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Systematic nature positive markets

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Abstract

Environmental markets are a rapidly emerging tool to mobilize private funding to incentivize landholders to undertake more sustainable land management. How units of biodiversity in these markets are measured and subsequently traded creates key challenges ecologically and economically because it determines whether environmental markets can deliver net gains in biodiversity and efficiently lower the costs of conservation. We developed and tested a metric for such markets based on the well-established principle of irreplaceability from systematic conservation planning. Irreplaceability as a metric avoids the limitations of like-for-like trading and allows one to capture the multidimensional nature of ecosystems (e.g., habitats, species, ecosystem functioning) and simultaneously achieve cost-effective, land-manager-led investments in conservation. Using an integrated ecological modeling approach, we tested whether using irreplaceability as a metric is more ecologically and economically beneficial than the simpler biodiversity offset metrics typically used in net gain and no-net-loss policies. Using irreplaceability ensured no net loss, or even net gain, of biodiversity depending on the targets chosen. Other metrics did not provide the same assurances and, depending on the flexibility with which biodiversity targets can be achieved, and how they overlap with development pressure, were less efficient. Irreplaceability reduced the costs of offsetting to developers and the costs of ecological restoration to society. Integrating economic data and systematic conservation planning approaches would therefore assure land managers they were being fairly rewarded for the opportunity costs of conservation and transparently incentivize the most ecologically and economically efficient investments in nature recovery.

KEYWORDS
biodiversity net gain, irreplaceability, offset market, prioritization

Mercados sistemáticos que favorecen a la naturaleza

Resumen: Los mercados ambientales se están convirtiendo rápidamente en una herramienta para movilizar el financiamiento privado que incentiva a los terratenientes a realizar un manejo de suelo más sustentable. La forma de medir las unidades de biodiversidad y su intercambio subsecuente en estos mercados genera retos ecológicos y económicos importantes pues determina si el mercado ambiental puede generar ganancias netas de biodiversidad y reducir eficientemente el costo de la conservación. Desarrollamos y probamos una medida para dichos mercados con base en el principio bien establecido del carácter irremplazable tomado de la planeación sistemática de la conservación. Si se usa como medida, este carácter evita las limitantes del comercio en términos comparables y permite que se capture la naturaleza multidimensional de los ecosistemas (p. ej.: hábitats, especies, funcionamiento) y a la vez consigue inversiones rentables llevadas por el gestor para la conservación. Usamos una estrategia de modelado ecológico integrado para probar si usar el carácter irremplazable como medida tiene más beneficios ecológicos y económicos que las medidas más simples de compensación de la biodiversidad que se usan comúnmente en las políticas sin pérdida neta y de ganancia neta. El uso del carácter irremplazable aseguró que no hubiera pérdida neta o incluso ganancia neta de la biodiversidad según el objetivo elegido. Las otras medidas no proporcionaron la misma seguridad y fueron menos eficientes según la flexibilidad con la cual se logran los objetivos de biodiversidad y cómo se traslapan con la presión del desarrollo. El carácter irremplazable redujo los costos de la compensación para los desarrolladores y los costos de la restauración ecológica para la sociedad. Por lo tanto, la integración de los datos económicos y las estrategias de planeación sistemática de la conservación les asegurarían a los gestores de los terrenos que se les está compensando de manera justa por los costos de oportunidad de conservación e incentivaría con transparencia las inversiones con mayor eficiencia ecológica y económica en la recuperación de la naturaleza.

PALABRAS CLAVE
ganancia neta de biodiversidad, irremplazable, mercado de compensación, priorización

系统性自然向好市场

【摘要】环境市场是一种正在迅速崛起的工具, 它通过调动私人资金来激励土地所有者采取更可持续的土地管理措施。如何衡量这些市场中的生物多样性单位并进行交易, 是生态学和经济学上的重要挑战, 因为它决定了环境市场能否带来生物多样性净收益并有效降低保护成本。我们基于系统性保护规划中已被广泛接受的不可替代性原则, 为此类市场开发了一种衡量指标并进行了检验。不可替代性作为一种指标, 避免了同类交易的局限性, 使人们能够捕捉到生态系统的多维性(如栖息地、物种、生态系统功能), 并同时实现由土地管理者主导、具有成本效益的保护投资。利用综合生态建模方法, 我们检验了使用不可替代性作为指标是否能在生态和经济上优于“净收益”和“无净丧失”政策中常用的更简单的生物多样性补偿指标。结果表明, 根据所选目标的不同, 使用不可替代性指标可确保生物多样性无净丧失甚至得到净收益。然而, 其他指标不能提供同样的保证, 且根据实现生物多样性目标的灵活性以及这些目标与发展压力的重叠情况, 其他指标的效率均低于不可替代性指标。不可替代性指标还降低了开发商的补偿成本和社会的生态恢复成本。因此, 将经济数据与系统性保护规划方法相结合, 可确保土地管理者在保护的机会成本方面得到公平的回报, 并透明地激励自然恢复中最具生态和经济效益的投资。**【翻译:胡怡思;审校:聂永刚】**

关键词: 不可替代性, 优先排序, 补偿市场, 生物多样性净收益

INTRODUCTION

More than 75% of Earth's land is degraded, and this has led to widespread biodiversity loss, undermining the well-being of billions of people and efforts to combat climate change (IPBES, 2019). Current evidence suggests multiple planetary thresholds have been exceeded (Steffen et al., 2015) and business as usual is highly likely to result in catastrophic collapse across many ecosystems (Armstrong McKay et al., 2022). Yet, numerous global commitments to reduce, stop, or even reverse current rates of biodiversity loss have not been met (Díaz et al., 2019; Tittensor et al., 2014). Instead, reversing global terrestrial biodiversity trends will only be achievable if strategic, coordinated, and above all ambitious actions are adopted (Leclère et al., 2020). To achieve a nature-positive future, private-sector funding of biodiversity conservation needs to be increased to complement established publicly funded programs. The ENACT initiative (Enhancing Nature-based Solutions for an Accelerated Climate Transformation) launched at COP27 calls for the mobilization of private finance to support action on nature and climate-related targets the world over, accompanied by robust environmental and social safeguards (IUCN, 2022).

Environmental markets can be used to mobilize private financing, which can incentivize landholders to undertake more sustainable land management actions (Schmalensee & Stavins, 2017). Such markets create income streams in the form of tradeable credits for landholders in return for undertaking actions to protect or enhance specified environmental goods and services, for example, biodiversity, carbon sequestration, and water quality. Demand (and thus buyer willingness to pay [WTP]) for these credits can be voluntary, arising from a demand from individuals or companies who wish to offset their negative environmental impacts, or they are created through government regulation, for example, through requiring developers to purchase credits to offset new buildings (Needham et al., 2019; Radu et al., 2020).

We considered regulated markets for biodiversity offsets where developers must purchase credits to mitigate impacts on biodiversity as a result of development activities, such as mine construction, housing, road building, and hydroelectric dams. Credits are supplied by landowners who switch their current land management (e.g., arable farming) to a more conservation-orientated alternative (e.g., wetland creation). In regulated offset markets, state-sanctioned intermediary bodies, such as offset banks, validate credits and enforce offset requirements placed on developers. By establishing an appropriate rate of exchange between sellers (landowners) and buyers (developers), biodiversity offset markets can, in principle, achieve no net loss of biodiversity or a net gain in some defined area at the lowest overall economic cost to society and are thus potentially economically efficient (Needham et al., 2019).

In regulated and voluntary nature markets, the choice of biodiversity metric plays a pivotal role in determining the market's ecological and economic performance (Simpson et al., 2021). This metric establishes the units in which biodiversity is traded, determining how a regulator or offset bank measures the gains in biodiversity resulting from restoration actions undertaken by landowners, and balances those gains against the expected biodiversity loss due to development. Simple metrics based on a combination of the area and condition of habitat are often preferred by regulators (Bull et al., 2014; zu Ermgassen et al., 2019) because it is easy to identify matching biodiversity units and because they are based on the assumption that habitat classes indirectly capture benefits on other aspects of the ecosystem (Marshall et al., 2020). However, these approaches rarely benefit biodiversity in the manner intended, or they fail to deliver gains in biodiversity in an economically efficient manner (Bull et al., 2014; Maron et al., 2012; zu Ermgassen et al., 2021).

We developed and then applied a new metric for application in biodiversity offset markets, and in environmental markets more broadly, that derives from the systematic conservation planning (SCP) literature (Margules & Pressey, 2000; McIntosh et al., 2017). Tools of SCP are designed to minimize the cost of achieving conservation targets. The importance of any specific site to achieving conservation targets is measured by its irreplaceability. A site that is essential to achieving targets is completely irreplaceable (i.e., its loss cannot be offset), whereas irreplaceability is low for sites that can be easily substituted for many others to contribute to conservation targets. Crucially, irreplaceability combines the importance of a specific site over multiple biodiversity features and thus captures trade-offs between features and ensures that overarching targets for each feature are achieved at the landscape scale. Irreplaceability represents a step change away from like-for-like compensation regimes in existing biodiversity offset markets (e.g., BBOP, 2009; Natural England, 2022; NSW DPE, 2022). Furthermore, if conservation targets are chosen to exceed their existing availability in a landscape, this embeds net gain as an implicit outcome where it is needed to meet specific targets.

We sought to demonstrate that an offset market steered by a metric derived from irreplaceability ensures the opportunity to achieve conservation targets is always protected and results in a network of conserved sites selected for being more economically efficient than sites obtained using simpler offset metrics. Irreplaceability as a metric thus offers a step change in the design of biodiversity offsets and environmental markets, which is important given the current fast rate of expansion in such nature markets globally.

METHODS

Irreplaceability recast for biodiversity offset markets

SCP is a rigorous, repeatable, and structured approach to designing protected areas that efficiently meet conservation objectives (Margules & Pressey, 2000). At an analytical level, the task is a classic resource allocation problem that either maximizes conservation outcomes within a given resource budget or minimizes the cost of achieving specified conservation targets (Moilanen et al., 2009). This structure has led to the use of SCP in supporting conservation decisions across the globe (McIntosh et al., 2017). A key strength of SCP is that it can be used to incorporate a wide variety of data types, including attributes of ecosystems at all levels of structural, taxonomic, and functional organization, as well as accounting for social, financial, and political constraints and opportunities (Ban et al., 2013; Knight et al., 2011). Suitable targets are often based on the principle of adequacy, which aims to maintain the viability and persistence of those features (Kukkala & Moilanen, 2013). Species-level targets may be informed by population viability analyses or habitat-level targets by species–area relationships, and functional targets may be informed by the need for particular services across landscapes (Bryan et al., 2010).

The value of any specific site is based on its marginal contribution to achieving the conservation targets by complementing what features are already secured. A key feature therefore of SCP is that, unlike ranking procedures, properties of reserve systems emerge from the combination of areas either through the complementarity of their composition or their connectivity in space. This suggests a strong potential advantage for using a metric derived from SCP in biodiversity offset markets, where a need exists to be able to compare ecological gains and losses across space between development sites (where biodiversity declines) and offset supply sites (where biodiversity is increased due to the action of the landowner). Moreover, a biodiversity offset metric needs to make sense in the context of an overall policy target of no net loss or net gain in a specific aggregate indicator of biodiversity. This combination of an aggregate target with the need to compare gains and losses across space suggests that a metric derived from SCP could have important advantages over the kinds of metrics investigated so far in the offset markets literature (Simpson et al., 2022).

Provided with data on feature values for all planning units, planning unit costs, and the desired targets for protection, SCP tools can be used to identify which sets of sites deliver conservation targets most efficiently (Moilanen et al., 2009). For convenience, we refer to features and planning units as species and sites, respectively, hereafter. Often targets can be achieved by many different combinations of sites because alternatives exist with similar, or at least complementary, values. The importance of any specific site to achieving conservation targets is measured by its irreplaceability. A site that is essential to achieving targets is irreplaceable (and its loss could not be offset), whereas irreplaceability is low for sites that can be substituted by many others. An exact calculation of irreplaceability rapidly becomes intractable as the number of combinations to test grows exponentially with the number of planning units (Pressey et al., 1993), and alternatives to estimate irreplaceability have been proposed (Ferrier et al., 2000). Most recently, Baisero et al. (2021) proposed a new metric for describing irreplaceability (α) that defines the extent to which a site k is essential for achieving the conservation of species s as

$$\alpha_{k,s} = \begin{cases} 0 & \text{if } t_s = 0, \\ 0 & \text{if } t_s \geq R'_s \text{ and } R_{k,s} = 0, \\ 1 & \text{if } t_s \geq R'_s \text{ and } R_{k,s} > 0, \\ \min\left(\frac{R_{k,s}}{R'_s - t_s},\ 1\right) & \text{otherwise,} \end{cases} \quad (1)$$

where the difference between the total availability of a species in the landscape R'_s and its target t_s indicates how much of that availability a site can contain ($R_{k,s}$) before it becomes irreplaceable. Baisero et al. (2021) defined β as the combined irreplaceability of a site by taking the complement of the product of replacement probabilities $\beta = 1 - \Pi(1 - \alpha_{k,s})$. However, this constrains site irreplaceability to between 0 and 1; consequently, it no longer indicates whether a site was irreplaceable for 1 or many species. To retain this distinction and make comparisons among sites in an offset market equivalent, we use summed α irreplaceability. Ferrier et al. (2000) also summed irreplaceability for a similar reason (albeit with a different formulation for each species); therefore, hereafter we refer to the sum of α irreplaceability ($\sum \alpha_{k,s}$), which we abbreviate it as $\sum\alpha$.

The biodiversity offset market

The structure of the biodiversity offset market was based on the model developed by Simpson et al. (2021). A single agent controls each land parcel or site in a landscape. Each agent decides to develop the land for housing, generate biodiversity offset credits by adopting a conservation land management practice, or keep the current land use of agriculture. For an agent to develop the land, each hectare acquired for, for example, new housing requires a number of offset credits to be purchased from an offset provider equal to the measured biodiversity value of the site. The developer's maximum WTP for an offset credit is determined by the expected value of land for housing and the need to purchase offset credits. Ranking this WTP from highest to lowest yields a downward-sloping demand curve for offset credits. This WTP varies over space due to variations in house prices and the value of each site for biodiversity. We assumed offset credits are supplied by agents on agricultural land (i.e., farmers). Farmers change their current agricultural land management practices in a way that increases biodiversity by a measured amount at the site. Every hectare given up to benefit biodiversity means 1 less hectare for agricultural production. Furthermore, the farmer may incur restoration costs in creating an offset credit. Therefore, the conversion cost to the farmer consists of the opportunity costs of the foregone agricultural output plus any associated restoration costs. This sum is the minimum price a farmer would be willing to sell an offset credit for, known as the minimum willingness to accept (WTA). Because agricultural productivity and profits vary across space (due, e.g., to variations in soil quality or site elevation), the minimum WTA of farmers to create biodiversity credits will also vary over space. Ranking farmers from lowest WTA to highest WTA generates a supply curve for offsets. Farmers and developers interact in this market to generate an equilibrium, market-clearing price for offsets at which marginal WTP and marginal WTA are equal, that is, where supply for credits equals the demand for credits.

Simulation

To demonstrate the operation of a biodiversity offset market with the $\sum\alpha$-irreplaceability metric, we simulated the probability of species occurrence in a 64 × 64 patch (or site) landscape. We used the R packages NLMR and landscapetools to control the degree of spatial autocorrelation in the baseline environmental gradient (Sciaini et al., 2018). However, α irreplaceability is determined by the global availability of that species, not its distribution, and the simulation of maps was solely intended to communicate the parallels with field data and empirical models. We simulated 3 communities, each with 200 species, with distributions that were either equally distributed across the environmental gradient or moderately and highly skewed toward one extreme to produce an overall gradient in richness (Leroy et al., 2016). We ran offset market simulations based on subsets of species from each community. The number of species rose from 5 to 50, and each simulation was repeated 10 times. More complex arrangements in response to multiple gradients are easily generated, but we did not consider them here. Likewise, we did not account for time lags or uncertainties in the ability of conservation actions to generate offset credits.

Four further pieces of information were generated for each site. The values of each patch of land for agriculture and for housing development were generated by defining their correlation to the environmental gradient (ranging from 0 to 1), although without a clear rationale for how these costs are expected to covary, both correlation coefficients were set to zero simulations. To reduce the likelihood that market trading stalls when WTA < WTP (and where therefore potential gains from trade still exist), the mean development value was set to double that of agricultural value. Next, each site was assigned to 1 of 3 initial land-use classes: agriculture, conservation, and development in a 70:20:10 split. Finally, a habitat layer was generated to indicate where habitat, and hence species, currently occurs on agricultural land and in conserved sites so as to define the baseline from which gains should be compared. Agricultural land patches without habitat but with suitable environmental conditions for species to occur were treated as areas with restoration potential. The final inputs were the conservation targets for each species. To illustrate a scenario of net gain, rather than no net loss, we set targets in all scenarios to be the equivalent of each species existing availability plus 20% of their restoration potential at agricultural sites.

After each offset trade, the $\sum\alpha$ irreplaceability was recalculated for all sites. An agricultural site that was not irreplaceable for any species (all individual $\alpha < 1$) and had the greatest WTP per unit loss in the metric (£/$\sum\alpha$) was selected for development. If the development site $\sum\alpha$ was 0 because the site had no species potential or because all species with potential had already achieved their targets, then no offset was required. Otherwise, an offset site with the lowest WTA per unit gain in the metric (£/$\sum\alpha$) was selected and either all or a fraction of species values at that site were assigned to the conservation class. The species values at the developed sites were removed from the global total R_s', and the values added by the offset were deducted from the remaining targets (t_s). These steps were repeated until all species conservation targets had been achieved or until there were no mutually beneficial opportunities to trade in biodiversity credits remaining (i.e., a market equilibrium where for all remaining sites WTP < WTA).

To rate the performance of an offset market based on $\sum\alpha$ irreplaceability, we compared the efficiency with which targets were achieved using alternative metrics for the same landscape. First, the R package prioritizr was used to identify the exact optimal combination of sites that achieved all conservation objectives for minimal cost (Hanson et al., 2022). Second, the offset market was rerun with 3 alternative site-based metrics that increasingly reduced the need for the information involved in strategic planning. The first offset metric (OM1) weighted site scores by the inverse of each species range, thereby favoring the rarest taxa in the landscape (Crisp et al., 2001). The OM1 scores were continually updated to reflect changes in global availability due to the market. The OM1 metric would require the same degree of knowledge as for the calculation of $\sum\alpha$ irreplaceability but without setting targets. Updates to planning unit scores reflected species' global availability but were not complementarity to areas already protected. Offset metric 2 (OM2) was equivalent to OM1, but values for each planning unit were not updated over time, meaning weights for each species were fixed at their starting value. This metric required the same initial understanding of species distributions as for OM1 but did not require an updating register of species affected by previous offset transactions. Finally, offset metric 3 (OM3) was based solely on how many species were present in each site, but not which species, meaning only a map of species richness would be required to guide a market.

The code and a full description of the results are in Appendix S1.

RESULTS

Economic efficiency of irreplaceability

Use of $\sum\alpha$ in an offset market resulted in continuous incremental progress toward conservation targets (Figure 1a). The potential economic gains from trade were realized as long as developers WTP exceeded farmers WTA, and this trading allowed conservation targets to be achieved for all species. Economic gains from trade were initially high when trading began (WTP >> WTA) (Figure 1b), but they declined rapidly as more expensive and less irreplaceable offsets were required to meet demand. At each stage, the market favored the greatest gains toward targets at the least cost, making an economically efficient solution more likely. Conversely, $\sum\alpha$ strongly disincentivized development on land with high $\sum\alpha$ scores because the number of offset sites required to replace their loss was typically prohibitive (Figure 1c).

The $\sum\alpha$ irreplaceability did not specifically prioritize sites that contained species rarely found in the landscape; it valued sites based on the difficulty of achieving conservation targets without them. Nonetheless, because there were typically fewer opportunities to conserve rare species (i.e., low replaceability), sites that contained those species tended to have high scores. Once a species target was reached (green line Figure 1d), its contribution to the $\sum\alpha$ of remaining agricultural sites was zero, meaning there was no benefit to its presence in new offsets or cost associated with its occurrence at new development sites. Nonetheless, some species eventually exceeded their targets because they were present at offset sites added later to achieve targets for other species (Figure 1a,d). Because the $\sum\alpha$ contribution of species with targets that had been met was zero, the burden for developers decreased and their WTP for offsets increased at sites that contained species whose targets had been met (red line Figure 1d).

Accounting for more species in the market

The distribution of biodiversity, in particular the degree of spatial overlap among multiple targets, determines the extent to which additional sites are required to protect additional species. The network was specific to the assemblage and how the ecological community correlated spatially with economic land values (Figure 2). Accounting for conservation targets of more species did not in itself increase the cost of conservation solutions, require more trades, or demand more space to meet targets (Figure 2b,c).

Irreplaceability-led offsetting versus optimal prioritization

Site prioritizations generated by SCP were mathematically optimal; they minimized the cost of land needed to achieve all conservation targets (Figure 3). When we assumed developer's

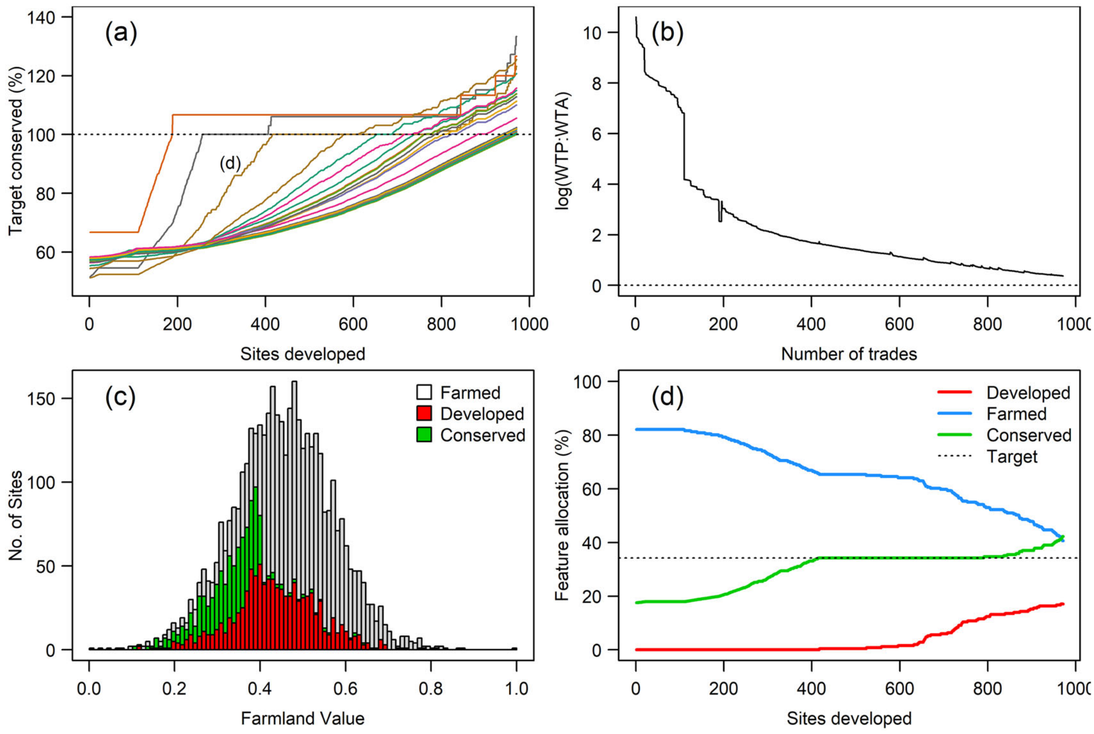

FIGURE 1 Example of a simulated offset market based on $\sum\alpha$ irreplaceability (i.e., the combined progress a site would deliver toward conservation goals for all species relative to the opportunity to achieve those goals elsewhere): (a) progress toward conservation targets (dotted line) for each species as new developments requiring offsets are built, (b) decline in the log ratio between willingness to pay (WTP) and willingness to accept (WTA) as representative of gains from trade, (c) distribution of values for purchasing agricultural land in the simulated landscape and the final proportion of those selected for development and conservation offsets, and (d) changes in the allocation of a single species (also identified in panel [a]) among land types as trading progresses.

WTP was sufficient to support continued trading, the $\sum\alpha$ offset market achieved all targets based on ~~a~~ very different networks of sites than the SCP solution (Figure 3b). In some cases, the $\sum\alpha$ offset market required fewer sites in total (Figure 3a), but the total cost of conserved sites was always equal to or, more likely, greater than SCP solutions. The total cost of sites selected for conservation in an $\sum\alpha$ offset market was only 2–11% greater than that with SCP, but this gap narrowed as the number of species increased (Figure 3c) because the flexibility by which all targets could be achieved was reduced. Conservation solutions selected by the market were more expensive than networks selected by SCP because the latter minimized the total agricultural value of properties included (WTA), but did not consider whether the sites also provided high returns to developers (WTP). Therefore, although irreplaceability ensured all conservation targets were met as efficiently as possible at the time of each trade, deviations from SCP solutions increased in likelihood as the mean WTP increased or as the correlation between WTP and conservation priorities increased.

Irreplaceability versus simpler offset metrics

T Markets where trade was governed by OM1, OM2, and OM3 typically failed to achieve all the targets (2%, 22%, and 1%, respectively), even when property values increased to support continued trading (Figure 4). The OM2 metric (sites weighted by species rarity) was only more successful because targets in all our scenarios were directly proportional to their availability; hence, this was the only situation in which fixed weighting could sometimes be appropriate. Yet, the few occasions when alternative metrics did achieve all targets relied on the subset of species selected to have narrow distributions, which restricted the flexibility of selection. In the minority of scenarios in which alternative metrics were successful, solutions were achieved with a higher number of sites and at greater cost (115–130%) than with $\sum\alpha$, and none were successful for a large number of species.

DISCUSSION

Land use and land management are central to addressing challenges of global biodiversity conservation, as well as food security, poverty alleviation, and climate change mitigation (Meyfroidt et al., 2022). The failure to coordinate appropriate and effective actions across sectors not only undermines commitments to drive a recovery of nature, but also further risks the sustained well-being of people. We found that if relevant parties engage in trading of biodiversity credits based on a metric derived from $\sum\alpha$ irreplaceability, an offset market can support the most efficient trajectory toward all conservation

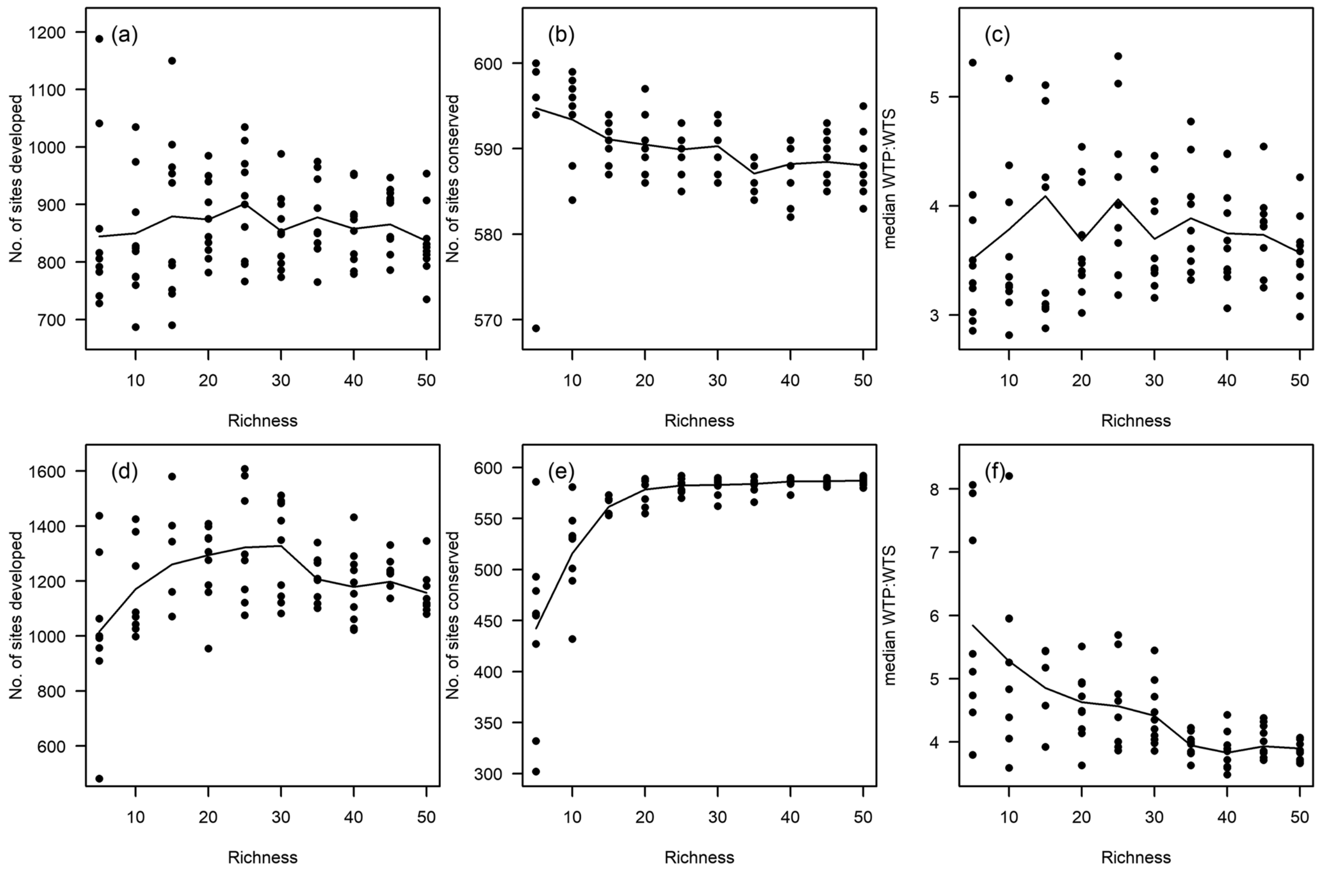

FIGURE 2 Variation in $\sum\alpha$-irreplaceability (defined in text and in Figure 1) offset market trading outcomes as the species richness of communities increases. Assemblages were drawn from communities of 200 with (a, b, c) a strong richness gradient or (d, e, f) no richness gradient (WTP, willingness to pay; WTA, willingness to accept). All conservation targets were achieved in each market simulation, and lines of best fit were added based on local polynomial regression.

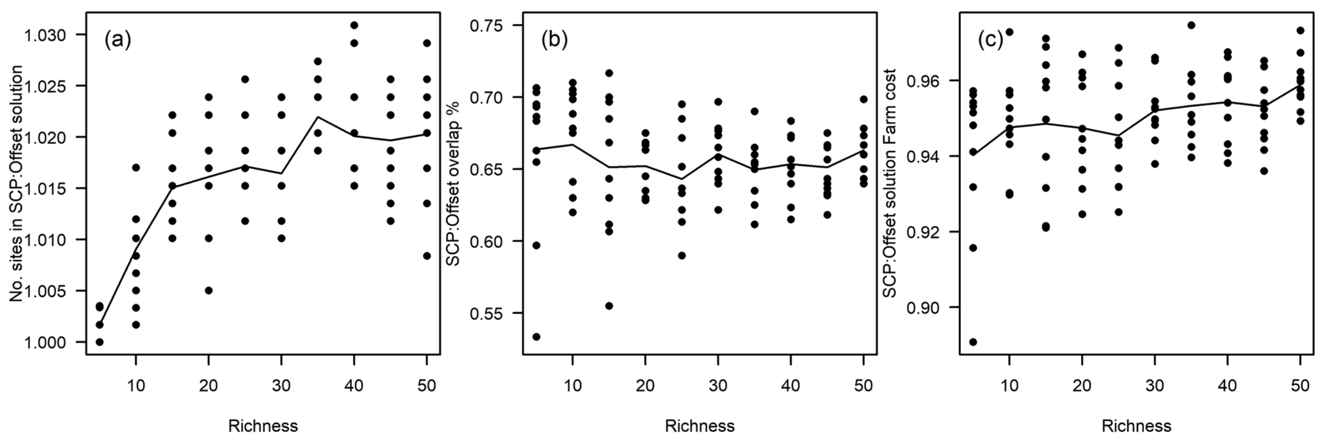

FIGURE 3 Illustration of the relation between conservation networks selected by $\sum\alpha$-irreplaceability offset market trading (defined in text and in Figure 1) and optimal systematic conservation planning (SCP) outcomes for the simulated community with a strong richness gradient: (a) ratio of network size, (b) percentage of planning units that overlap the optimal network, and (c) ratio of network cost.

targets. That is, designing an offset market with $\sum\alpha$ irreplaceability as its metric delivered a low-cost way of meeting biodiversity targets.

Our approach challenges the current school of thought that states like-for-like trading should be mandatory in a policy design to ensure no net loss (or achieve a net gain in biodiversity) (Bull et al., 2015; zu Ermgassen et al., 2020). As a metric, $\sum\alpha$ irreplaceability relaxes the need for equivalent species in each transaction and instead motivates restoration of species and

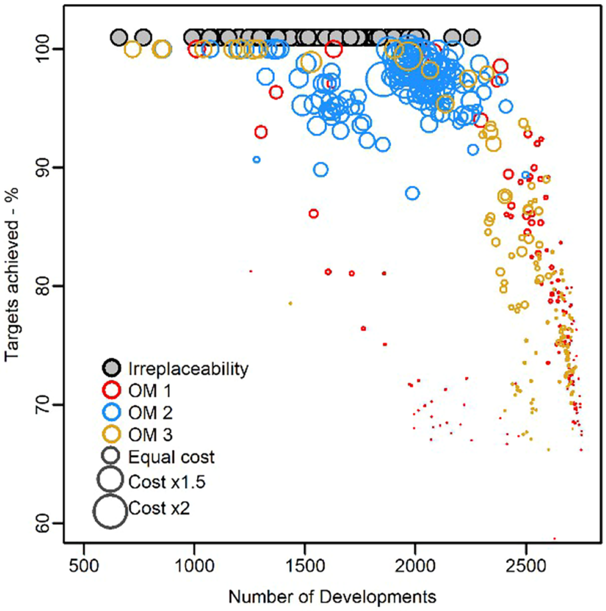

FIGURE 4 Conservation success and efficiency of offset market solutions based on ∑α irreplaceability (defined in text and in Figure 1) and alternative offset metrics described in text (OM 1–OM 3). Costs are based on the value of farmland assigned to conservation solutions.

ecosystems in greatest need (relative to targets) and identifies where that action is most efficient economically. This element of prioritization ensures offsetting conserves the most important sites and species first, irrespective of whether they face direct development pressure. Indeed, the rationale for such prioritization is entirely transparent, and, although many targets are combined to effectively rank each site, this can easily be traced back to its value for different conservation targets. It has been hypothesized that increasing the complexity of offset trading metrics, in a similar vein to ∑α irreplaceability, is likely to reduce the number of trades and hence the economic efficiency of the policy instrument (Needham et al., 2019). In contrast, we found that simpler metrics are unlikely to achieve their primary goal or guide effective progress toward conservation targets. We also found that the economic cost of solutions based on ∑α irreplaceability was not dependent on the number of conservation targets considered. In line with previous research, we found (continue to use past tense for your results) that the location of offset sites and overall cost of conservation actions are dictated by the overlap among ecological targets and ecological and economic heterogeneity across the landscape (Doyle & Yates, 2010; Drechsler, 2021; Kangas & Ollikainen, 2019; Simpson et al., 2022). Finally, when we selected conservation targets that exceeded species' initial availability because we anticipated restoration potential, then net gain, rather than no net loss, was achieved at the market scale.

The adoption of systematic planning tools allows conservation objectives to be achieved efficiently, but rather than relying on new national parks and reserves to stall biodiversity loss, our intention was to recognize the value of effective off-reserve management (Wilson et al., 2007) and engage private finance in conservation. SCP algorithms may define optimal solutions to meet all conservation targets, but in practice these networks are hard to implement when land is privately owned and landowner decisions are based on the relative payoffs from alternative uses (Knight et al., 2011; McIntosh et al., 2017). Although high ∑α values and associated offset costs would incentivize developers to consider alternatives for development to some sites in the SCP network, if WTP is still sufficiently high to be profitable, then the offset market must settle for a more expensive complement of sites to replace non-irreplaceable options. The basis of SCP is that priority sites are not simply the cheapest or the most ecologically diverse; rather, these sites best complement and add to what is already conserved. By introducing regulations requiring developers to offset the predicted impacts of development on biodiversity, a biodiversity offset market generates a positive financial return for farmers investing in conservation that did not exist prior to this market being created. We demonstrated that ∑α irreplaceability is an effective market metric that allows farmers and developers to independently engage in trades, while ensuring an underlying strategic approach is taken to secure the targets deemed critical to biodiversity conservation.

An ongoing problem in the successful implementation of biodiversity offset markets, and environmental markets more broadly, is the lack of regulatory capacity to implement the program with an emphasis on the follow-up monitoring of newly created sites (BenDor et al., 2009; Brownlie et al., 2017; zu Ermgassen et al., 2021). Similarly, a market based on the ∑α metric could result in higher transactions costs. The metric is dynamic because the values of sites would ideally be recomputed after each successful trade. The uncertainty these updates create may lead to lower gains from trade being realized, eroding the ability of the offset market to deliver conservation actions cost-effectively. We did not address these potential costs.

Avoiding previous mistakes

The quality of knowledge of biodiversity is critical to estimating the appropriate allocation of land for conservation and to quantify trade-offs. Rather than rating performance according to the resources or finance committed, ∑α credits provide the greatest reward to landowners able to deliver high marginal gains in ecological outcomes at low financial cost (Pressey et al., 2021). However, to identify the importance of a site in achieving conservation targets, ∑α-irreplaceability credits combine knowledge of how ecological assets are distributed throughout the market's jurisdiction, not just in sites associated with offset trading. Such information is not static and should be updated routinely by the market metric to reflect their changing stocks. The same information would still be required to weight the alternative metrics in Figure 4, but they typically failed to achieve conservation goals because they could not recognize when losses would be regarded as irreplaceable. Given that inadequate monitoring has been cited as a key constraint to global action for many years (Pressey et al., 2021), as well as in the context of prior attempts to organize biodiversity markets (Kujala et al., 2022; Maron et al., 2012; zu Ermgassen et al., 2021), a change in approach is required if biodiversity is to be valued correctly.

First, a key principle underpinning $\sum\alpha$-irreplaceability market offsets is that losses to development would not be sanctioned if they cannot be replaced. It is key that the market represents as many asset types as possible, even if their distribution is uncertain, to avoid unintentional losses of biodiversity being permitted because those features were absent from $\sum\alpha$ calculation (Popov et al., 2022). In this study, the wide variation in outcomes for different subsets of taxa illustrated the risks associated with conservation policies reliant on small numbers of indicator species whose suitability to represent the conservation needs of biodiversity and ecosystem processes is unknown (Yong et al., 2018). In this context, the value of ecological monitoring data gains new meaning. If understanding of an ecological feature, such as species distribution, is poor, one should err on the side of caution and protect a higher number of sites to be confident the target has been reached (IUCN, 2007). Without this prudent approach, land and ecological assets on which society depends may be lost before there is the knowledge to react. If caution due to data shortages leads to an overestimation of the area required to achieve targets, this increases the difficulty of achieving targets and consequently the financial costs of offsetting for developers. It would therefore be in the interests of both market regulators and developers to improve monitoring to minimize the uncertainty of site's $\sum\alpha$ irreplaceability, balancing the cost of further monitoring against expected efficiency gains for the market (Bolam et al., 2019; Eyvindson et al., 2019). In addition, although the cost of monitoring has traditionally been prohibitive, modern tools such as acoustics, molecular methods, automated imaging, and remote surveys with drones and satellites have dramatically increased the ability to monitor many ecological systems at scale (Besson et al., 2022; Keitt & Abelson Eric, 2021). It is beyond the scope of our paper to provide an overview of these methods, but the capacity to efficiently verify restoration outcomes will grow, particularly if sampling design can be strategically adapted to minimize uncertainties in $\sum\alpha$ (Brown et al., 2013).

The biodiversity market is created by a demand for credits. In our simulated market, trading was enforced by a regulator, rather than emerging from a voluntary demand for credits. However, the guarantee that conservation targets will be safeguarded and eventually achieved cannot be made if developer participation in offset trading is voluntary. The market regulator receives updates from monitoring sources to maintain oversight of each asset's progress toward targets at the market scale, thereby determining local site $\sum\alpha$ scores and the credits required for trades (Kujala et al., 2022). The regulator is also able to intervene in the economic efficiency of the market, for example, by subsidizing restoration costs to farms to increase the market supply of $\sum\alpha$-irreplaceability credits. Although we recognize that defining site $\sum\alpha$ irreplaceability based on the potential recovery of a site (Sutherland, 2022) and forecasting of the time frame and risks (Ladouceur et al., 2023; Laitila et al., 2014) are challenging, these uncertainties are motivations for targeted research, rather than barriers to adoption (Bolam et al., 2019; Eyvindson et al., 2019). Public support and trust will be strengthened if individuals can transparently understand how local, and potentially highly visible, losses are accompanied by secure gains at the landscape scale designed to benefit society and the economy (Cvitanovic et al., 2021). Landowners with spatial, strategic advantages due to the location of their land may be able to leverage payments from developers that are well in excess of their opportunity costs if their property is key to achieving a conservation target (Lennox et al., 2012).

Beyond biodiversity offset markets

Even with introduction of planning regulation, to avert substantial biodiversity loss and degradation of ecosystem services, society must raise its ambitions to restore ecosystems (Leclère et al., 2020). The resources available for conservation action are woefully inadequate compared with the resources invested in activities that further degrade or destroy nature (Dasgupta, 2021), and yet the expected benefits of conservation investment often far outweigh the costs (Bradbury et al., 2021; DEFRA, 2022). The evidence of an ecological crisis is so serious that any action or investment is seen as positive, but this lack of discrimination weakens the motivation of individuals and companies to support more transformative change. The $\sum\alpha$-irreplaceability credits can be used to recognize and reward private investment in conservation because they provide a comparable metric of performance in a market, even if 2 sites or actions affect different ecological assets.

In an $\sum\alpha$-irreplaceability market, investors can anticipate the relative costs of their actions and define the performance of their investments in restoration and conservation for biodiversity in net terms. The $\sum\alpha$-irreplaceability metric could therefore be key to allowing fair recognition of investors' contributions and be used to build public trust that companies' statements of environmental responsibility match their claims.

The debates associated with pathways to sustainability and a nature-positive recovery are highly value laden, wicked problems (DeFries & Nagendra, 2017; Meyfroidt et al., 2022), but societies cannot expect ecosystem recovery to emerge from a piecemeal approach. Land is finite, and reconciling demands and interactions of complex multisector systems requires strategic oversight to avoid scenarios of ecological, economic, and societal collapse (Shin et al., 2022; Steffen et al., 2015). Ecologists can identify what targets are required as a minimum to sustain species, ecosystem, or process, but targets must ultimately be defined collaboratively with economists, social scientists, health economists, and politicians. Incentivizing outcomes using insights from systematic planning will become increasingly important as the collective benefits of multiple land uses diverge (Jung et al., 2021; Moilanen et al., 2005). Adopting $\sum\alpha$ irreplaceability would enable authorities to identify and minimize the conflict between conservation targets and other land uses, thereby incentivizing greater private sector investment in actions that accelerate the speed with which nature's recovery is achieved.

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REFERENCES

Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S. E., Rockström, J., & Lenton, T. M. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science*, *377*, Article eabn7950.

Baisero, D., Schuster, R., & Plumptre, A. J. (2021). Redefining and mapping global irreplaceability. *Conservation Biology*, *36*, Article e13806.

Ban, N. C., Mills, M., Tam, J., Hicks, C. C., Klain, S., Stoeckl, N., Bottrill, M. C., Levine, J., Pressey, R. L., Satterfield, T., & Chan, K. M. A. (2013). A social–ecological approach to conservation planning: Embedding social considerations. *Frontiers in Ecology and the Environment*, *11*, 194–202.

BenDor, T., Sholtes, J., & Doyle, M. W. (2009). Landscape characteristics of a stream and wetland mitigation banking program. *Ecological Applications*, *19*, 2078–2092.

Besson, M., Alison, J., Bjerge, K., Gorochowski, T. E., Høye, T. T., Jucker, T., Mann, H. M. R., & Clements, C. F. (2022). Towards the fully automated monitoring of ecological communities. *Ecology Letters*, *25*, 2753–2775.

Bolam, F. C., Grainger, M. J., Mengersen, K. L., Stewart, G. B., Sutherland, W. J., Runge, M. C., & McGowan, P. J. K. (2019). Using the Value of Information to improve conservation decision making. *Biological Reviews*, *94*, 629–647.

Bradbury, R. B., Butchart, S. H. M., Fisher, B., Hughes, F. M. R., Ingwall-King, L., MacDonald, M. A., Merriman, J. C., Peh, K. S.-H., Pellier, A.-S., Thomas, D. H. L., Trevelyan, R., & Balmford, A. (2021). The economic consequences of conserving or restoring sites for nature. *Nature Sustainability*, *4*, 602–608.

Brown, J. A., Salehi, M. M., Moradi, M., Panahbehagh, B., & Smith, D. R. (2013). Adaptive survey designs for sampling rare and clustered populations. *Mathematics and Computers in Simulation*, *93*, 108–116.

Brownlie, S., von Hase, A., Botha, M., Manuel, J., Balmforth, Z., & Jenner, N. (2017). Biodiversity offsets in South Africa—Challenges and potential solutions. *Impact Assessment and Project Appraisal*, *35*, 248–256.

Bryan, B. A., Raymond, C. M., Crossman, N. D., & Macdonald, D. H. (2010). Targeting the management of ecosystem services based on social values: Where, what, and how? *Landscape and Urban Planning*, *97*, 111–122.

Bull, J. W., Hardy, M. J., Moilanen, A., & Gordon, A. (2015). Categories of flexibility in biodiversity offsetting, and their implications for conservation. *Biological Conservation*, *192*, 522–532.

Bull, J. W., Milner-Gulland, E. J., Suttle, K. B., & Singh, N. J. (2014). Comparing biodiversity offset calculation methods with a case study in Uzbekistan. *Biological Conservation*, *178*, 2–10.

Business and Biodiversity Offsets Programme (BBOP). (2009). *Biodiversity offset design handbook*. https://www.forest-trends.org/publications/biodiversity-offset-design-handbook/

Crisp, M. D., Laffan, S., Linder, H. P., & Monro, A. (2001). Endemism in the Australian flora. *Journal of Biogeography*, *28*, 183–198.

Cvitanovic, C., Shellock, R. J., Mackay, M., van Putten, E. I., Karcher, D. B., Dickey-Collas, M., & Ballesteros, M. (2021). Strategies for building and managing 'trust' to enable knowledge exchange at the interface of environmental science and policy. *Environmental Science & Policy*, *123*, 179–189.

Dasgupta, P. (2021). *The economics of biodiversity: The Dasgupta review*. HM Treasury.

DeFries, R., & Nagendra, H. (2017). Ecosystem management as a wicked problem. *Science*, *356*, 265–270.

Department for Environment, Food and Rural Affairs (DEFRA). (2022). *Environment Act targets: Summary of evidence and approach*. https://consult.defra.gov.uk/natural-environment-policy/consultation-on-environmental-targets

Díaz, S., Settele, J., Brondízio, E. S., Ngo, H. T., Agard, J., Arneth, A., Balvanera, P., Brauman, K. A., Butchart, S. H. M., Chan, K. M. A., Garibaldi, L. A., Ichii, K., Liu, J., Subramanian, S. M., Midgley, G. F., Miloslavich, P., Molnár, Z., Obura, D., Pfaff, A., … Zayas, C. N. (2019). Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science*, *366*, Article eaax3100.

Doyle, M. W., & Yates, A. J. (2010). Stream ecosystem service markets under no-net-loss regulation. *Ecological Economics*, *69*, 820–827.

Drechsler, M. (2021). Bundling of ecosystem services in conservation offsets: Risks and how they can be avoided. *Land*, *10*(6), Article 628. https://doi.org/10.3390/land10060628

Eyvindson, K., Hakanen, J., Mönkkönen, M., Juutinen, A., & Karvanen, J. (2019). Value of information in multiple criteria decision making: An application to forest conservation. *Stochastic Environmental Research and Risk Assessment*, *33*, 2007–2018.

Ferrier, S., Pressey, R. L., & Barrett, T. W. (2000). A new predictor of the irreplaceability of areas for achieving a conservation goal, its application to real-world planning, and a research agenda for further refinement. *Biological Conservation*, *93*, 303–325.

Hanson, J. O., Schuster, R., Morrell, N., Strimas-Mackey, M., Edwards, B. P. M., Watts, M. E., Arcese, P., Bennett, J., & Possingham, H. P. (2022). *prioritizr: Systematic conservation prioritization in R*. R package version 7.2.2. https://CRAN.R-project.org/package=prioritizr

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). (2019). *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Author.

International Union for Conservation of Nature (IUCN). (2007). *Guidelines for applying the precautionary principle to biodiversity conservation and natural resource management, as approved by the 67th meeting of the IUCN council 14–16 May 2007*. Author.

International Union for Conservation of Nature (IUCN). (2022). *Egyptian COP27 Presidency, Germany and IUCN announce ENACT Initiative for Nature-based Solutions*. https://cop27.eg/#/presidency/initiative/enact

Jung, M., Arnell, A., de Lamo, X., García-Rangel, S., Lewis, M., Mark, J., Merow, C., Miles, L., Ondo, I., Pironon, S., Ravilious, C., Rivers, M., Schepaschenko, D., Tallowin, O., van Soesbergen, A., Govaerts, R., Boyle, B. L., Enquist, B. J., Feng, X., … Visconti, P. (2021). Areas of global importance for conserving terrestrial biodiversity, carbon and water. *Nature Ecology & Evolution*, *5*, 1499–1509.

Kangas, J., & Ollikainen, M. (2019). Economic insights in ecological compensations: Market analysis with an empirical application to the Finnish economy. *Ecological Economics*, *159*, 54–67.

Keitt, T. H., & Abelson Eric, S. (2021). Ecology in the age of automation. *Science*, *373*, 858–859.

Knight, A. T., Grantham, H. S., Smith, R. J., McGregor, G. K., Possingham, H. P., & Cowling, R. M. (2011). Land managers' willingness-to-sell defines conservation opportunity for protected area expansion. *Biological Conservation*, *144*, 2623–2630.

Kujala, H., Maron, M., Kennedy, C. M., Evans, M. C., Bull, J. W., Wintle, B. A., Iftekhar, S. M., Selwood, K. E., Beissner, K., Osborn, D., & Gordon, A. (2022). Credible biodiversity offsetting needs public national registers to confirm no net loss. *One Earth*, *5*, 650–662.

Kukkala, A. S., & Moilanen, A. (2013). Core concepts of spatial prioritisation in systematic conservation planning. *Biological Reviews*, *88*, 443–464.

Ladouceur, E., Isbell, F., Clark, A. T., Harpole, W. S., Reich, P. B., Tilman, G. D., & Chase, J. M. (2023). The recovery of plant community composition following passive restoration across spatial scales. *Journal of Ecology*, *111*, 814–829.

Laitila, J., Moilanen, A., & Pouzols, F. M. (2014). A method for calculating minimum biodiversity offset multipliers accounting for time discounting, additionality and permanence. *Methods in Ecology and Evolution*, *5*, 1247–1254.

Leclère, D., Obersteiner, M., Barrett, M., Butchart, S. H. M., Chaudhary, A., De Palma, A., DeClerck, F. A. J., Di Marco, M., Doelman, J. C., Dürauer, M., Freeman, R., Harfoot, M., Hasegawa, T., Hellweg, S., Hilbers, J. P., Hill, S. L. L., Humpenöder, F., Jennings, N., Krisztin, T., … Young, L. (2020). Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature*, *585*, 551–556.

Lennox, G. D., Dallimer, M., & Armsworth, P. R. (2012). Landowners' ability to leverage in negotiations over habitat conservation. *Theoretical Ecology*, *5*, 115–128.

Leroy, B., Meynard, C. N., Bellard, C., & Courchamp, F. (2016). virtualspecies, an R package to generate virtual species distributions. *Ecography*, *39*, 599–607.

Margules, C. R., & Pressey, R. L. (2000). Systematic conservation planning. *Nature*, *405*, 243–253.

Maron, M., Hobbs, R. J., Moilanen, A., Matthews, J. W., Christie, K., Gardner, T. A., Keith, D. A., Lindenmayer, D. B., & McAlpine, C. A. (2012). Faustian bargains? Restoration realities in the context of biodiversity offset policies. *Biological Conservation*, *155*, 141–148.

Marshall, E., Wintle, B. A., Southwell, D., & Kujala, H. (2020). What are we measuring? A review of metrics used to describe biodiversity in offsets exchanges. *Biological Conservation*, *241*, Article 108250.

McIntosh, E. J., Pressey, R. L., Lloyd, S., Smith, R. J., & Grenyer, R. (2017). The impact of systematic conservation planning. *Annual Review of Environment and Resources*, *42*, 677–697.

Meyfroidt, P., Meyfroidt, P., de Bremond, A., Ryan, C. M., Archer, E., Aspinall, R., Chhabra, A., Camara, G., Corbera, E., DeFries, R., Díaz, S., Dong, J., Ellis, E. C., Erb, K. H., Fisher, J. A., Garrett, R. D., Golubiewski, N. E., Grau, H. R., Grove, J. M., … Zu Ermgassen, E. K. H. J. (2022). Ten facts about land systems for sustainability. *Proceedings of the National Academy of Sciences of the United States of America*, *119*, Article e2109217118.

Moilanen, A., Franco, A. M. A., Early, R. I., Fox, R., Wintle, B., & Thomas, C. D. (2005). Prioritizing multiple-use landscapes for conservation: Methods for large multi-species planning problems. *Proceedings of the Royal Society B: Biological Sciences*, *272*, 1885–1891.

Moilanen, A., Wilson, K. A., & Possingham, H. (2009). *Spatial conservation prioritization: Quantitative methods and computational tools*. Oxford University Press.

Natural England. (2022). *Biodiversity Metric 3.1: Auditing and accounting for biodiversity—User guide*. Author.

Needham, K., de Vries, F. P., Armsworth, P. R., & Hanley, N. (2019). Designing markets for biodiversity offsets: Lessons from tradable pollution permits. *Journal of Applied Ecology*, *56*, 1429–1435.

NSW Department of Planning & Environment (DPE). (2022). *Biodiversity credit pricing guide: Guidance for pricing biodiversity credits under the Biodiversity Offsets Scheme*. Author.

Popov, V., Shah, P., Runting, R. K., & Rhodes, J. R. (2022). Managing risk and uncertainty in systematic conservation planning with insufficient information. *Methods in Ecology and Evolution*, *13*, 230–242.

Pressey, R. L., Humphries, C. J., Margules, C. R., Vane-Wright, R. I., & Williams, P. H. (1993). Beyond opportunism: Key principles for systematic reserve selection. *Trends in Ecology & Evolution*, *8*, 124–128.

Pressey, R. L., Visconti, P., McKinnon, M. C., Gurney, G. G., Barnes, M. D., Glew, L., & Maron, M. (2021). The mismeasure of conservation. *Trends in Ecology & Evolution*, *36*, 808–821.

Radu, C., Caron, M.-A., & Arroyo, P. (2020). Integration of carbon and environmental strategies within corporate disclosures. *Journal of Cleaner Production*, *244*, Article 118681.

Schmalensee, R., & Stavins, R. N. (2017). The design of environmental markets: What have we learned from experience with cap and trade? *Oxford Review of Economic Policy*, *33*, 572–588.

Sciaini, M., Fritsch, M., Scherer, C., & Simpkins, C. E. (2018). NLMR and landscapetools: An integrated environment for simulating and modifying neutral landscape models in R. *Methods in Ecology and Evolution*, *9*, 2240–2248.

Shin, Y.-J., Midgley, G. F., Archer, E. R. M., Arneth, A., Barnes, D. K. A., Chan, L., Hashimoto, S., Hoegh-Guldberg, O., Insarov, G., Leadley, P., Levin, L. A., Ngo, H. T., Pandit, R., Pires, A. P. F., Pörtner, H. O., Rogers, A. D., Scholes, R. J., Settele, J., & Smith, P. (2022). Actions to halt biodiversity loss generally benefit the climate. *Global Change Biology*, *28*, 2846–2874.

Simpson, K. H., de Vries, F., Dallimer, M., Armsworth, P. R., & Hanley, N. (2021). Understanding the performance of biodiversity offset markets: Evidence from an integrated ecological–economic model. *Land Economics*, *97*(4), 836–857.

Simpson, K. H., de Vries, F. P., Dallimer, M., Armsworth, P. R., & Hanley, N. (2022). Ecological and economic implications of alternative metrics in biodiversity offset markets. *Conservation Biology*, *36*, Article e13906.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*, Article 1259855.

Sutherland, W. J. (2022). *Transforming conservation: A practical guide to evidence and decision making*. Open Book Publishers. https://doi.org/10.11647/OBP.0321

Tittensor, D. P., Walpole, M., Hill, S. L., Boyce, D. G., Britten, G. L., Burgess, N. D., Butchart, S. H., Leadley, P. W., Regan, E. C., Alkemade, R., Baumung, R., Bellard, C., Bouwman, L., Bowles-Newark, N. J., Chenery, A. M., Cheung, W. W., Christensen, V., Cooper, H. D., Crowther, A. R., … Ye, Y. (2014). A mid-term analysis of progress toward international biodiversity targets. *Science*, *346*, 241–244.

Wilson, K. A., Underwood, E. C., Morrison, S. A., Klausmeyer, K. R., Murdoch, W. W., Reyers, B., Wardell-Johnson, G., Marquet, P. A., Rundel, P. W., McBride, M. F., Pressey, R. L., Bode, M., Hoekstra, J. M., Andelman, S., Looker, M., Rondinini, C., Kareiva, P., Shaw, M. R., & Possingham, H. P. (2007). Conserving biodiversity efficiently: What to do, where, and when. *PLoS Biology*, *5*, Article e223.

Yong, D. L., Barton, P. S., Ikin, K., Evans, M. J., Crane, M., Okada, S., Cunningham, S. A., & Lindenmayer, D. B. (2018). Cross-taxonomic surrogates for biodiversity conservation in human-modified landscapes—A multi-taxa approach. *Biological Conservation*, *224*, 336–346.

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. *Conservation Letters*, *12*, Article e12664.

zu Ermgassen, S., Maron, M., Corlet Walker, C. M., Gordon, A., Simmonds, J. S., Strange, N., Robertson, M., & Bull, J. W. (2020). The hidden biodiversity risks of increasing flexibility in biodiversity offset trades. *Biological Conservation*, *252*, Article 108861.

zu Ermgassen, S., Marsh, S., Ryland, K., Church, E., Marsh, R., & Bull, J. W. (2021). Exploring the ecological outcomes of mandatory biodiversity net gain using evidence from early-adopter jurisdictions in England. *Conservation Letters*, *14*, Article e12820.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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