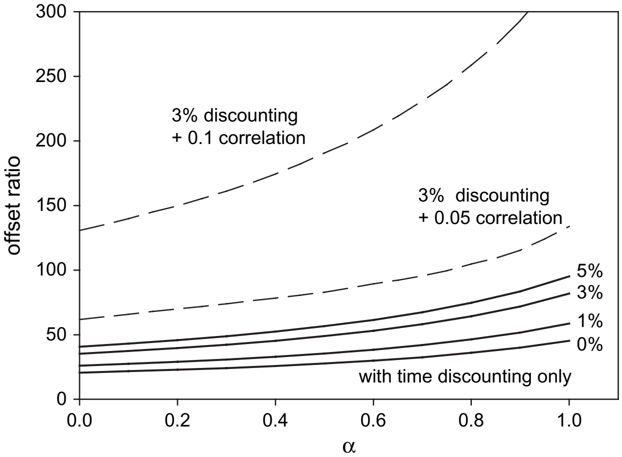

Figure 5. The robustly fair offset ratio when assuming time discounting on top of the uncorrelated chance of failure (solid lines; Equation 7 applied on N_{prob}; cf dashed line in Fig. 2). Offset ratio when adding a further 5 or 10% correlation on top of 3% time discounting (dashed lines; Equation 7 applied on N_{corr}).

We have left for last the hardest factor in our analysis, that is, correlation (dashed lines in Fig. 5). If the restoration success of individual sites is strongly correlated with the restoration success at other sites, then restoration either succeeds in (almost) all sites or fails simultaneously in all sites. Notably, with strong correlation, increasing the number of restoration sites does not notably decrease the probability of complete failure. Figure 5 demonstrates a major influence of correlation on the offset ratio. A small 10% correlation increases the fair offset ratio from approximately 80 to 340 when assuming 3% yearly time discounting.

Discussion

Using various assumptions, our estimate of the fair offset ratio increases quickly from two to hundreds in our simple example. This potentially surprising result is due to the criterion on which we have based our analyses. Instead of using the mean expected value of the restoration areas to determine the offset ratio, we look at the robustness of the proposed exchange in not producing a net loss. These criteria are completely different. The mean expected value criterion is based on the assumption that conservation value of restoration sites grows as expected. However, it is quite possible that although a proposed exchange promises high expected conservation value, it, at the same time, has a high likelihood of (almost) complete failure. This would be the case, e.g., when a large area of similar habitat is restored using a single method, which is not guaranteed to work. In this case, the mean expectation for the conservation value of the restoration areas is high (because the area is large), but the probability of correlated failure across the entire region is large as well (because the effectiveness of the restoration action is not guaranteed). Furthermore, the time evolution of the conservation value of a site is subject to severe info-gap uncertainties.

The influence of time discounting on the offset ratio may be large as well. In fact, if the improvement of conservation value is slow enough, it is questionable whether the habitat should be considered restorable at all (Morris et al. 2006). Still, correlation in restoration success between different areas is the factor that has the greatest influence on the offset ratio in our analysis. Is correlation, of the type we have simulated here, likely to be relevant for real-world planning situations? We believe so. Correlation in restoration success will be increased by (1) uniform habitat quality and environmental conditions across the restoration sites; (2) the same restoration action being applied across all areas; and (3) physical proximity of restoration sites. All these conditions apply commonly in the real world. We would expect an effective absence of correlation only if different restoration actions are applied in different habitat types occurring in different regions. However, if restoration areas are close to each other, some level of correlation is likely to be present. This is because, according to the basic principles of spatial population ecology (Hanski 1998), dispersal and establishment of species into the area will depend on the distance to nearby source areas and on the quality and species composition of these source areas (Donald & Evans 2006). If the restoration sites effectively share the same colonization source areas, then it can be expected that a similar set of species will eventually colonize the restoration areas. Or, if sources are far away, some species of conservation value might fail to reach any of the restoration sites (Bakker et al. 2000). Furthermore, if restoration areas become suitable for the focal species only after a lengthy maturation of vegetation, then it is possible that nearby population sources will disappear before the restoration areas become sufficiently suitable to allow colonization. Correlated failure can of course be avoided by selecting offset areas that already hold reasonable conservation value and therefore require protection rather than restoration.

In summary, when calculating offsets, one should recognize that loss is immediate but gain is uncertain and may not be achieved for a long time into the future. Accounting for uncertainty in offset calculations, and aiming at offsets that robustly avoid net loss, may suggest much higher offset ratios than recommended by matching of mean expected utilities. To obtain a reliably good offset solution, one should employ a bet-hedging strategy, where presently valuable offset areas are preferred, and restoration effort is split among an anticorrelated, or at least uncorrelated, set of sites—that is, where different restoration actions are applied across environmentally different, and spatially dispersed, sites. We emphasize that the offset ratios obtained in our hypothetical example are specific to this example and should not be used as any practical guideline. If compensation areas are of better quality than the development site, then the appropriate offset ratio could even be less than one. The important observation here is the potentially large influence that uncertainty and time discounting could have on fair offset ratios.

The present theoretical analysis is only a first step toward the calculation of robustly fair offset ratios. For example, we used an aggregate one-dimensional measure of conservation value, whereas in general, one would aim at a satisfactory outcome across a broad range of biodiversity features simultaneously, accounting for complementarity, retention of the features in the landscape, and certainty of species' occurrences in sites. One could require that offsetting is robustly fair for all features simultaneously, which implies potentially large offset ratios and an optimization strategy analogous to target-based reserve selection (Margules & Pressey 2000) accounting for retention (Pressey et al. 2004; Moilanen & Cabeza 2007). An alternative is to require that summed conservation value across features does not decline, allowing a reduction of one feature to be compensated via increased representation for other features, which resembles the additive benefit function approach to reserve selection (Arponen et al. 2005; Moilanen 2007). This approach would allow much flexibility for offsetting, which has potential for both success and misuse.

Also, our analysis does not cover the involved mathematical details of how to handle partial correlation in restoration success between restoration options. We have assumed areas of equal size and cost. Uncertainty could be relevant for many other components of our model, such as the failure probability or correlation, instead of just the development of conservation value at compensation areas. We have also ignored questions of connectivity, spatial population dynamics, and questions of persistence. Performing offset calculations involving such complications will allow for increasingly robust and realistic allocation of habitat restoration effort.

Implications for Practice

- Uncertainty in effectiveness of restoration action should be accounted for when calculating offsets, otherwise a long-term net loss for conservation is likely.
- Time discounting of conservation value, with a rate comparable to the economic return expected from the development site, should be used in offset calculations when conservation value grows slowly in the compensation areas.
- If the same restoration action is applied to a set of environmentally similar sites that are close to each other or effectively combining into one larger compensation area, then success of restoration action is likely to be highly correlated across sites, implying a risk of net loss even if the compensation area is large.
- From an uncertainty–analytic view, the safest offset solution consists of a set of different areas that are treated in variable ways, catering for the needs of partially different groups of species. An informed bet-hedging strategy is less likely to fail a minimal performance requirement (NNL) than a strategy that relies on the success of one particular action at one large compensation area.

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