Five rules for scientifically-credible nature markets

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Abstract

Nature markets are proliferating rapidly around the world, yet it is underacknowledged that they have been practiced in various forms for decades. A large body of scientific research has shown that nature markets regularly do not achieve their environmental objectives, and provides generalisable lessons to support their ongoing improvement. The scale of the biodiversity crisis and the enduring popularity of nature markets means it is now critical to stop reproducing the same mistakes. Here we synthesise international research from the history of nature markets and summarise five rules which are necessary precursors for achieving their environmental aims. We propose a checklist for investors, policymakers, and civil society to assess whether nature markets are likely to be delivering scientifically-credible outcomes. We score the world's largest nature markets against these rules and show all face integrity risks. Lastly, we outline critical evidence-based actions that can be taken to push nature markets towards greater integrity.

Introduction

Nature conservation and restoration is systemically underfunded, and economic activities that destroy biodiversity remain profitable and subsidised[1]. The current policy narrative is that a substantial increase in private nature finance is required[1,2]. A dominant proposed mechanism for attracting private finance into nature is through commodification mechanisms (methods for creating a tradeable unit of e.g. biodiversity, or carbon) and markets to enable trade. These 'nature markets' (to date mostly for wetlands, biodiversity and land-based carbon) come in various forms with different demand drivers: some are driven by regulation to achieve specific environmental objectives (such as 'no net loss' of biodiversity[3]), others are voluntary. These markets share the common characteristics of defining and enabling the trade of credits which correspond to changes in environmental quality through land management activities that aim to deliver nature conservation or restoration outcomes. Nature markets currently generate approximately $13 billion of revenue per year in exchange for nature loss or emissions elsewhere[1], but they are expected to scale up given multiple policy drivers, including new market frameworks in Australia, the EU and the UK, Article 6.4 of the Paris Agreement, target 19 of the Kunming-Montreal Global Biodiversity Framework and corporate disclosure initiatives[4].

Whilst nature markets are often referred to as 'innovative' financial instruments, in reality they have been practiced for decades[5]. New markets are routinely developed without heeding the large body of scientific research indicating how to achieve scientifically-credible outcomes[6–11]. For example, a major evaluation of the effectiveness of decades of wetland mitigation banking in the United States demonstrated that ‘developer-led’ offsets were consistently delivering low quality outcomes because of low standards and weak enforcement. In 2008, regulators then recommended to harmonise standards between mitigation banks and developer-led offsets, thereby helping redirect investment away from low quality on-site mitigation and towards relatively higher quality mitigation banks[12]. Despite this, England’s new nature market (“Biodiversity Net Gain”) operationalised in 2024 replicated the known flaws in the previous US system by having more rigorous standards and enforcement mechanisms for ‘off-site’ mitigation purchased through the market than developer-led mitigation delivered within developments[13,14]. The consequence of this has been far less private investment in nature via the off-site nature market than government predicted[13,15,16]. Similar patterns of multiple governance regimes with different standards undermining each other have also occurred in systems such as species conservation banking in the United States[17,18].

Our aim here is to delineate clearly, based on learnings from robust counterfactual-based impact evaluations of nature markets around the world, the key dimensions for ensuring that a given nature market scientifically-credibly achieves its defined environmental objective. We use ‘scientifically-credible’ to mean that on average credits traded in these markets correspond to real and identifiable environmental improvements, that sum to the overall objective of the market (e.g. achieving no net loss of biodiversity). We consider this a necessary precursor to the subsequent step of ensuring the market then delivers its environmental outcomes at least cost, including by minimising transaction and administrative costs, which we do not address here (but have been addressed in market design literature elsewhere[19–21]). We argue that ensuring nature markets achieve their environmental objectives is critical because if they do not, they are not serving their intended policy function. They may lower compliance costs for developers and polluters, but at the expense of public good environmental outcomes. The environmental effectiveness of nature markets is also critical to their long-term sustainability. Environmentally ineffective markets can reduce trust amongst market participants and the public, deter investment and participation, and create reputational risk for buyers. Continued failure could ultimately lead to the collapse of these markets[6], illustrated by the collapse in demand for avoided deforestation carbon credits following the identification of widespread additionality problems[22,23].

We acknowledge alternative perspectives on the purpose of nature markets. Some argue that, in the absence of a nature market, no action would be taken and therefore nature markets can be considered effective if they achieve any positive outcomes at all, however small. Others compare the outcomes of nature markets with other public policy instruments for achieving similar objectives, and contend that, even with low effectiveness, nature markets achieve benefits more cheaply than alternative instruments[24,25]. We do not advance these perspectives here – our focus is on requirements for ensuring nature markets achieve their environmental objectives in full.

The gulf between nature market theory and practice

Nature markets have strong conceptual appeal. Their principal function is to lower the social costs of achieving desired environmental outcomes[26]. 'Nature' projects are issued allowances for improving environmental outcomes and they are purchased by entities causing environmental harm, who use them to offset their impacts. The invisible hand of the market finds the cheapest way of realising the desired environmental outcome (which may be to not cause the negative impact in the first place[27]) and the scheme administrators ensure integrity by upholding well-designed scheme rules.

The practice of nature markets is more complicated. Policies that force polluters to internalise their environmental costs always face political resistance, leading to compromises in their design[5,28,29]. Entities that cause environmental harm are incentivised to reduce compliance costs[30]. This means that there is often demand-side pressure on market designers to weaken standards to promote participation and increase the supply of low-cost allowances[29]. Potential sellers of credits have a similar interest in gaining access to the market and lowering transaction costs, which can place further pressure on the design of rules that are intended to uphold integrity.

Once nature markets are operational, pressures on administrators continue[29]. Supply-side participants can become a new lobby that seeks to advance their own interests. Scheme regulators can face political pressure to lower standards to appease polluters, project proponents, and perceived conflicts between environmental mitigation measures and economic growth[31,32]. There is also the threat of regulatory capture[33].

The ongoing pressures can result in the weakening of rules or divergences between rules and market operation in practice. Resource and capacity constraints within regulatory bodies can also lead to gaps and failures[13,32,34]. For example, the most popular project type under Australia's carbon credit scheme is 'human-induced regeneration of permanent even-aged native forests' (HIR). As the name suggests, by law, HIR projects are supposed to involve natural regeneration of permanent even-aged native forests on cleared lands that did not contain pre-existing mature trees when the projects started. However, the scheme regulator has allowed HIR projects to be located on uncleared lands containing large numbers of pre-existing mature trees and shrubs. This has undermined project integrity and additionality[34].

R**ules for ecologically-effective nature markets**

Our proposed rules are derived from a combination of policy design analysis and an assessment of the empirical evidence on the real-world implementation and outcomes of nature markets (Figure 1). Three of our rules are extensions of the existing commonly-agreed principles of additionality, leakage and permanence[35] that are based on real-world observations of how those principles have been violated in practice; one relates to scientific validity of the metrics on which the markets are based, and the final rule relates to governance, particularly the importance of robust regulatory agencies and the need for active third party involvement in rule making, monitoring and enforcement.

1) Ensure the nature market's proxy metric correlates with the desired outcome

To render a commodity out of nature, it is necessary to agree a set of methodologies and rules that govern the creation of a 'unit' of nature or its services[36]. Nature markets are at their most economically efficient when that unit is treated as fungible[20], and there are low transaction costs (e.g. costs related to project development and registration, monitoring, reporting and verification (MRV)). These fungible units necessarily mask often consequential complexities[20,36–38]. Nature market methodologies are also often implemented in practice by workers with limited environmental expertise, so there is a strong pressure to use simple, easy-to-apply measurement systems[30,39–42].

Yet by focussing only on certain components of nature or using simple or subjective scoring in metrics, these fungible units may not actually correlate meaningfully with the desired nature-related policy outcome. For example, England's Biodiversity Net Gain market aims to achieve 10% net gain of biodiversity, but recent studies have shown that the habitat extent and condition metric it uses does not correlate with critical components of biodiversity such as invertebrate species richness or abundance[43,44]. The majority of species conservation banks in the US use a metric representing simply the area of habitat protected[45].

It is critical that nature markets either use real trusted primary observations that capture intended environmental outcomes in their calculation methods, or that they use proxies for these outcomes for which there is an empirically-demonstrated, robust relationship with the outcome variable of interest or policy goal[46]. Where the desired policy goal correlates closely with changes in land cover (e.g. forest carbon offsets, US wetland mitigation[47]), the calculation method may validly draw upon satellite data reflecting real-time changes in land cover. However, where the desired policy goal is to demonstrate an improvement in an environmental variable related to biodiversity or carbon which cannot be reliably measured using remote sensing, these markets must either measure the variable at site-scales, or use a scientifically-proven valid proxy[48]. This is becoming increasingly possible with innovations in conservation technologies; several emerging voluntary biodiversity credit standards measure real-time changes in aspects of biodiversity at a site using remote monitoring technologies (e.g. eDNA, ecoacoustics)[36]. This contrasts with methods used in traditional biodiversity offset markets where credits are awarded by measuring the state of nature at the project site at some baseline time period, with (often overoptimistic[49,50]) assumptions then made about how nature will change over the forthcoming period and credits awarded based on that projection, with no requirement to formally monitor whether nature is changing in line with those up-front projections.

Using ecologically-relevant site-scale metrics can sometimes increase transaction costs, thereby increasing the cost of supply[31,39]. However, because most nature markets are offset markets where the credit price provides an incentive for developers and polluters to avoid environmental impacts, fewer trades is not necessarily a marker of failure – it may represent effective impact avoidance[31,51]. Demonstration of the environmental outcomes delivered by nature markets (including the way they help disincentivise harming nature by pricing it[51]) must be re-prioritised as the key indicator of their effectiveness, rather than an incomplete, singular focus on market ‘scale’, financial value[52], and volume of trades (e.g.[52]) simply because such data are more frequently collected and reported.

2) Assume non-additionality unless demonstrated otherwise

Additionality measures the extent to which the relevant environmental outcome has been rendered in exchange for payment. If the outcomes are not additional, there are no services rendered – it is a transfer payment.

Most nature markets rhetorically aim to ensure additionality[53], and assume that land managers who opt in to delivering offsets or credits for sale are delivering environmental improvements that would not have otherwise have been delivered. All the world's largest nature markets are compensation markets[1]. Without additionality, the net outcome of nature markets coupled with the harm they claim to be compensating for is further damage to the environment.

The great challenge for nature markets is overcoming adverse selection, where asymmetries of information between transacting parties prompts selective participation to the detriment of counterparties[6,54,55]. The critical information asymmetry concerns whether the action or environmental outcome that is credited and sold would have occurred anyway. Project proponents are in a superior position to judge the additionality of their actions and associated outcomes. They are also strongly incentivised to supply non-additional 'services'. It is difficult to design and administer rules that screen out non-additional projects. Non-additional projects have low opportunity costs, allowing them to provide cheaper units than those from additional projects, threatening their viability[56].

Consistent with economic theory, in most of the impact evaluations of nature markets comparing the outcomes at project sites with statistically-matched or synthetic controls to date the majority of gains have been non-additional[22,50,57–61]. A notable exception is the US wetland mitigation market which has delivered substantial additional wetland area[21]. In the context of offset schemes involving the avoidance of forest loss or degradation, non-additionality has been pervasive[22,50,57].

In practice, these shortcomings stem from overestimated additionality in crediting methods. For example, some carbon markets allow project proponents to propose their own counterfactual (the scenario of what would have happened in absence of the nature market project), thus providing proponents with a commercial incentive to maximise profit through their significant influence over the volume of credits issed[6,22]. In other cases, additionality is treated as all-or-nothing – if a criterion is met, such as through some kind of (often gameable) 'financial additionality' test[62], then all of the beneficial outcomes at the enrolled site are considered additional to what would otherwise have occurred, whether or not that is the case.

Given the scale and strength of evidence from across multiple systems, we argue that nature markets should start on the conservative assumption that land management outcomes are non-additional, and that high-quality and credible evidence is required to demonstrate otherwise[63]. If the nature market makes no attempt to rigorously assess the additionality of credits traded within it, it is likely the majority of credits are non-additional.

There are ways of managing additionality risks. An essential first step is to exclude the riskiest project types, where it is difficult to differentiate between additional and non-additional actions and outcomes, and to have high confidence that only additional outcomes will be credited. This will rule out some low-cost opportunities for abatement, thereby potentially increasing the cost of achieving the scheme's environmental objective. However, the failure to exclude high risk project types from the scope of nature markets at the outset can give rise to ongoing threats to their environmental integrity, including by encouraging lobbying. For example, under lobbying pressure, the Australian government reduced the stringency of the entry criteria for soil carbon credits under the ACCU scheme in 2021, leading to a flood of credits issued for gains in soil carbon which have subsequently been found to be attributable primarily to fluctuations in rainfall rather than offset management[64].

Generally, active ecological restoration projects will typically have lower additionality risks than 'avoided loss' projects because they require significant capital outlays and are directly observable[47]. However, additionality of restoration projects cannot be assumed because, they may still have occurred anyway without the incentives associated with the market[58]. For example, analyses of Australia's restoration-based HIR carbon credit projects (from which the Australian government has committed to purchase >$1.5 billion in credits) suggest most observed changes in tree cover are attributable to seasonal factors (rainfall) rather than the project activities (largely grazing control)[58].

The most scientifically-robust way of accounting for additionality is to only release credits for sale into these markets after they have already been estimated to be demonstrably additional, relative to an unbiased counterfactual[6], which so far has most commonly involved using a quasi-experimental approach such as statistical matching coupled with difference-in-difference analysis or synthetic controls[22,57–59,65,66]. Decades of methodological development in impact evaluation mean creating nature markets where only projects with a high probability of additionality are permitted to participate is now technically possible[6] (for markets where the outcome variable is an environmental feature that can be robustly measured through remote sensing).

Whilst only releasing credits after they have been proven effective and estimated to be additional may sound infeasible, it is critical for scientific credibility[6,67]. In practice, most carbon credits are only released after an ex-post evaluation, but until recently ex-post evaluations only considered project outcomes while the counterfactual set at the beginning of the project was not reassessed. However, academic research institutions have developed low cost methods that automate the identification of control areas, and estimate additionality in near real-time[35,68]. A transparent, open-access and science-based approach to estimating additionality over time vastly reduces the costs associated with bespoke project-by-project verification[6]. These approaches are now used by carbon credit ratings agencies and have been integrated in newer methodologies for afforestation, reforestation and revegetation (ARR) and improved forest management (IFM) schemes (eg[69,70]), with some credit providers already adopting this model (e.g.[71]).

Credits based on up-front projections of additionality or released according to a credit release schedule might be acceptable in certain contexts[8], but only if there is strong evidence that outcomes will both occur and be additional (e.g. more likely for restoration-based systems). In these situations, risks can be reduced if conservative assumptions are used and conflicts of interest within assessment methods eliminated, so that on average ex-post evaluations align with the ex-ante projections rather than demonstrating that up-front projected gains have been overestimated[6,8]. Governance mechanisms to ensure enforcement action can be taken if projects develop in a way that deviates from the ex-ante projection of additionality would also be required (see Rule Five).

3) Ensure the market does not induce effects elsewhere that undermine its outcomes

Leakage occurs when changes to land management activities shift production and its associated damages elsewhere[72]; widely acknowledged in fields such as land system science (via 'telecouplings')[73,74]. Many economists argue that, in a globally-interconnected economy with growing or equilibrium demand for agricultural or forest commodities, any reductions in supply of natural products will be compensated for by increased supply elsewhere, either of the same commodity or a substitute[75,76]. If demand leaks into areas of high carbon or biodiversity value, leakage can erode the environmental benefits of nature projects[72].

Whether leakage reduces or eliminates the environmental benefits of a nature project depends on the context. Where agricultural/forest commodity yields are low and benefits to nature are high, the effects of displaced production may be low, but alternatively in some cases leakage may exceed the local benefits created by nature markets[77]. For example, a restoration project on agricultural land will necessarily lead to a reduction of agricultural production, which could be displaced to other locations either locally or globally. If the displacement results in the clearing of new land for agriculture, the project’s net climate or ecological benefits might be near zero. In other cases, substitution could result in intensification of agricultural production elsewhere, in this case resulting costs to nature from leakage may be negligible compared to the project’s benefits (e.g. where there is an intensification of already cleared land involving the use of low-carbon farming practices).

Leakage effects can occur through a range of direct and indirect channels. Nature markets must have processes that fully account for leakage risks. Leakage remains understudied, challenging to address, and a critical avenue for further research. To date, the most scientifically rigorous method for addressing leakage would be for standards bodies or regulators to ensure coupling nature markets with interventions that also lead to improvements in the efficiency of the production of that commodity elsewhere[75], so that there is no overall increase in the land area required to satisfy that amount of demand. Other methods include applying high discount rates to credits; this practically amounts to using larger multipliers or buffer pools (credits which are held back by scheme administrators to insure against some risks of credit non-delivery[11]).

4) Ensure outcomes can be independently verified

A critical rule relates to society’s capacity to hold project proponents and the regulators themselves to account. Third-party scrutiny of nature markets is critical to their iterative improvement. Every single counterfactual-based impact evaluation of a nature market to date has been fundamentally enabled by public data availability; and to date each of these impact evaluations has identified that the nature market has not achieved its full environmental objectives[22,47,57–59,61,66]. Transparency has enabled learning and iterative improvement. Yet, these markets remain opaque in many cases, and information is often either publicly inaccessible or accessible in disaggregated forms that make independent verification infeasible[78,79]. Providing complete and sufficiently detailed information in a way that can be easily accessed by the public not only provides accountability but also ensures market confidence for buyers, which remains a critical barrier to attracting investment to nature markets[6,80].

A recent assessment demonstrated that none of the world’s biodiversity offsetting systems’ public registries reveal enough information to evaluate whether they have achieved their ecological objectives[78]. In some cases, publicly available data may be highly incomplete and substantial sections of the reporting required to ensure policy accountability may be voluntary to disclose[81]. Different subcomponents of the nature markets may have different levels of transparency; for example in England, the off-site offset market is available from a government website, yet the vast majority of the biodiversity gains delivered through the nature market are delivered on-site, recorded over 200 local authority planning websites[14]. In other cases, shapefiles of project locations are publicly available, but project proponents and regulators can defend projects claiming that satellite data is an unsuitable proxy for project performance and that only private site-level data is suitable, without releasing the relevant site-level data[82], leaving claims of effectiveness non-falsifiable.

Once shapefiles are publicly-available, this enables independent stakeholders to observe many important changes in ecological characteristics at project sites via remote sensing. Remote sensing approaches can infer ecological characteristics including the structure, composition and functioning of vegetation, and one-off and periodic disturbances[83]. They will always be associated with some error, and methodological decisions made during modelling alter the estimates produced. This is particularly problematic when modelling is carried out by stakeholders with motivations towards specific interpretations[84]. For this reason, peer-reviewed layers, which are less vulnerable to subjective interpretation, may be preferable even though they can be associated with lower overall accuracy or biases in certain contexts[85].

Various detailed guides to nature market transparency exist which outline the fundamental information which must be disclosed to enable public accountability[78,80]; most critical is disclosing spatial data for project sites.

5) Have a credible pathway for detecting and penalising non-compliance over the long-term

When a buyer purchases a product that does not do its job in any other conventional market, they switch their purchasing behaviour, and the seller loses credibility and revenues. Buyers in conventional markets may also have regulatory avenues to seek recourse, e.g. under consumer protection laws or ombudspersons. In nature markets, there are few such protections – because the quality of the credits is not directly observable, buyers must trust that they represent the relevant environmental improvements, now and over time. Buyers also often have little incentive to verify the integrity of claims regarding the ecological outcomes of nature units[6,86], especially if they have been deemed compliant with legislation or voluntary standards.

The asymmetries of information that exist between sellers and buyers elevate the importance of regulation. The effective operation of these markets is contingent on robust governance structures that include capable, well-resourced regulatory agencies and rules and processes that facilitate active third-party involvement in rule making, monitoring and enforcement[87].

Nature market regulators are often underfunded to the degree that they cannot effectively perform their duties[13,32], occasionally even susceptible to regulatory capture[88,89]. Even when regulators have mechanisms available to address non-compliance, they may lack the capacity to exercise these powers in practice[13,1488]. In voluntary markets overseen by standards bodies which do not have the power to create and enforce legislation, there may be limited practical opportunities for enforcement. Where standards bodies have a commercial interest in the volume of credits they issue, their financial incentives may oppose identifying or addressing over-crediting in the first place.

Effective long-term governance is critical because scientifically-credible nature credits should be as durable as the damages they compensate for. Since most environmental damage is permanent, from an ecological perspective project outcomes should be maintained permanently if they are to deliver effective compensation. While some biodiversity markets do require outcomes to be secured in perpetuity (e,g. Victoria, Australia, some US species conservation banks), many markets specify permanence periods of less than 50 years (e.g. 25 years for the Australian Carbon Credit Unit (ACCU) scheme, 30 years for BNG in England, 40 years for voluntary carbon markets[90]). Shorter permanence periods (with the value of credits commensurately discounted[9,91]) are seen to represent a practical compromise to encourage market participation[92], with the critical trade-off being that any reversal of project outcomes at the end of a permanence period leads to a net ecological negative impact in the context of offsetting.

Governance becomes especially challenging when projects are forward credited for environmental benefits that are expected to be achieved in the future (ex-ante crediting). Where this occurs, regulators can be left without the capacity to withhold credits in the event of non-compliance. For example, in the US wetland mitigation system the majority of offset credits are released within the first three years of mitigation banks being initiated[93], and the ecological condition of wetland mitigation banks often declines over time[94]. Such arrangements systemically threaten the long-term outcomes delivered by nature markets. They also implicitly incentivise over-crediting as the probability of non-compliance being detected and enforced is small (often near zero).

Solutions exist. Some of the risks of non-compliance can be addressed through improved crediting methods and policy design. One mechanism for addressing non-compliance is only releasing credits ex-post[6,67]. Other key policy mechanisms include ensuring regulators have the power to impose fines and other sanctions for non-compliance, and having clawback mechanisms to enable the withdrawal of credits if they are issued in breach of scheme rules[95]. Other solutions focus on the implementation side such as appropriately staffing and resourcing regulators and implementing standardised monitoring that enables regulators to detect projects at a high risk of non-compliance.

The politics and financial dynamics of nature markets means that regulators cannot be relied on as a complete solution. There is often pressure to reduce the stringency of the rules to increase participation and credit supply, and for regulators to adopt an accommodating approach to non-compliance, penalising only the most egregious breaches[29]. Active third-party involvement in rulemaking, monitoring and enforcement helps mitigate these pressures. It is essential that third parties have the ability to seek legal remedies in the courts for breaches of scheme rules, either by scheme administrators or market participants. These types of ‘open standing’ requirements are a common feature of environmental laws, having first been introduced in the United States in 1970 and spreading globally since. They are now one of the three pillars of the Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters (Aarhus Convention). The theory is that these provisions can enhance compliance with environmental rules through both direct and indirect means: directly by providing third parties with the power to uphold scheme rules through the courts; and indirectly by incentivising regulators and participants to be more mindful of scheme rules due to the threat of third-party proceedings[96,97].

Performance of a sample of key nature markets

We distil our five rules into a concise checklist against which to assess the scientific credibility of a nature market, for use by policymakers, investors and civil society. While there is no objective method for establishing what the ‘right’ questions are for evaluating the scientific integrity of a nature market, these questions have achieved consensus across our research team who have conducted academic evaluations of seven nature markets around the world[13,17,34,50,57,58,98–100], spanning voluntary and mandatory nature-based carbon and biodiversity markets.

We then assess a sample of the world’s largest nature markets or specific crediting methodologies within these nature markets against our proposed checklist (Table 1; Figure 2). We identify that none satisfy all our proposed rules, suggesting that future nature markets have the potential to exceed the effectiveness of past attempts by learning from their historical shortcomings.

Rule	Questions	Rationale	Example	Design recommendations
Policy design				
1. Ensure nature market's proxy correlates with desired outcome	Does the nature market issue credits based on some form of direct measurement of the state of nature?	*Nature markets should measure the state of nature in some form rather than relying entirely on modelled estimates*	Under the human-induced regeneration (HIR) methodology in Australia's carbon credit scheme, credits are issued based on modelled changes in forest cover but credited sequestration is not empirically validated. The model used to credit abatement assumes land has been previously cleared, but it is routinely applied to land with existing vegetation, leading to over-crediting[58].	Do not base the release of credits purely on modelled estimates without validation against primary observations
	Does the nature market require the re-measurement of that state of nature using primary observations throughout the crediting period to ensure that the state of nature is changing in line with expectations?	*Ideally nature markets would be based on (and credits released after) real observations of the change in nature rather than only assessing the state of nature up front and then making assumptions about how nature will change across the duration of the project without validating these changes using primary observations.*	In Victoria's offset system biodiversity gains are currently projected and awarded up-front. Proponents are required to submit annual reports demonstrating they are implementing management measures, but not that the state of nature is changing in line with the expectations of the up-front projections used to generate credits[101]	Where the nature market's outcome variable relates to a land cover variable, link credit issuance to real-time satellite data Ensure monitoring of the state of nature at the project over time rather than relying purely on up-front projections
	If the nature market utilises a proxy to approximate the state of nature, has it been empirically demonstrated that the proxy outcome correlates strongly with the desired policy outcome?	*If the proxy is not rigorously validated, then the nature market will likely deliver an outcome misaligned with the overall policy outcome.*	In Biodiversity Net Gain in England, empirical work shows no consistent correlation between the magnitude of the policy's fully habitat-based biodiversity metric and exogenous indicators of biodiversity such as wildlife or insect abundance or diversity[44,98]	Where the nature market's outcome variable is an ecological proxy, do not operationalise the proxy until it has been validated empirically by independent and rigorous science, and ensure proxy is applied only in contexts where modelled assumptions match reality

2. Assume projects are non-additional unless proven otherwise	Does the nature market documentation include some attempt to estimate the quantity of additional benefit from projects, and the magnitude of additionality of credits?	*Nature markets tend to assume that additionality is binary and that all credits are 100% additional if they have passed some simple additionality criteria, but impact evaluations typically demonstrate that additionality is continuous. In addition, projects that opt-in to nature markets are often those with systematically lower opportunity costs and additionality, so this must be accounted for*	In Victoria's offset market, all biodiversity gains are assumed to be additional as long as they are considered to be 'in addition to existing obligations under legislation, existing agreements or contracts'[102]. In contrast, carbon credit developer Revalue for example only releases credits once they have been estimated to be additional by comparing land cover outcomes at project sites with sites derived from synthetic control methods[71]	Use evidence-based and conservative rules to establish plausible counterfactuals to ensure crediting aligns with reality[63], such as identifying control sites (which could be known land parcels[57], or placebos[68] or pixels drawn from the wider landscape[100]) using statistical matching and tracking and comparing changes in land cover outcomes between projects and control sites in near-real time[6] Only release credits after they have been proven to have achieved their ecological goals ('ex-post')[6,67]
	Has a robust independent impact evaluation comparing the outcomes of the nature market against an unbiased credible counterfactual demonstrated that the amount of additional gain on average aligns with that claimed?	*To date, the most scientifically-credible methods for estimating additionality compare the outcomes in treated sites with matched, unbiased control or quasi-control sites.*	Impact evaluation methods have been used to identify high levels of additionality in the US wetland mitigation system[47] but widespread over-crediting in international voluntary forest carbon offsets[22], Australia's forest-based carbon offsets[58], and Victorian biodiversity offsets[57]	Increase multipliers or buffer pools by an amount inversely proportional to the average additionality of projects within the nature market (i.e. if additionality is known to be 20%, then credits can deliver their stated objectives by having a buffer pool that corresponds to 400% of the number of credits sold in that transaction) Use well-designed auctions that exploit competition between landholders to elicit bids for offsets, thereby accounting for the relative non-additionality of low bids which reflect their low opportunity costs[21]
3. Ensure	Does the nature market	*Current science cannot rule out*	Most national or sub-national	Ensure nature market projects

markets do not induce effects elsewhere that undermine outcomes	acknowledge leakage and make any adjustments to the number of credits allocate to account for leakage?	*that leakage may be large and undermine environmental outcomes.*	biodiversity offsetting markets do not consider leakage.	are not located in areas of high agricultural productivity and are therefore highly exposed to leakage risks[72]. Where the nature market results in a transitions away from productive land uses, couple credits with agricultural productivity activities to deliver yield improvements equal to the amount of displaced commodity production[35].
	Does the nature market acknowledge that it cannot be ruled out that leakage may approach 100%, and therefore uses conservative estimates of leakage in its calculation methods?	*Current science cannot rule out that leakage may be large and may in some cases be equivalent to 100% of the foregone production resulting from the nature market intervention.*	In the international voluntary carbon market some key methodologies do recognise and take some steps to correct for leakage; but they typically use the minimum possible value rather than a conservative estimate[75,103].	Increase multipliers/reduce credit issuance or increase buffer pools by an amount estimated to reflect market leakage.
Governance				
4. Ensure outcomes can be independently verified	Are spatial data delimiting projects and credited areas in the nature market publicly available?	*Publicly available shapefiles is the bare minimum required for third-party oversight of nature markets; public data availability has been the critical factor that has enabled impact evaluations of nature markets, identification of problems, and therefore their iterative improvement.*	In Biodiversity Net Gain in England the locations of the vast majority of biodiversity units delivered through the policy are 'on-site' gains found on unique webpages for every single development affected by the policy across >200 local authority planning websites, and shapefiles are not provided so they require manual digitalisation, which are therefore not practically publicly accessible[14]	Ensure that shapefiles and the data needed to reproduce claims are easily accessible for external audit[78].
	Where projects are claiming outcomes that cannot solely be verified through remote sensing, are all the site-specific	*Nature markets will always be able to avoid reform through plausible deniability unless all data required to develop a*	The Regulator of Australia's carbon credit scheme has previously drawn on analyses using national-scale satellite	Full disclosure of site-specific data used to make the claims[79].

	data used to support the claim publicly available?	*credible estimate of whether or not they have achieved their policy objectives is publicly available.*	imagery to argue that the integrity of carbon credit projects is sound, yet following the publication of peer-reviewed academic literature which points to low performance and compliance of forest carbon projects, the Regulator now argues "only using national-scale models of tree cover is unreliable" for evaluating project performance, and field-based measurements (which are not publicly available) is required to assess project integrity[34,58,82], but they have not then made that data publicly available, making the claims non-falsifiable	
5. Credible detection of non-compliance, and enforcement of non-compliance	Is the regulator or a third party conducting and publicly reporting ecological monitoring to evaluate ecological changes at some project sites?	*Many systems rely on self-reported ecological progress by project developers instead of monitoring by the regulator themselves or an independent third party.*	None of the world's biodiversity offsetting registers report whether the gains included in the offset register were achieved in reality[78].	Invest in sufficient capacity in regulators.
	Is there evidence that the regulator is taking enforcement action in the majority of cases following the detection or reporting of non-compliance?	*Regulators are often chronically under-resourced or captured, and therefore unable to perform their compliance function even if they have legal power on paper.*	Major risks that regulators do not have the capacity to take enforcement action have been explicitly identified in England[14] France[104] and Australia[32].	Develop the capacity for civil society to hold regulators to account if they demonstrably are not implementing their compliance function.
	Does the regulator have powers to revoke credits that have been issued if ex-post monitoring demonstrates non-	*Having legal powers to take enforcement action and exercising these powers is essential to ensuring the*	Some US mitigation banks enable credits to be debited back to the bank if the site is	Develop credible and accepted processes for clawing back non-compliant credits that

compliance?	*credibility of the units sold in nature markets.*	disturbed[105].	have been sold in the market.
Does the regulator use this power in the majority of cases where long-term non-compliance has been demonstrated?	*Having legal powers to take enforcement action and exercising these powers is essential to ensuring the credibility of the units sold in nature markets.*	Too early to evaluate.	

535

Our assessment reveals interesting patterns. Firstly, carbon markets clearly exhibit fewer measurement challenges than biodiversity markets because of the well-established scientific relationships between land cover observable by satellite and carbon stocks and sequestration, greatly increasing the potential for scientific credibility. Secondly, the voluntary carbon market clearly outperforms regulated markets in terms of transparency and the rigour of measuring outcomes, but the inability for standard-setters to create or enforce legislation, coupled with demand being voluntary, weakens their capacity to address non-compliance. This is intuitive, as in voluntary markets standard bodies and sellers must convince buyers that their credits represent real environmental improvements as this is their fundamental product; whereas in regulatory markets the product is merely compliance. The nature market which has demonstrated additionality (in terms of area) most consistently is the US wetland mitigation system, where a major component of the policy is active restoration or creation of wetlands. This is in stark contrast with the ‘avoided loss’-type systems in the REDD+ component of the international voluntary carbon market and Australian biodiversity offset markets, which have to date insufficiently dealt with adverse selection and have therefore delivered limited additionality[22,57]. Therefore, future nature markets need to learn from the shortcomings and successes of both voluntary and regulatory markets.

This analysis reveals many useful design principles for countries that are considering adopting nature markets. It is much easier to create a scientifically-credible and demonstrably effective nature market if the market’s outcome can be monitored via remote sensing, as this greatly increases the ease of monitoring, estimation of additionality, and creation of standardised assessment methods that improve oversight and reduce transaction costs[6,35,68]. Nature markets where project proponents opt-in to selling credits (and there is no process for addressing adverse selection such as auctions) are likely to have low additionality, unless the actions incentivised by the nature markets are capital-intensive changes in land cover that are very unlikely to have occurred anyway. Publicly-accessible shapefiles of all projects are critical to ensuring scheme integrity by enabling third-party evaluation and accountability, as regulators are subject to their own political and economic pressures and are often therefore unable to uphold market integrity alone. And long-term governance of nature markets is critical, yet remain largely untested in many regions as insufficient time has passed, and so more evidence on how to design effective long-term governance are profoundly needed[28].

The analysis also demonstrates that major integrity risks are pervasive across nature markets, and it is therefore critical to continue debates about what are the most effective and cost-effective tools and policies for addressing biodiversity loss[106,107]. Nature markets face one major constraint not faced by most other public conservation policies: the conservation gains from offsets are cancelled out by equal and opposite losses elsewhere[108], and can therefore by definition play a limited role in delivering overall improvements in biodiversity in line with the vision of the Kunming-Montreal Agreement. They must be seen in their context as a targeted instrument for addressing specific, unavoidable, and offsettable damage[109] (i.e. harms which ecological science suggests can feasibly be offset) which is designed to complement, rather than replace, alternative public conservation policies such as protected area expansion and enhanced regulation of economic activities causing biodiversity loss[2]. They play no role in addressing many of the underlying drivers of biodiversity loss such as international tax and debt injustices[110,111], ecologically unequal exchange[112], excessive meat consumption[113], damaging subsidies[114] or underfunding of protected areas[115] – although they remain an important mechanism for pricing nature loss and incentivising impact avoidance in the specific economic sectors where they are applied[51].

Conclusion

Nature markets are considered a critical tool in global biodiversity governance are now firmly embedded in global and national policy goals. Yet, their historical track record demonstrates significant deficiencies that risk being repeated in current efforts to scale up nature markets[116]. Our analysis indicates that to date no nature markets evaluated achieve all the criteria that we argue are critical for ensuring they achieve their full environmental objectives in the long term. In this paper we aim to aid policymakers, market designers and civil society to enable them to identify which core characteristics of nature markets really matter and hold current and emerging markets to account, as they continue their rollout across the 21st century.

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Table and Figure Captions

Figure 1) Five rules for nature markets. 1) Several nature markets are constructed to deliver a biodiversity proxy that scientific research has demonstrated does not correlate with the desired policy outcome. Here, an example is the use of land cover as a proxy for on-site biodiversity (or whichever biodiversity outcome is specified in policy), without checking whether it is a valid proxy. 2) Most nature markets evaluated have demonstrated widespread additionality failures; it is now critical to start from the assumption that a project will be non-additional and place the burden of proof on demonstrating additionality, rather than the other way round. 3) Leakage is known to be a critical risk to nature market outcomes and remains understudied. 4) All evaluations of nature markets have found they have not achieved their full environmental objectives, and this has only been detected because of publicly-accessible data that enabled independent stakeholders to validate or invalidate claims. As a minimum, shapefiles of project sites need to be available so that third-parties can independently check outcomes using trusted primary observations, such as peer reviewed remote sensing layers. 5) Governance systems need to be in place to ensure robust enforcement of scheme rules and active involvement of third parties in rule-making, monitoring and enforcement.

Figure 2. Performance of a sample of the world's most high profile nature markets against the five rules, based on qualitative assessment by the authors. All empirical evidence used to substantiate the judgements provided in the Supporting information. Green = criterion met; light orange = criterion partially met or variation in methodologies used within the nature market with varying standards; red = criterion not met; grey = insufficient information to make judgement; colourless = not applicable.

Table 1. Checklist of key questions capturing whether nature markets are likely to be scientifically-credible for each of the rules.