Global Ecology and Conservation 54 (2024) e03039

Contents lists available at ScienceDirect

Global Ecology and Conservation

journal homepage: www.elsevier.com/locate/gecco

Monitoring in biodiversity offsetting

Atte Moilanen [a,b,*], Joel Jalkanen [a], Panu Halme [c,d], Eini Nieminen [c,d], Janne S. Kotiaho [c,d], Heini Kujala [a]

[a] Finnish Natural History Museum, University of Helsinki, P.O.Box 17, FI-00014, Finland
[b] Department of Geosciences and Geography, University of Helsinki, FI-00014, Finland
[c] Department of Biological and Environmental Science, University of Jyväskylä, P.O. Box 35, FI-40014, Finland
[d] School of Resource Wisdom, University of Jyväskylä, FI-40014, Finland

ARTICLE INFO

Keywords:
Biodiversity offsets
Ecological compensation
Monitoring
Conservation actions
Ecological restoration
Conservation management

ABSTRACT

Biodiversity offsetting is the process of using protection, habitat restoration and habitat maintenance to compensate for ecological damage to biodiversity caused by human activity, such as construction of infrastructure projects. Offsetting has been criticized for failure to deliver biodiversity no net loss, the common goal of offsetting. Reasons of failure can be broadly divided into failures in planning, failures in project-level implementation, and systemic failures of offset frameworks. One way to fail is inadequate monitoring that does not observe deficient implementation or unexpectedly poor outcomes of restoration or maintenance. Here, we consolidate understanding about the role and importance of monitoring in offsetting. We review different types of monitoring relevant in the context of offsetting and consider monitoring from the perspective of an individual project versus the offset system. We organize pros and cons of different types of monitoring from the perspective of different actors involved in offsetting. We also discuss funding for monitoring and the development of the offset framework: where should the money come from. Overall, we provide conservation managers a useful summary that can be used to formulate, update, and improve offset monitoring schemes, both for individual projects and for regional or national offset frameworks.

1. Introduction

Biodiversity offsetting, here offsetting in short, is a method of conservation science for balancing human-caused ecological losses with ecological gains generated through actions such as habitat restoration, establishment of new protected areas, or some form of habitat management (Gibbons and Lindenmayer, 2007; McKenney and Kiesecker, 2010; Wende et al., 2018). Offsetting is often justified with the polluter pays -principle (Nash, 2000). The goal of offsetting is usually no net loss (NNL), i.e., ecological losses incurred by development are fully balanced by commensurate gains (McKenney and Kiesecker, 2010; Maron et al., 2018; Maseyk et al., 2020). Approximately 100 countries either employ mandatory offsets or recommend or enable voluntary offsets (GIBOP, 2019). Some businesses and offset schemes are even moving toward Biodiversity Net Gain (BNG) or Net Positive Impact (NPI), both in voluntary offsets and in mandatory schemes (Rainey et al., 2015; UK DEFRA, 2024).

The prevalent concern about offsets is that they have been frequently observed to fail (Walker et al., 2009; Spash, 2015; Lindenmayer at al., 2017; Theis et al., 2020). The first major reason for failure is poor offset system design, including insufficient policy

* Corresponding author at: Finnish Natural History Museum, University of Helsinki, P.O.Box 17, FI-00014, Finland.
E-mail address: atte.moilanen@helsinki.fi (A. Moilanen).

https://doi.org/10.1016/j.gecco.2024.e03039
Received 19 March 2024; Received in revised form 10 June 2024; Accepted 13 June 2024
Available online 14 June 2024
2351-9894/

requirements. For instance, in a review of compliance to offset policy Theis et al. (2020) found that many projects have been officially labelled a success due to high compliance with legislative requirements. At the same time, there was only a weak positive relationship between compliance and success in achieving good ecosystem functioning (Theis et al., 2020). This finding suggests that policy requirements often fail to support credible ecological design criteria for NNL (Moilanen and Kotiaho, 2018).

A second cause for offset failure is lack of regulatory oversight, enforcement, and accounting, including deficient implementation (Gordon et al., 2015; Lindenmayer et al., 2017; Guillet and Semal, 2018; Gibbons et al., 2018). In an early review of past offsets, Quigley and Harper (2006) concluded that lack of monitoring and enforcement rather than poor offset design were more often the cause for noncompliance and unfinished compensation projects. Anecdotal evidence suggest that offset compliance is frequently neglected and on-the-ground action poorly implemented, a problem potentially caused by the lack of supervision, monitoring, enforcement, and sanctions (Bull et al., 2014; Poulin et al., 2016; Gamarra and Toombs, 2017). Past reviews suggest that in 5–20 % of cases, agreed offset actions were never implemented (Quigley and Harper, 2006; Tischew et al., 2010; Poulin et al., 2016; May et al., 2017). An extreme example of implementation failure is found by Poulin et al. (2016) in a post-hoc evaluation of 558 permits of the Canadian province Quebec's wetlands conservation program. While mitigation and compensation measures were required of permits, the net loss of habitat was estimated at 99 %.

Overall, data is sparse about successful offset cases, partly due to lack of transparency around biodiversity offset and their outcomes (Salzman et al., 2018; Kujala et al., 2022). Only a few countries have publicly accessible offset registers that allow the examination of details of offset cases (Kujala et al., 2022). Recently, Josefsson et al. (2022) evaluated evidence about the ecological gains from offsets. They analysed 40 publications about offsets and found that NNL could not be verified, because as a rule even the losses were not estimated and reported. The centralized database of the US mitigation banking system has thousands of cases listed, but with very little tangible information about actual outcomes, monitoring, and achievement of NNL (Morgan and Hough, 2015).

Monitoring is frequently named as an essential part of offset framework design (IUCN, 2016; Maron et al., 2016). It is required by many offset policies (e.g., Quigley and Harper, 2006; Tischew et al., 2010; Brown et al., 2013; May et al., 2017; Theis et al., 2020). Evaluating and monitoring offsets comprises of two elements. First, the verification of the compliance of the restoration/management measures to document whether they have been implemented successfully and as agreed. Second, monitoring the ecological responses to the action to verify that the offset has produced the biodiversity gains expected. However, actual evidence and reporting about monitoring is sparse. Bull et al. (2013) found that offset schemes had been inconsistent in meeting conservation objectives because of the challenge of ensuring compliance and effective monitoring. Lack of proper reference baselines and pre-impact impact monitoring are known sources of offset failure (Bull et al., 2014; Pope et al., 2021). In a meta-analysis, Josefsson et al. (2022) found that losses were reported so vaguely, if at all, that as a rule NNL could not be verified from published information. This is especially relevant, because measuring losses is still much easier than predicting gains from the offset actions. Earlier, Levrel et al. (2012) reported that the duration of monitoring is usually so short that offset gains could not be verified. Evaluation of the nation-wide French offset system found deficient reporting of initial state of both impact areas and offset areas combined with a ubiquitous lack of monitoring (Bezombes et al., 2019; Le Texier et al., 2024). Overall, the lack of monitoring and reporting is a frequent theme in scientific literature whereas well designed and transparently documented offset cases seem to be a far exception. The very fact that only four countries has publicly accessible offset registers (Kujala et al., 2022) underscores the prevalent lack of information and transparency.

Here were summarize perspectives to the monitoring of biodiversity offsets. To set the stage, there is a major division between verification of initial offset implementation vs long-term monitoring of biodiversity response. Biodiversity response can be monitored to verify an individual offset case, but also for improved understanding about offset actions, which in turn can help improve the national offset framework (Lockhart, 2015; Peterson et al., 2018; Calvet et al., 2019; Dorrough et al., 2019). Developers and regulators will have different perspectives towards monitoring, which should be acknowledged when aiming at a balanced, operational offset framework. The potentially significant resources spent in monitoring should be well spent.

Table 1
Aims of offset monitoring.

Aim	Explanation
(ia) Project-level verification of compliance	
Verify implementation	Verification soon after implementation that offset actions have been done at planned locations, in planned size and using methods agreed upon in the offset plan.
Verify that implementation meets set ecological criteria	Verification either soon or a few years after implementation that the actions have succeeded adequately against set criteria, e.g., that *x*% of planted trees are still alive after *y* years.
(ib) Project-level verification that offsets have achieved NNL or NPI	
Verify ecological gains	To verify via monitoring that both short- and long-term ecological improvements have emerged as expected. Not necessarily needed, if the ecological response to the action is well-known from prior studies.
(ii) Learning for the benefit of the offset system and conservation science at large	
Learn more about the performance of individual offset actions	1) To assist developers/offset providers to plan offsets that are more likely to succeed. 2) To help regulators to evaluate the correctness and credibility of offset proposals. 3) To reduce uncertainty about expected responses of actions. 4) To evaluate emerging methods / technology.
Facilitate selection of actions in planning	1) To facilitate well-informed selection of cost-effective offset actions. 2) To allow improved cost-efficiency of offsetting as accumulation of knowledge decreases the need for monitoring resources, while likelihood of offsetting success increases.

2. Aims of offset monitoring

There are two operationally very different purposes for offset monitoring: project-level verification and learning (Table 1). For verification, the environmental regulator can specify implementation criteria that need to be met for the action to be deemed correctly implemented, including ecological indicators of action success. The verified actions and meeting of implementation criteria are key conditions to offset compliance, and in many offset schemes meeting these two milestones translate into a successfully implemented offset. To observe whether NNL has been achieved, the ecological gains of an offset action need to be further monitored and documented (Fig. 1, Table 1).

In addition to project-level verification, monitoring should increase knowledge about the effectiveness of offset actions. Statistically robust *a-priori* information about the ecological effectiveness of offset actions would be missing for most action-environment pairs in most countries. If longer-term monitoring has never been done, adequacy of ecological gains may be based on assumption, which does not necessarily guarantee NNL (e.g., Lindenmayer et al., 2017; Theis et al., 2020). Hence, there is need for learning at the level offset framework. Lack of knowledge about actions is undesirable for both the developer and regulator since low confidence in the expected gains can translate into slower processing times, lower likelihood of approval, and higher multipliers. From the perspective of biodiversity, lack of knowledge might lead to optimistic assumptions about the effectiveness of offset actions and the underestimation of the risk of failure, leading to multipliers that are too low to achieve NNL. It is a policy question whether a certain (additional) fraction of offset cost must be allocated to support knowledge generation at the scale of the offset system.

3. Components of monitoring

We discuss components of monitoring strategies summarized in Table 2. In this paper we specifically refer to monitoring, i.e. focus on biodiversity changes over time, which operationally requires multiple surveys over time. Monitoring applies both to in-advance offsets and offsets done at the same time or after development. If any type of after-treatment monitoring of the project and / or offset sites is to be done, corresponding baseline surveys or before-monitoring should be implemented before treatment. E.g. Christie et al. (2020) and Josefsson et al. (2020) show schematic illustrations of different monitoring strategies.

3.1. None

No monitoring should not be an option as it exposes the offset framework to both accidental failure and outright deliberate fraud (Spash, 2015). Complete lack of monitoring may nevertheless follow from weak governance or under-resourced environmental administration, where monitoring policy is obscure or monitoring is mandatory but not enforced in practice (Quigley and Harper, 2006; Clare and Krogman, 2013).

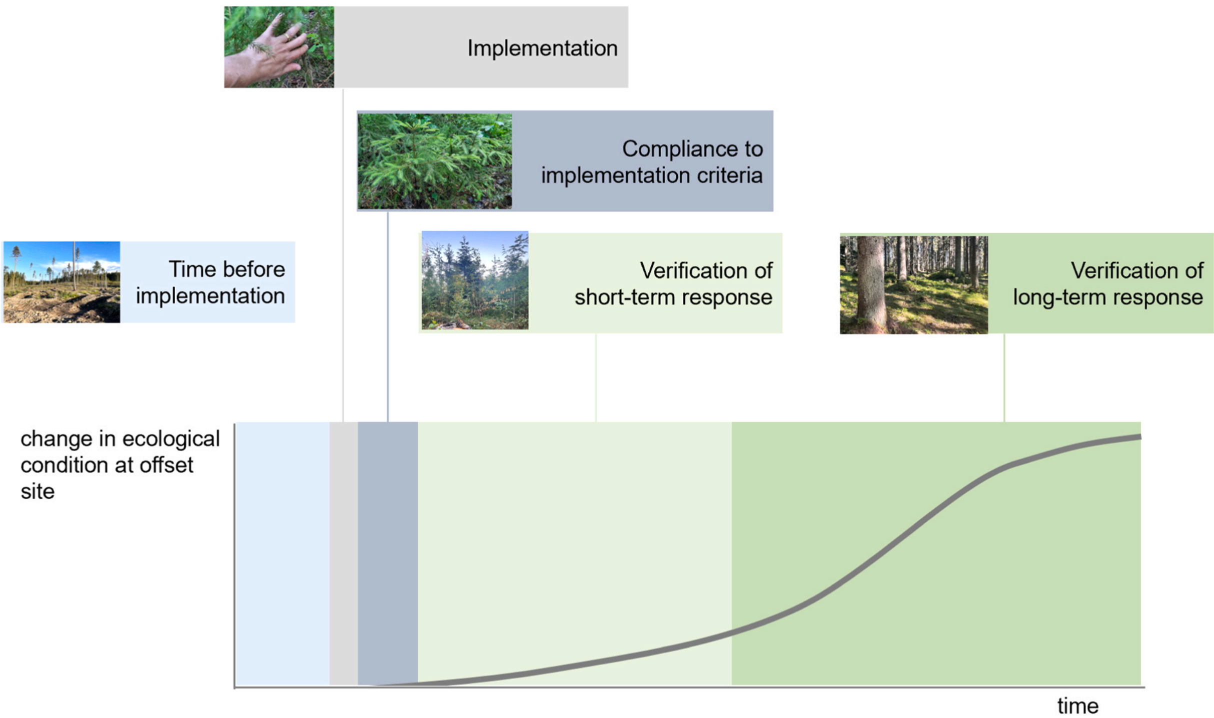

Fig. 1. Illustration of the timelines for verifying compliance and the ecological response (grey line) to offset action.

Table 2
Different components of monitoring and implications of their use. Needs are incremental, when adding monitoring steps.

Monitoring strategy, incremental order	Gains	Needs (time, competencies, money)	Regulator, pros & cons	Developer, pros & cons
No monitoring	None	None	*Pros.* None. *Cons.* Allows offset failure.	*Pros.* Zero expense or effort. *Cons.* No credibility.
Project scale				
B – Before-monitoring; establishment of baselines	Baseline survey or short monitoring of biodiversity around the area of development and / or offset sites. Possibly required as part of EIA. Needed in the estimation of losses in the development area.	Expertise in habitat / species -specific surveys. Data storage in a manner that allows later data analysis and synthesis.	*Pros.* Initial state of biodiversity known. *Cons.* No direct information about biodiversity response.	Pros. Slightly elevated credibility. Cons. Increased cost. Longer waiting times for permitting, as survey needs to be done in advance.
I – Implementation only	Verified implementation according to requirements. Can be sufficient for well-known offset action. Note: does not include monitoring of ecological response.	Comparatively simple and inexpensive. May still require multiple visits, if problems are observed and need correction. Requires a-priori information about ecological response, removing the need to monitor. Short-term commitment, from one to few years.	*Pros.* Verified implementation of action. Simple to understand. *Cons.* No observed information about biological response.	*Pros.* Known obligation of minimal duration possible. *Cons.* Some cost, minimal in relation to other project costs.
A – After or Before-After short-term	Observation of initial response of biodiversity to offset actions. Because no controls, response cannot be properly distinguished from natural variation or effects of other external drivers.[a]	Should be paired with before-monitoring. Expertise in surveys. More monitoring steps => increased cost. Some statistical skills for data analysis. Still short-term commitment.	*Pros.* Verified initial biodiversity response. *Cons.* Long-term biodiversity response not observed. In the absence of controls risk of misleading results[a]	*Pros.* Known (short-term) obligation with additional credibility. *Cons.* More surveys, longer commitment and elevated costs. Risk of misleading results remains[a]
A – After or Before-After long-term	Information of long-term response is more useful than that of the short-term. Better understanding of the changes taking place.	As above, but with longer commitment and higher accumulative expenses. Interpretation remains confounded by temporal trends.[a]	*Pros.* Improved information about long-term response. *Cons.* Guarantees needed for maintenance of long-term monitoring effort.	*Pros.* Further elevated credibility. *Cons.* Elevated costs and longer commitment Causes of trends still not clear[a]
Monitoring in areas external to the project: preferably in coordination with other projects or national monitoring schemes.				
CI – Control-Impact (negative control)	Independent control sites are added, where changes in the environment are followed in the absence of action. This is to gain understanding about background trends. CI designs assume the differences between control and impact sites are only due to the action, which is potentially confounded by unaccounted differences between control and impact sites. Degree of replication influences strength of statistical inference.	Need for a set of suitable control sites that are of same environment and starting condition as offset areas and which are independent from each other and from the offset areas. Monitoring the control sites increases effort and resource needs significantly. Additional expertise in experimental design and statistical analysis. Typically major, long-term effort.	*Pros.* Through time and replicates, much stronger estimate of response to action. Improved estimates of action-specific multipliers. Best knowledge to improve policy and develop the offset framework. *Cons.* Need for long-term coordination, methodological competence, and guidance to actors. Probable resource needs.	*Pros.* Much improved credibility. *Cons.* Much elevated costs, long commitment, and complicated analysis. Burden might be shared with other developers and / or the society.
R – Reference (positive control)	Comparison to reference sites in natural or desirable condition. May observe external trends that impact the reference sites. Improved understanding about the position of an area on the degraded – natural -axis. Measures the improvement of offset sites towards "target".	Need for suitable reference sites that need to be monitored long-term along with offset areas and possible (negative) control sites. Relatively small additional complication to statistical analysis.	*Pros.* Improved indication of the biodiversity response to offset actions. *Cons.* Relatively small additional cost of monitoring smallish number of relatively static reference sites.	Pros. Rather light form of monitoring that improves credibility. Cons. Slightly elevated costs.

[a] In the absence of controlled study, the contribution of offset action on observed changes cannot be fully distinguished from stochastic environmental variability or effects of external drivers of long-term trends, including such as climate change or regional extinction debt. Misattribution of cause of trend might result in unfair regulatory consequences. Some useful information may still be gained, for example, about the utilization of new resources provided ("usage of next boxes", etc.).

3.2. Project-scale establishment of baselines or before-monitoring

If changes in biodiversity at the project sites and / or offset sites are to be monitored, the chronologically first step is establishment of baselines via a baseline survey or (short) before monitoring. Establishing the baseline may require repeated surveys across a few (2−3) years to account for interannual fluctuations of animal populations. Establishment of baselines for the project area is commonly required by an environmental impact assessment.

Before-monitoring of offset areas is an effort separate from the monitoring of the project area. If before-monitoring is followed with after-monitoring, consistent survey protocols need to be observed across different survey rounds.

3.3. Monitoring of implementation action (compliance)

The minimal first step towards credibility is to monitor implementation, verifying that actions done meet set criteria that indicate successfully executed implementation. Details about the actions and implementation criteria are typically given in the offset plan and approval condition documents. The regulator may visit the offset site and require additional action if implementation is not satisfactory.

3.4. Project-level after-monitoring, short-term or long-term

The objective of after-monitoring (A) is to verify that the restoration and/or maintenance actions are producing approximately the biodiversity gains expected. After-monitoring might be applied alone, but more usefully it is combined with before-monitoring.

When implemented at the project level, after monitoring might be arranged using survey methods that are somewhat specific to the individual offset case. Consequently, offsets might be monitored using inconsistent methods, designs, metrics, and rigour of monitoring (Maron et al., 2012; Marshall et al., 2020b; Josefsson et al., 2021) and it may be difficult to compare and draw general conclusions about the effectiveness of offset actions across the projects.

Changes in biodiversity after the offset actions can be followed either short-term (5–15 years) or long-term, which could be for multiple decades (Damiens, et al., 2021). We emphasize that the timelines are indicative, differ widely between offset schemes and the type of actions taken, and can overlap with the implementation monitoring period. While the difference between short-term and long-term monitoring is not conceptually large, it has significant operational implications. Many if not most ecological responses to restorative actions accrue over the long-term (Maron et al., 2012, Damiens et al., 2021) and the true response may not become observable in short-term monitoring. This may result in incorrectly estimated gains, if the long-term improvement of the offset diverges from what was expected (Maron et al., 2012).

On the other hand, the coordination and resources needed for long-term monitoring – money, field-work personnel, analytical capacity, data storage and reporting – are large and need to be arranged in a credible manner. The increased likelihood that external environmental trends influence results would preferably need to be controlled. By definition, the final results of monitoring will be available only after a significant time delay. Also, if working at the species level, there may be unintended consequences for species not the target (possibly mediated via species interactions), which are hard to anticipate in offset planning.

3.5. Project-level before-after-monitoring

In a Before-After (BA) design biodiversity is measured at the offset area both before and after offset action. BA monitoring significantly improves the quality of monitoring results both in terms of direction and accuracy in comparison to after monitoring alone (Christie, 2020). Yet, without controls the response cannot be distinguished from background trends.

3.6. Control-impact designs within a broader offset framework

In a Control-Impact (CI) design, the offset sites (impact) and similarly degraded but untreated (negative) control sites are monitored to establish the difference made by (offset) action (Christie et al., 2020). The increased requirement here is that standard methods should be used across several offset projects so that information can be synthesized. This is not a trivial task, because there is an implied need for long-term coordination across offset projects about implementation of actions, monitoring, and the measurement of biodiversity response.

Replicates for treatment and control sites are needed to gain improved confidence about the biodiversity response and variance around it. Untreated control sites are needed to separate the effects of action from effects of external trends (Maron et al., 2012; De Palma et al., 2018). For example, the population density of a species can be influenced both by offset actions and changes in regional environmental conditions. As a complication, control sites are usually not fully identical to impact sites, which complicates analysis (England et al., 2021).

The credibility of information obtained from such empirical research is fundamentally determined by study design. Both BA and CI type monitoring are also prone to biased estimates in the response (Mahlum et al., 2017; De Palma et al., 2018), which needs to be acknowledged and understood. Their success is determined by adequate sample size and biological, spatial, and temporal coverages. The emphasis on statistical power promotes increasing sample size, but focusing solely on that may reduce the biological, spatial or temporal coverage, each with their own problems. The least biased data can be obtained from replicated and controlled studies, such as randomised before-after-control-impact (BACI), randomized control trial (RCT), and non-randomized before-after-control-impact study designs (Christie et al., 2020). Even so, studies about conservation interventions apply such study designs relatively seldom: it was the design of choice only in 23 % (Christie et al., 2020) of the 4260 studies in Conservation Evidence database (Sutherland et al., 2019). Limited resources, short funding timescales, and logistical constraints are among the reasons behind the utilization of the suboptimal study designs (Butsic et al., 2017). As a further complication, the starting conditions of offset areas can differ (Josefsson et al., 2020), which may influence the expected response, again needing more replication to cover such variation. Precision and power analyses can help improve monitoring planning and sample size determination both in a frequentist and Bayesian frameworks (e.g., Legg and Nagy, 2006).

3.7. Reference-impact designs within a broader offset framework

As a modification of the CI design, in Reference-Impact (RI) design the condition of offset site is compared to dedicated reference sites that represent the desired end result for the offset. Hence, unlike BA and CI designs, which seek to establish the observable change in biodiversity following offset actions, RI design simply measures the shortfall to a target state (Josefsson et al., 2021). Like control sites, the reference sites may reveal the presence of external environmental trends.

3.8. Long-term monitoring and adaptive management

Monitoring may link to outcome-based adaptive management, in which the management regime is adjusted according to what is found by monitoring (Maron et al., 2016; Thorn et al., 2018). The implementation of the offset should always be corrected (adaptively) if deficiencies are found. If adaptive management is linked to biodiversity response, longer-term monitoring becomes mandatory, and additional reparatory actions might be needed far in the future, elevating the responsibilities of and potential costs to the developer, offset provider, and/or regulator. Use of adaptive management will reduce potential for net negative biodiversity outcomes and outright misuse of offsets (Spash, 2015; Maron et al., 2016). The drawback is that adaptive management requires both monitoring and analytical expertise and involves difficult questions such as how to deal with natural yearly fluctuations in population sizes.

4. What is monitored and how?

Beyond the general design and execution of the monitoring scheme, there are technical considerations that affect the accuracy of monitoring results (Henry et al., 2008). The biological coverage of the monitoring is typically defined by the offsetting framework and is often compulsory only for some species and habitat types. Results about how well species and habitat data yield corresponding results are mixed, as individual species do not necessarily follow a general vegetation response and different species groups may respond very differently to different environmental changes (Devictor et al., 2008; Cristescu et al., 2013; Hanford et al., 2017; Marshall et al., 2020). For example, fragmentation is more harmful to amphibians than birds (Henry et al., 2008) and therefore their predicted responses to biodiversity offsetting may depend on landscape structure. Consequently, monitoring of the changes in species populations is necessary for solid verification of offset gains.

The two extremes of spatial coverage in biological monitoring are i) an exhaustive scheme where the total area of interest is monitored, and ii) a scheme where only a few plots are monitored based on a random or systematic sampling. Whether to use a combination of high spatial coverage with low local sampling effort or low spatial coverage combined with high local sampling effort depends on the target variables (Schmeller et al., 2017). It has been observed that use of a systematic sampling scheme can notably increase the statistical power of the monitoring (Carvalho et al., 2016). A general problem is potential lack of unified monitoring metrics, which can much complicate comparisons across offset cases. In this context, multi-metric indices are becoming increasingly important. Basic indexes such as richness, plant health and invasive species number are first used to evaluate specific offsets. They are then combined into general indexes to facilitate cross offset comparisons (Cousins, 2016).

Temporally, monitoring can cover both the long-term interannual scale and the short-term intra-annual scale. Adequate temporal coverage both before and after offset action allows, in principle, separation of annual variation from the actual trend of interest. Timing of surveys might also need to be fine-tuned to match taxonomic phenology, such as breeding or flowering events. As a downside, increasing coverage at any of the scales requires either more surveys or increased resources per survey, and thus more resources overall.

5. Theoretical desires vs operational reality

Verification of implementation is obviously needed, but achieving learning at the level of offset system is far from trivial. Difficult questions include: i) what are the realities of implementing a statistically robust monitoring scheme in an offset framework, ii) what is the role of a single offset project in providing statistically valid information about the effects of an action, and iii) when is monitoring of the biodiversity response actually needed?

First, a response does not always need to be monitored, if sufficient accumulated knowledge and experience about the action is available from prior studies. If so, actions should be implemented in a similar manner and in similar environmental conditions to past experiments. There will however be an underlying assumption that our current knowledge is sound and robust, which is not always the case. There can also easily be project to project differences that can alter responses and might benefit from monitoring. These observations support the notion that even if the biodiversity response is approximately known, implementation still needs regulatory oversight and some monitoring might be beneficial, so that expected gains can be achieved and verified.

If pre-existing information about the effects of an action is inadequate, gains need to be estimated and the outcome monitored. Estimating the gain can be done in various ways. Best practises exist for the synthetization of evidence from variable and limited data, as developed by the conservation evidence initiative (Sutherland et al., 2019; Christie et al., 2020). The minimal approach is to use expert assessment of the likely outcome, but expert knowledge is not always reliable (Burgman et al., 2011).

For ideal ecological monitoring schemes (BACI-R) to have statistical power, there should be enough replicates and control sites for each offset action-environment pair. It can be assumed that in many countries there would be a small number of species or environments that trigger many offset cases. The most used offset actions could be properly evaluated for such species and environments, but even here achieving randomized patterns of implementation can be hard (Josefsson et al., 2020). BACI-designs effectively require that someone, most likely the regulator, must be in the position to coordinate and maintain long-term monitoring. It will by definition take many years or decades before full information is available from a BACI-design, especially since replicates would start at different times following different projects, which needs to be accounted for in experimental design and statistical analysis (Ferraro, 2009; Josefsson et al., 2020). Fortunately, a sequential (staircase) BACI-design can both improve the statistical power of analysis and reduce overall monitoring costs (Loughin et al., 2021).

As a rule, there would also be a considerable number of species and environments that trigger offsets more rarely and for which effective restoration or maintenance actions are known poorly if at all. With such environments, we immediately encounter the reality that the replication required by a BACI-scheme simply will not be available. The question therefore arises, how should the monitoring of such offsets be organised to gain data that is as precise and applicable as possible? Also, it is possible that offsets should not be allowed without improved information about the performance of alternative offset actions.

Before-after (BA) monitoring can establish the local biodiversity responses for rare action-environment pairs. As a weakness, the observed effects of offset action might be biased, they cannot be distinguished from the effects of external environmental trends, and the uncertainty around the observed local effect cannot be quantified due to lack of replicates (Mahlum et al., 2018; De Palma et al., 2018; Christie et al., 2019). Background trends could be factored in by coupling external data from existing national monitoring schemes or suitable citizen science data, although these have known statistical challenges (Josefsson et al., 2020). Also, using a before-after-reference (BAR) scheme is probably easier to set up than the replication required by BACI, as good-condition reference sites might be relatively easy to identify – possibly inside protected areas - and would act as a point of reference for a desirable end state for all offsets.

The lack of replicates is more difficult to circumvent, and responses based on one or a few BA-monitoring series will have unavoidable uncertainty and biases that cannot be eliminated. One option is to compensate for this uncertainty through the use of larger offset ratios in frameworks that allow their use (Maron et al., 2015). Given enough time, the number of replicates might increase and changing land-use practices might make currently rare action-environment pairs more common. Yet, without properly designed controls for background effects and with non-random sampling, increasing BA or CI replication does not improve their precision but tends to simply reduce the uncertainty around the biased response estimate (De Palma et al., 2018; Christie et al., 2019). Hence, a desirable strategy would be to design BA monitoring in a manner that allows transferring to a BACI design as more replicates become available. This in turn requires standardised monitoring practices - what is monitored, when, how and how often - so that data across offsets can be combined later.

All the above make it apparent that offset verification and learning about offset actions requires coordination, resources, personnel, and skills to carry out the monitoring and statistically non-trivial analyses. Data should also be stored so that it is accessible for future analysis and synthesis (Kujala et al., 2022).

Table 3
Arrangement of monitoring and benefits / risks from the perspective of developer and regulator.

Division of payment and responsibility	Regulator pays and arranges	Developer pays, regulator arranges monitoring	Developer pays and arranges monitoring, reports to regulator
Regulator, pros	Can arrange monitoring in most appropriate manner possible	Developer pays, as is appropriate Regulator can coordinate monitoring scheme to maximize information gain	Developer pays, as is appropriate Less need for own work
Regulator, cons	Fails PPP: not a true offset, as part of expenses are outsourced to the society. Society becomes responsible for confirming offset success. Responsibility for complex task.	Responsibility for complex, long-term task. Risk of outsourcing costs to the regulator and the society if payments do not cover true costs. Society becomes responsible for confirming offset success.	Reduced control over how monitoring is done, assuming no national monitoring standard is enforced. Risk of substandard monitoring and data heterogeneity. Does not remove the need for spot checks to verify monitoring. Need to assess the reliability of subcontractors who monitor.
Developer, pros	Little cost, little responsibility.	Only money required, often a lump sum at the start. Coordinated monitoring may reduce cost of offsetting to all developers.	Can try to minimize the costs of monitoring
Developer, cons	Public opinion may be negative due to avoidance of PPP.	Cannot directly influence costs of monitoring.	Developer responsible for both confirming offset success and reparatory actions, if failure is observed. High responsibility for task that likely is not the competence of the developer. Need for long-term involvement.

6. Who should pay and who should monitor?

Monitoring incurs unavoidable costs that arise from planning, potential consultancy fees, acquisition of gear, setting up survey plots, fieldwork, travel, and data analysis among others. Since biodiversity offsetting follows the philosophy of the Polluter Pays Principle (PPP), offset policies commonly state that monitoring costs need to be covered by the developer (Quigley and Harper, 2006). Table 3 summarizes alternative monitoring arrangements from the perspectives of developer and regulator. Monitoring might also be outsourced to third parties, such as consultants or government research institutes, but similar considerations to Table 3 will apply.

In all options, the length of the developer's commitment needs to be considered. For how many years can a developer realistically be obligated to carry out monitoring? How is continuity secured if businesses are sold or go bankrupt; can some type of trust fund be set up or instruments of offset banking be utilized? If long-term monitoring is further coupled with adaptive management so to require outcome-based compliance, the scheme might incur unrealistically large additional costs to business. Shifting the responsibility of monitoring to the regulator does not automatically alleviate these issues, as proponents may not be capable or willing to cover the true costs of long-term monitoring. Indeed, it has been observed that payments made by the developer often fall short from the actual monitoring budget needs, as the industry actively lobbies to keep such payments low (Brown et al., 2013).

Due to costs and operational complications, monitoring should be arranged cost-effectively and it may be necessary to consider some form of cost and burden sharing, especially when aiming at learning at the system-level. Most obviously, monitoring of control and reference sites could be allocated to the regulator. Alternatively, if the regulatory environment so allows, the costs of long-term monitoring schemes could also be allocated entirely to the developers through fees. This investment would be in acknowledgment of the need to maintain and develop information needed to run a national offset scheme and it would be on top of the case-specific investment into on-the-ground conservation action.

7. Practical way forward

While there are commonalities, the way forward may be different at the project level compared to the level of the offsets system.

At the project level from the perspective of a developer:

i) Find out the environment / species + offset action combinations that have adequate information about responses available. Following the mitigation hierarchy, minimize impacts in project planning so that any residual impacts are primarily in habitats for which credible offset actions are known. Document measures taken for impact avoidance and minimization.
ii) Avoid the need to use poorly understood combinations of environment / species + action, as these may be associated with additional uncertainty, time delays, and expense.
iii) Always arrange monitoring for the implementation of actions and take corrective measures where deficiencies are observed. This is needed for transparency and credibility.
iv) When the use of less well understood actions is necessary, collaborate with national / regional authorities to provide a contribution to the collation of information about environment-action pairs.

In the long run, a national offset scheme should aim to collate a library of environment-action pairs that are well understood.

From the perspective of the regulator and offset scheme:

i) Emphasize *a-priori* impact avoidance, to minimize the need for offsetting.
ii) Always require monitoring of implementation, to minimize risk of non-compliance.
iii) Find out which environment / species + offset action combinations already have decent information about responses available and consider whether monitoring of implementation is enough for these pairs.
iv) Of poorly understood environment-action pairs, identify habitats for which offset needs will be highest and for which replicates are therefore feasible over time. Create a standard for monitoring methods and metrics. Facilitate contribution of project to an experimental framework with control sites to get proper response functions. Facilitate data collation and analysis.
v) Consider setting a requirement for adaptive management, if information is lacking for an environment-action pair, but development will nevertheless take place. This may imply work-intensive long-term monitoring.

8. Conclusions

Both offsetting and monitoring are comparatively difficult topics that involve conceptual and operational complications. Here, we have examined the role of monitoring in verifying offset compliance and performance, and in improving offset schemes. Given extensive evidence about various offset failures, reviewed above, monitoring is perhaps also needed to adjust misguided assumptions about expected gains.

Offset implementation needs to be monitored always, to rule out failure due to straightforward lack of action and compliance. Confirming that offsets achieve NNL is difficult without some long-term commitment to monitoring at the level of offset system. Monitoring is also needed to deliver trust in the mechanism delivering NNL as required. Improving offsets schemes through learning from offset outcomes further requires coordination of monitoring across projects, which implies both resources and an active role from the regulator(s).

While it was not possible to systematically review current offset monitoring practices of different countries, literature suggests that current approaches fall far short from the ideal. In the absence of enforcement, monitoring may be omitted altogether. For example, Quigley and Harper (2006) and Brown et al. (2013) found that all monitoring was omitted in 57 % and 33 % of cases, respectively. Monitoring may also be done in an *ad hoc* manner, using varying methods, metrics, and reporting, even for the same biodiversity attributes (Marshall et al., 2020; May, 2017; zu Ermgassen et al., 2019), which makes data synthesis across projects effectively impossible. Furthermore, monitoring results might be ignored by the regulator, even if they show clear failure or divergence from intended gains (Maron et al., 2012; Brown et al., 2013). Finally, monitoring results are rarely made public and in no cases are there public summaries that could be used to assess the success of offset schemes (zu Ermgassen et al., 2019; Kujala et al., 2022). Consequently, countries should also adopt publicly accessible offset registers, where details of offset plans and monitoring can be accessed transparently (Blicharska et al., 2022; Kujala et al., 2022). Learning cannot be achieved, and significant resources will thus be wasted, if details of offset plans and implementation remain hidden due to poor environmental governance or business confidentiality.

There is an awkward and important question to be addressed: can monitoring without a proper design be a waste of resources and do more harm than good? If we utilize varying designs with no controls and small sample size, there is an illusion of creating information about offset outcomes while in reality estimates might be significantly off and attribute to false trends, or the data may be incompatible for useful analyses. It seems evident that as the bare minimum we need to shift from current *ad hoc* practices to more standardised monitoring requirements for individual offset projects so that the utility of monitoring results can be increased. This requires active guidance from authorities that govern environment-related regulation.

In theory, monitoring schemes that allow continued learning and improvement of offset actions could correct many of the frequently mentioned challenges around biodiversity offsetting. Reducing uncertainty around offset outcomes reduces the need of regulatory scrutiny and large multipliers, thereby lowering offset costs. Yet, achieving such informative data from monitoring requires long-term commitment to coordinated, skilfully designed and well-funded monitoring schemes, strong environmental regulation including legal accountability and potential cost-sharing between developers and the society, despite the Polluter Pays Principle.

Here we have focused on the monitoring of offsets implemented by restoration or management. We have not addressed the design of avoided (averted) loss offsets via protection, which also requires large-scale information about the causes and actual rates of biodiversity loss in different environments (Gordon et al., 2015; Maseyk et al., 2020). Going beyond offsetting, there is an increasing global need to implement ecological restoration under changing environmental conditions. Here, the same conservation actions as used in offsetting can also be implemented due to motivations different from offsetting.

CRediT authorship contribution statement

Panu Halme: Writing – original draft, Funding acquisition, Conceptualization. **Eini Nieminen:** Writing – original draft, Conceptualization. **Janne Kotiaho:** Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Atte Moilanen:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Funding acquisition, Conceptualization. **Heini Kujala:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Joel Jalkanen:** Writing – original draft, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

Acknowledgments

All authors thank the Academy of Finland and Strategic Research Council grant #345709 (project BOOST), for support.

References

Bezombes, L., Kerbiriou, C., Spiegelberger, T., 2019. Do biodiversity offsets achieve No Net Loss? An evaluation of offsets in a French department. Biol. Conserv. 231, 24–29.
Blicharska, M., Hedblom, M., Josefsson, J., Widenfalk, O., Ranius, T., Öckinger, E., Widenfalk, L.A., 2022. Operationalisation of ecological compensation–obstacles and ways forward. J. Env. Manag. 304, 114277.
Brown, M.A., Clarkson, B.D., Barton, B.J., Joshi, C., 2013. Ecological compensation: an evaluation of regulatory compliance in New Zealand. Impact Assess. Proj. Apprais. 31 (1) https://doi.org/10.1080/14615517.2012.762168.
Bull, J.W., Gordon, A., Law, E.A., Suttle, K.B., Milner-Gulland, E.J., 2014. Importance of Baseline Specification in Evaluating Conservation Interventions and Achieving No Net Loss of Biodiversity. Conserv. Biol. 28, 799–809.
Bull, J.W., Suttle, K.B., Gordon, A., Singh, N.J., Milner-Gulland, E.J., 2013. Biodiversity offsets in theory and practice. Oryx 47, 369–380.
Burgman, M., Carr, A., Godden, L., Gregory, R., McBride, M., Flander, L., Maguire, L., 2011. Redefining expertise and improving ecological judgment. Conserv. Lett. 4, 81–87.
Butsic, V., Lewis, D.J., Radeloff, V.C., Baumann, M., Kuemmerle, T., 2017. Quasi-experimental methods enable stronger inferences from observational data in ecology. Basic Appl. Ecol. 19, 1–10.

Calvet, C., Le Coent, P., Napoleone, C., Quetier, F., 2019. Challenges of achieving biodiversity offset outcomes through agri-environmental schemes: Evidence from an empirical study in Southern France. Environ. Econ. 165, 113–125.
Carvalho, S.B., Gonçalves, J., Guisan, A., Honrado, J.P., 2016. Systematic site selection for multispecies monitoring networks. J. Appl. Ecol. 53, 1305–1316.
Christie, A., Amano, T., Martin, P., Abecasis, D., Adjeroud, M., Alonso, J.C., et al., 2020. Quantifying and addressing the prevalence and bias of study designs in the environmental and social sciences. Nat. Comm. 11 (1), 11.
Clare, S., Krogman, N., 2013. Bureaucratic slippage and environmental offset policies: the case of wetland management in Alberta. Soc. Nat. Resour. 26, 672–687. https://doi.org/10.1080/08941920.2013.779341.
Cousins, L.J., 2016. Biodiversity Assessment: moving towards an evidence-based index for biodiversity offsetting. PhD thesis, Univ. Essex. 〈https://repository.essex.ac.uk/16676/〉.
Cristescu, R.H., Rhodes, J., Frére, C., Banks, P.B., 2013. Is restoring flora the same as restoring fauna? lessons learned from koalas and mining rehabilitation. J. Appl. Ecol. 50, 423–431. https://doi.org/10.1111/1365-2664.12046.
Damiens, F.L.P., Backstrom, A., Gordon, A., 2021. Governing for “no net loss” of biodiversity over the long term: challenges and pathways forward. One Earth 4, 60–74. https://doi.org/10.1016/j.oneear.2020.12.012.
De Palma A., Sanchez-Ortiz K., Martin P.A., Chadwick A., Gilbert G., Bates A.E., Börger L., Contu S., Hill S.L.L., Purvis A. 2018. Chapter four - Challenges with inferring how land-use affects terrestrial biodiversity: study design, time, space and synthesis. Pp. 163–199 in Bohan D.A., Dumbrell A.J., Woodward G, and Jackson M., (eds). Next Generation Biomonitoring: Part 1. Advances in Ecological Research 58. https://doi.org/10.1016/bs.aecr.2017.12.004.
Devictor, V., Julliard, R., Clavel, J., Jiguet, F., Lee, A., Couvet, D., 2008. Functional biotic homogenization of bird communities in disturbed landscapes. Glob. Ecol. Biogeogr. 17, 252–261. https://doi.org/10.1111/j.1466-8238.2007.00364.x.
Dorrough, J., Sinclair, S.J., Oliver, I., 2019. Expert predictions of changes in vegetation condition reveal perceived risks in biodiversity offsetting. PLOS ONE 14 (5).
Ferraro, P.J., 2009. Counterfactual thinking and impact evaluation in environmental policy. N. Dir. Eval. 2009, 75–84.
Gamarra, M.J.C., Toombs, T.P., 2017. Thirty years of species conservation banking in the US: Comparing policy to practice. Biol. Conserv. 214, 6–12.
Gibbons, P., Lindenmayer, D.B., 2007. Offsets for land clearing: no net loss or the tail wagging the dog? Ecol. Manag. Restor. 8, 26–31.
Gibbons, P., Macintosh, A., Constable, A.L., Hayashi, K., 2018. Outcomes from 10 Years of Biodiversity Offsetting. Glob. Change Biol. 24, e643–e654.
GIBOP, 2019. Global Inventory of Biodiversity Offset Policies (GIBOP). International Union for Conservation of Nature. The Biodiversity Consultancy, Durrel, UK.
Gordon, A., Bull, J.W., Wilcox, C., Maron, M., 2015. Perverse incentives risk undermining biodiversity offset policies. J. Appl. Ecol. 52, 532–537.
Guillet, F., Semal, L., 2018. Policy flaws of biodiversity offsetting as a conservation strategy. Biol. Conserv. 221, 86–90.
Hanford, J.K., Crowther, M.S., Hochuli, D.F., 2017. Effectiveness of vegetation-based biodiversity offset metrics as surrogates for ants. Conserv. Biol. 31, 161–171. https://doi.org/10.1111/cobi.12794.
Henry, P.Y., Lengyel, S., Nowicki, P., Julliard, R., Clobert, J., Čelik, T., Henle, K., 2008. Integrating ongoing biodiversity monitoring: potential benefits and methods. Biodiv. Conserv. 17, 3357–3382.
IUCN, 2016. IUCN Policy on Biodiversity Offsets. International Union for Conservation of Nature. 〈https://portals.iucn.org/library/sites/library/files/resrecfiles/WCC_2016_RES_059_EN.pdf〉.
Josefsson, J., Hiron, M., Arlt, D., Auffret, A.G., Berg, Å., Chevalier, M., Glimskär, Q., et al., 2020. Improving scientific rigour in conservation evaluations and a plea deal for transparency on potential biases. Conserv. Lett. 13, e12726.
Josefsson, J., Widenfalk, L.A., Blicharska, M., Hedblom, M., Part, T., Ranius, T., Ockinger, E., 2021. Compensating for lost nature values through biodiversity offsetting-Where is the evidence? Biol. Conserv. 257, 109117.
Kujala, H., Maron, M., Kennedy, C.M., Evans, M.C., Bull, J.W., Wintle, B.A., et al., 2022. Credible biodiversity offsetting needs public national registers to confirm no net loss. One Earth 5, 650–662.
Le Texier, M., Gelot, S., Pioch, S., 2024. Big Cities, Big Impacts? A spatial analysis of 3,335 ecological offsets in France since 2012. J. Environ. Manag. 357, 120704.
Legg, C.J., Nagy, L., 2006. Why most conservation monitoring is, but need not be, a waste of time. J. Env. Manag. 78, 194–199.
Levrel, H., Pioch, S., Spieler, R., 2012. Compensatory mitigation in marine ecosystems: Which indicators for assessing the "no net loss" goal of ecosystem services and ecological functions? Mar. Policy 36, 1202–1210.
Lindenmayer, D.B., Crane, M., Evans, M.C., Maron, M., Gibbons, P., Bekessy, S., Blanchard, W., 2017. The anatomy of a failed offset. Biol. Conserv. 210, 286–292.
Lockhart, A., 2015. Developing an offsetting programme: tensions, dilemmas and difficulties in biodiversity market-making in England. Environ. Conserv. 42, 335–344.
Loughin, T.M., Bennett, S.N., Bouwes, N., 2021. Comparison of staircase and asymmetrical before–after, control–impact (ABACI) experimental designs to test the effectiveness of stream restoration at increasing juvenile steelhead density. Can. J. Fish. Aquat. Sci. 78, 670–680. https://doi.org/10.1139/cjfas-2020-0096.
Mahlum, S., Cote, D., Wiersma, Y.F., Pennell, C., Adams, B., 2018. Does restoration work? It depends on how we measure success. Restor. Ecol. 26, 952–963. https://doi.org/10.1111/rec.12649.
Maron, M., Brownlie, S., Bull, J.W., Evans, M.C., von Hase, A., Quétier, F., Watson, J.E.M., Gordon, A., 2018. The many meanings of no net loss in environmental policy. Nat. Sust. 1, 19–27.
Maron, M., Hobbs, R.J., Moilanen, A., Matthews, J.W., Christie, K., Gardner, T.A., Keith, D., Lindenmayer, D.B., McAlpine, C.A., 2012. Faustian bargains? Restoration realities in the context of biodiversity offset policies. Biol. Conserv. 155, 141–148.
Maron, M., Ives, C.D., Kujala, H., Bull, J.W., Maseyk, F.J.F., Bekessy, S., Gordon, A., et al., 2016. Taming a wicked problem: resolving controversies in biodiversity offsetting. BioScience 66, 489–498. https://doi.org/10.1093/biosci/biw038.
Marshall, E., Valavi, R., O' Connor, L., Cadenhead, N., Southwell, D., Wintle, B.A., Kujala, H., 2020. Quantifying the impact of vegetation-based metrics on species persistence when choosing offsets for habitat destruction. Conserv. Biol. 35, 567–577. https://doi.org/10.1111/cobi.13600.
Marshall, E., Wintle, B.A., Southwell, D., Kujala, H., 2020b. What are we measuring? A review of metrics used to describe biodiversity in offsets exchanges. Biol. Conserv. 241, 108250 https://doi.org/10.1016/j.biocon.2019.108250.
Maseyk, F.J., Maron, M., Gordon, A., Bull, J.W., Evans, M.C., 2020. Improving averted loss estimates for better biodiversity outcomes from offset exchanges. Oryx 55, 393–403.
May, et al., 2017. Are Offsets Effective? An Evaluation of Recent Environmental Offsets in Western Australia. Biol. Conserv. 206, 249–257. https://doi.org/10.1016/j.biocon.2016.11.038.
McKenney, B.A., Kiesecker, J.M., 2010. Policy development for biodiversity offsets: a review of offset frameworks. Env. Manag. 45, 165–176.
Moilanen, A., Kotiaho, J.S., 2018. Fifteen operationally important decisions in the planning of biodiversity offsets. Biol. Conserv. 227, 112–120.
Morgan, J.A., Hough, P., 2015. Compensatory Mitigation Performance: The State of the Science. Natl. Wetl. Newsl. 37, 5–13.
Nash, J.R., 2000. Too much market? Conflict between tradable pollution allowances and the polluter pays principle. Harv. Environ. Law Rev. 24, 1–59.
Peterson, I., Maron, M., Moilanen, A., Bekessy, S., Gordon, A., 2018. A quantitative framework for evaluating the impact of biodiversity offset policies. Biol. Conserv. 224, 162–169. https://doi.org/10.1016/j.biocon.2018.05.005.
Pope, J., Morrison-Saunders, A., Bond, A., Retief, F., 2021. When is an offset not an offset? A framework of necessary conditions for biodiversity offsets. Environ. Manag. 67, 424–435.
Poulin, M., Pellerin, S., Cimon-Morin, J., Lavalle, S., Courchesne, G., Tendland, Y., 2016. Inefficacy of wetland legislation for conserving Quebec wetlands as revealed by mapping of recent disturbances. Wetl. Ecol. Manag. 24, 651–665.
Quigley, J.T., Harper, D.J., 2006. Compliance with Canada's Fisheries Act: A field audit of habitat compensation projects. Env. Manag. 37, 336–350. https://doi.org/10.1007/s00267-004-0262-z.
Rainey, H.J., Pollard, E.H.B., Dutson, G., Ekström, J.M.M., Livingstone, S.R., Temple, H.J., Pilgrim, J.D., 2015. A review of corporate goals of nonet loss and net positive impact on biodiversity. Oryx 49, 232–238.
Salzman, J., Bennett, G., Carroll, N., Goldstein, A., Jenkins, M., 2018. The Global Status and Trends of Payments for Ecosystem Services. Nat. Sust. 1, 136–144. https://doi.org/10.1038/s41893-018-0033-0.

Schmeller, D.S., Böhm, M., Arvanitidis, C., Barber-Meyer, S., Brummitt, N., Chandler, M., Belnap, J., 2017. Building capacity in biodiversity monitoring at the global scale. Biodiv. Conserv. 26, 2765–2790.
Spash, C.L., 2015. Bulldozing biodiversity: The economics of offsets and trading-in Nature. Biol. Conserv. 192, 541–551.
Sutherland, W.J., Taylor, N.G., MacFarlane, D., Amano, T., Christie, A.P., Dicks, L.V., et al., 2019. Building a tool to overcome barriers in research-implementation spaces: The Conservation Evidence database. Biol. Conserv. 238, 108199.
Theis, S., Ruppert, J.L., Roberts, K.N., Minns, C.K., Koops, M., Poesch, M.S., 2020. Compliance with and ecosystem function of biodiversity offsets in North American and European freshwaters. Conserv. Biol. 34, 41–53.
Thorn, S., Hobbs, R.J., Valentine, L.E., 2018. Effectiveness of biodiversity offsets: An assessment of a controversial offset in Perth, Western Australia. Biol. Conserv. 228, 291–300.
Tischew, et al., 2010. Evaluating restoration success of frequently implemented compensation measures: results and demands for control procedures. Restor. Ecol. 18, 467–480. https://doi.org/10.1111/j.1526-100X.2008.00462.x.
UK DEFRA 2024. Biodiversity net gain. UK Government, 〈https://www.gov.uk/government/collections/biodiversity-net-gain〉, accessed May 22, 2024.
W. Wende, G.-M. Tucker, F. Quétier, M. Rayment, M. Darbi, Switzerland. In: W. Wende, G.-M. Tucker, F. Quétier, M. Rayment, M. Darbi (Eds.), Biodiversity Offsets: European perspectives on no net loss of biodiversity and ecosystem services. Springer International Publishing, 2018.
Walker, S., Brower, A.L., Stephens, R.T.T., Lee, W.G., 2009. Why bartering biodiversity fails. Conserv. Lett. 2, 149–157.
zu Ermgassen, S., Baker, J., Griffiths, R.A., Strange, N., Struebig, M.J., Bull, J.W., 2019. The ecological outcomes of biodiversity offsets under "no net loss" policies: A global review. Conserv. Lett. 12, e12664.