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Perspective

Avoiding carbon leakage from nature-based offsets by design

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SUMMARY

With nature-based offsets emerging as a core strategy for meeting near-term climate targets, it is essential they deliver real and verifiable mitigation gains. However, the interventions that generate offsets can have unintended effects that cause carbon leakage and ultimately reduce mitigation. Although leakage is "old news" and various anti-leakage measures have been considered, there is little evidence that current practices to address leakage actually work. In this perspective, we present evidence that leakage is vastly underestimated in practice and argue that current efforts to improve accounting methods are unlikely to deliver the accuracy required. We therefore propose and elaborate an alternative approach to address leakage by design, based on a new conceptual framework for understanding leakage in nature-based interventions. We further outline three principles that offset developers, certifiers, and consumers can implement now to improve the credibility of nature-based offsets, without negating further ambition and investment in nature-based solutions.

INTRODUCTION

Amid current enthusiasm for decentralized, market-led climate change solutions, ecosystems are widely seen as near-term linchpins of global mitigation strategies. Land use (notably forests) provides a quarter of planned mitigation under the Paris Agreement,[1] and COP26 (Glasgow) signaled global willingness to allow international transfers of nature-based mitigation. Nature-based offsets already feature in most market emissions pricing schemes[2] and are central to corporate net-zero pledges.[3] Driven by corporate commitments,[4] voluntary offset markets neared US$2 billion in traded value in 2021, with 67% originating in forestry and land-use projects.[5] Support for nature-based mitigation is broad (projects offer both low-cost mitigation and environmental benefits), and estimates of total potential are high (20%–30% of mitigation needed to keep global warming to 1.5°C).[6] Not all nature-based mitigation will (or should[7,8]) substitute for emissions reductions, but the role of nature-based offsets is rapidly expanding.

Most pathways to nature-based mitigation depend on altering the state of coupled ecological-economic systems.[9,10] The effect of such interventions can be tracked as credits in a carbon accounting framework, which become offsets when used to substitute for other mitigation actions. If the underlying carbon accounting is inaccurate, offsetting may prove a dangerous distraction. Recent work[11–13] has highlighted widespread overestimation of the degree to which nature-based interventions have altered the state of the world to generate mitigation (i.e., their additionality), but another source of inaccuracy—carbon leakage—merits equal attention. Leakage occurs when some effects of an intervention fall outside the accounting boundary used to track mitigation effects (e.g., an action causing emissions reductions in one place may also cause increases elsewhere). These beyond-boundary effects are extremely difficult to measure,[14,15] particularly when economic markets are implicated (so-called market leakage).

Today's voluntary and compliance markets routinely transact nature-based offsets on the premise that methods to account for leakage are sufficiently accurate,[16–18] and leakage is often framed as a tractable problem for which "sophisticated and robust tools"[2] and "policy levers to manage risks"[7] are available. Yet the main approach currently in use (adjusting issued credits using a leakage discount factor) has been recognized as insufficiently rigorous "in the long run,"[19] and how best to deal with leakage is controversial.[20,21] Among specialists, the problems are well known: Richards and Andersson[22] argued over 20 years ago that both theoretical and practical challenges prevent the accurate measurement of leakage associated with a specific intervention, concluding that "either the reliability of project analysis will be low or the costs of analysis will be high, and quite possibly both." Concern about leakage followed the first forestry offset projects in the early 1990s,[23–25] and three decades of work have now thoroughly explored the issue: several reviews exist,[19,26,27] and research interest remains high.[9,14,28] However, the solutions proposed are either politically intractable (i.e., scaling up accounting frameworks to include all beyond-boundary effects[21,29–33]) or poorly understood and inconsistently applied.[15,30] In the absence of a viable alternative, nature-based offsets continue to be issued and retired using ad hoc leakage accounting methods of unknown accuracy.

In this perspective, we aim to develop a viable alternative for dealing with carbon leakage from nature-based offsets. We

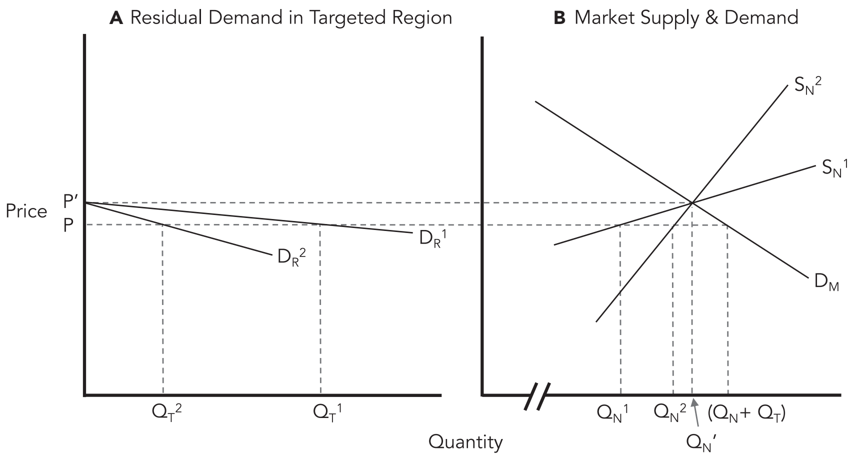

Figure 1. Market leakage occurs because price signals induce agents outside a targeted region to change behavior

Supply and demand diagrams allow a precise illustration of this phenomenon. S_N is supply from all non-targeted producers and is shown for two cases, relatively elastic supply (S_N^1) and relatively inelastic supply (S_N^2). The initial equilibrium quantity is $Q_N + Q_T$, the sum of supply from the non-targeted area (right panel) and targeted area (left panel). An intervention resulting in $Q_T = 0$ will cause the price to increase from P to P′, producing a new equilibrium at Q_N'. For the case of relatively inelastic supply, non-targeted producers had been producing Q_N^2 prior to the intervention, and market leakage is $Q_N' - Q_N^2$. For the case of relatively elastic supply, market leakage is $Q_N' - Q_N^1$. In both cases market leakage results from producers outside the targeted region moving up their supply curves due to the change in price resulting from the supply restriction in the targeted region. Note that $(Q_N' - Q_N^1)/Q_T^1 > (Q_N' - Q_N^2)/Q_T^2$, i.e., market leakage is proportionately greater for more competitive markets, such as those with fewer barriers to entry or lower transaction costs to displacing supply.

focus on market leakage, reviewing its theoretical basis, the empirical literature, and current accounting practice. We present evidence that suggests nature-based offsets in use today are systematically underestimating market leakage effects, and argue that attempts to refine leakage measurement will not deliver the accuracy needed in practice. We then propose a novel approach to designing nature-based interventions and associated offset markets to avoid the leakage problem: a framework for thinking about market leakage that enables identification of how and when it arises from nature-based interventions. Leveraging the available evidence through our framework, we outline three principles for a design-based solution to the market leakage problem that preclude the need for (currently unachievable) precision in leakage accounting. Our proposed alternative approach provides a conservative solution that can be immediately implemented within today's decentralized offset regimes, as well as clarifying ongoing misunderstandings about market leakage in a nature-based context.

THE PROBLEM WITH MARKET LEAKAGE

While a number of classifications of leakage[14,15,19,24,34] now exist (including impacts via connected ecological systems,[15] information, motivation, and institutions,[24] or spatial interactions[35]), we focus on two canonical types involving economic agents: "direct" leakage and "market" leakage. Direct (or "activity") leakage arises when the economic agents targeted by an intervention shift activities outside of the accounting boundary, whereas market leakage arises when non-targeted agents adjust their behavior in response to altered economic incentives. While activity leakage is relatively tractable (targeted agents are known, and their actions are observable), market leakage is not. Teasing out market leakage effects from background economic activity is extremely difficult, since which agents are responding to changes in incentives and how much of their behavior is due to this response depends on unobservable motivations.

The mechanism by which market leakage operates is information transmission through price. In an economic model of a single market equilibrium, reducing output from one producer causes prices to rise, moving the system out of equilibrium and incentivizing producers and consumers to respond as the system adjusts along a new equilibrium path. The net result of such equilibrium adjustments in interconnected markets is complex, but theory provides some general guidance.[36,37] All else being equal, market leakage will be lower if demand is elastic with respect to price or alternative products are not substitutable, and higher when supply is more elastic with respect to price, substitutable goods have a higher net carbon footprint, or supply restrictions are small (Figure 1). These theoretical conditions raise concerns about market leakage from nature-based offsets, which typically operate within globalized "food, fuel, and fiber" commodity markets where products are highly substitutable, demand is relatively inelastic with respect to price,[38–40] and markets are very large relative to the size of interventions.

While there are several approaches to measuring market leakage, each has its limitations. Partial or general equilibrium models are arguably the most suitable because they are developed specifically to capture market interdependencies (equilibrium effects) by simulating the actions of economic agents. Unfortunately, subtle changes in parameters can substantially alter results[39] (as demonstrated under our first principle below), and building such models requires highly specialized personnel and abundant data. Accounting-based approaches (e.g., input-output analysis or material flow analysis) offer an alternative and can provide compelling circumstantial evidence[41,42] but cannot separate out the causal impact of a specific intervention. Quasi-experimental econometric techniques can, but rely on assumptions about the independence of pseudo-controls that are violated by the presence of leakage effects. Many researchers therefore apply simple zone-based methods,[43,44] also widely used to quantify activity-shifting leakage (e.g., from protected areas[45,46]). This requires the assumption that leakage occurs within known areas that are unaffected by background economic incentives, an untenable premise in the well-functioning and large-scale markets where indirect effects are of most concern. Although innovations are ongoing,[47,48] an accessible, replicable, and accurate method of estimating market leakage has not yet been found.

Thus far, assessments of market leakage from nature-based interventions in the literature have focused primarily on "stop-harvest" forest mitigation projects, frequently leveraging established partial equilibrium models. Leakage estimates for developed countries from these models are typically at least 70% of reduced output, measured either as forestry production[37,49–52] or carbon stocks.[53] Lower estimates (50% or less) have been found for the specific case of a global carbon price,[54] or in a developing country context when international leakage is deemed negligible[55] (e.g., Kuik[56] estimates 0.5%–11.3% market leakage from large national supply restrictions in developing countries, but this result depends on methodological choices and is contradicted by other evidence[47]). Afforestation scenarios may possibly produce lower leakage than avoided conversion (e.g., $\leq$43% vs. $\leq$ 92% in one estimate[36]) because of productivity differences or the availability of underutilized land.

Carbon leakage from non-forest interventions is less well studied. Kim et al.[57] find about 15% leakage from crop conversion, while econometric studies of leakage from conservation reserves (also known as "slippage") suggest that leakage is important[58] but possibly low[59]: estimates include 4% activity leakage (measured as forest cover loss)[43] and 20% market leakage (measured as farm area,[60] although criticisms of this estimate[61–63] highlight measurement challenges). Since marginal farmland may be preferentially enrolled in conservation programs,[43] estimated leakage in this context may in fact be low because additionality is weak (an idea we return to in the next section). Further econometric evidence is available for forest-to-agriculture conversion in Brazil,[47,64,65] but only adds to the uncertainty, as leakage estimates range from insignificant to essentially all program gains. A growing literature also considers carbon leakage associated with the unilateral adoption of various climate policies (e.g., carbon taxes), but the potential for these studies to inform leakage estimates for nature-based offset projects is unclear.

In our view, the empirical literature on market leakage supports two inferences. First, leakage from nature-based interventions can be very high. Failing to identify the true level of leakage could lead to credits that grossly overstate actual mitigation impacts, and widespread use of these credits as offsets could put climate policy targets in jeopardy. Second, leakage is context specific.[36] Results from one intervention (or averages of them[66]) do not provide an accurate estimate of leakage from another intervention. The problem with market leakage is thus a problem of measurement: to accurately assess market leakage, the dynamic adjustment of a complex system must be measured every time.

A CONCEPTUAL FRAMEWORK FOR AVOIDING LEAKAGE BY DESIGN

If market leakage cannot be accurately measured in practice, nature-based interventions must be designed to minimize leakage risk while ensuring that offset markets are able to identify and apply high-risk offerings in ways that do not jeopardize critical near-term mitigation goals. Doing so requires a nuanced understanding of when and how leakage arises. We therefore elaborate a conceptual framework for understanding leakage in coupled economic-ecological systems and apply this framework to the complete set of possible nature-based mitigation interventions to identify design choices that lead to leakage risk.

Our approach is derived from the observation that when nature-based interventions are used as offsets, the solution space is bounded by the need to simultaneously satisfy three well-known criteria: permanence, additionality, and (no) leakage.[67] Reframing these criteria as simultaneous constraints is important. Recent debate[68–74] around the biophysical potential of nature-based mitigation has tended to consider each issue separately, obscuring overlaps and trade-offs between them. Reframing them as simultaneous constraints unifies the challenges to real nature-based mitigation, thereby scoping down the set of possible nature-based interventions and enabling a design-based solution to market leakage.

In implementing this new simultaneous constraints framework, our main concern is the existence and implications of a conceptual "duality" between additionality and leakage that emerges from our approach. When a market system is in equilibrium, any intervention that achieves additionality by altering supply or demand in a particular market will transmit information to connected markets through price changes (both for products in that market and for markets for secondary products or production inputs). The resulting adjustments across the entire economic system are known to economists as general equilibrium effects; those that fall outside a carbon accounting boundary are also known as leakage. This is the duality at the heart of our design-based solution: when carbon accounting does not cover the entire economic system, additionality and leakage are two sides of the same coin. Carbon credits that rely on altering supply or demand to claim additional mitigation also inherently create market leakage risk. Conversely, market interventions that do not generate leakage risk are likely not additional.

To apply this insight to design credible nature-based offset markets, we must focus on the additionality claim(s) made to issue carbon credits. Nature-based interventions do not necessarily rely on altering market supply or demand to achieve additionality, and a single offset project may involve multiple additionality claims; for example, forest cover loss may be avoided by banning logging while also improving household fuelwood efficiency. Whether market leakage is important relative to intended mitigation therefore depends on the degree to which a project alters market equilibria to claim additionality. To identify at-risk additionality claims, we trace out the set of possible mitigation interventions in coupled economic-ecological systems (Figure 2) and apply our concept of simultaneous constraints to identify those interventions at risk of market leakage.

Of course, there are other constraints beyond permanence, additionality, and leakage (e.g., maintaining non-carbon values or establishing the certainty of emissions baselines). Including these challenges leads us to identify three most credible categories of nature-based intervention (gray highlights in Figure 2). In economies, interventions that reduce aggregate demand or decarbonize production are at relatively lower risk of market leakage (especially if decarbonization results from non-transferable innovation). Interventions that reduce supply are at high risk. Interventions that transition economically unused ecosystems between stable states can also generate leakage-free mitigation while avoiding the problems associated with reducing disturbance or establishing non-native ecosystem states. Thus, by reframing challenges to nature-based mitigation as simultaneous

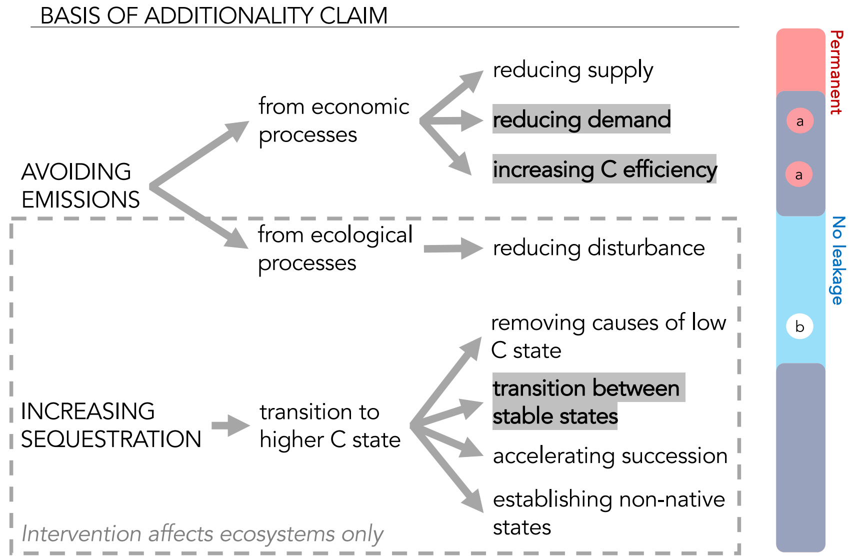

Figure 2. Generalized classification of nature-based interventions (flowchart) showing permanence or leakage constraints (colored bars)
Starting with the basic dichotomy of avoiding emissions or increasing sequestration, we identify eight ways in which nature-based interventions can generate additional mitigation. Three of these (gray highlight) have minimal leakage risk, are permanent, and satisfy other criteria such as preserving biodiversity (see main text). Note that (a) our preferred economic interventions (gray highlight) can still cause market leakage in some circumstances, and (b) removing causes of low-carbon states can cause ecological leakage.

constraints and focusing on the additionality claims made to issue carbon credits, it becomes possible to identify design choices that lead (or not) to market leakage risks.

To justify these claims, it is helpful to examine the different additionality pathways for nature-based mitigation presented in Figure 2. We first consider interventions in ecosystems alone (i.e., no economic implications and no market leakage; dashed box in Figure 2). The primary way such interventions deliver mitigation is by increasing sequestration, which requires transitioning ecosystems to higher carbon states. If the new state is naturally occurring, it may be a later successional stage (e.g., shrubland to forest). Since succession would have occurred anyway, baseline dynamics must be netted out in crediting (i.e., the offset is additional in time only; accelerating succession in this way can still deliver useful mitigation if baseline succession is slow). If the new state is not naturally occurring (e.g., shrubland to non-native plantation), non-carbon values such as preferences for native biodiversity restrict large-scale deployment.

However, unlike the economic concept of a unique equilibrium, ecological systems can exist in multiple naturally occurring stable states[75] (e.g., savanna/closed forest, rock/kelp). Understanding why ecosystems persist in a stable low-carbon state when naturally occurring high-carbon states are possible allows us to differentiate two important subcategories of ecosystem interventions. Both currently active processes (abiotic or biotic disturbance agents, such as fire or grazing megafauna[76]) and the effects of past actions (path dependency) can cause stable low-carbon states. Removing the most important active processes (fire, pests, pathogens) is unlikely to be permanent, and accurately modeling baselines is extremely challenging. Meanwhile, more tractable removals of "ecosystem engineers" (e.g., large grazers) is constrained by ecological leakage if relocated or non-carbon values if eliminated. Conversely, if low-carbon stable states exist because of the history of past events alone (i.e., due to path dependency), interventions can shift ecosystems between stable equilibria to achieve both additionality and permanence without market implications or leakage risk. Restoring degraded but abandoned land is the most prominent example.

The pathways classified as "avoiding emissions from economic processes" in Figure 2 reintroduce economic considerations. Following the "duality" we identify above, any economically additional intervention in this category alters market equilibrium by definition, thus producing price changes that result in altered economic behavior (leakage) throughout the connected economic system. There are only two exceptions: if the carbon intensity of ecologically derived goods can be reduced while maintaining the flow of such goods into economies (e.g., via material or process substitutions), price changes may not occur, and if no substitutes exist for such goods then price changes are irrelevant. When neither condition is met, reducing market leakage below 100% of claimed mitigation requires that alternative output is only available at higher prices, thereby causing quantities demanded to fall. This assumption is a problem for (relatively) small projects without market power, a category that arguably encompasses most nature-based offsets issued to date.

Nature-based interventions that reduce supply to markets are accordingly highly likely to be interventions at high risk of leakage. This is true whether what is being reduced is the supply of goods or of factors of production such as land, and even if this reduction is temporary. We recognize, however, that reducing supply is not the only way market-exposed nature-based offsets can claim additionality. Reducing the carbon footprint of economic activity (i.e., increasing emissions efficiency) can deliver economic additionality without leakage (provided the price and quantity of outputs remains unchanged) and is an important mitigation strategy.[77] This broad category of interventions includes projects that maintain output while reducing inputs (e.g., optimal rotation grazing) and those that substitute low-carbon for high-carbon service delivery (e.g., green infrastructure). The other option is to reduce demand, which can avoid emissions or generate sequestration without causing adverse effects outside the accounting boundary by removing anthropogenic causes of low-carbon ecosystem states.

Of course, general equilibrium effects must still be considered whenever markets beyond the accounting boundary are implicated. For example, increases in efficiency can lead to increased production via price reductions or firm entry (i.e., rebound effects[26]), and reduced demand can suppress prices and incentivize increased consumption elsewhere. Such effects depend on the connection between interventions and external markets. For example, rebound effects from culturally specific changes in resource management are less likely, while rebound effects from transferable technological innovation are more likely. The primary concern, however, are interventions that alter markets by increasing prices or reducing the supply of outputs, which are more directly tied to leakage risk. Finally, note that efficiency gains must be demonstrated within a credited project to credibly avoid the leakage problem. It is not sufficient to assume strong spatial and temporal coordination between multiple projects when issuing credits, although this is a common assumption in large-scale assessments of nature-based mitigation potential.[10,78,79]

THREE PRINCIPLES TO AVOID LEAKAGE BY DESIGN

The conceptual framework outlined above allows leakage risk to be located within specific nature-based additionality claims. Doing so provides a means for project proponents to design nature-based interventions that avoid market leakage risks and for buyers (or evaluators) to assess the likely leakage risk of an intervention. To facilitate application, the remainder of this perspective outlines three key principles for moving offset markets toward the design-based solutions our framework implies.

Our first principle captures a necessary design feature to control market leakage at the level of an individual project issuing carbon credits, while our second principle provides a critical demand-side safeguard for compliance carbon markets. Our third principle proposes a general rule for designing offset markets to deal with leakage (and other sources of uncertainty) and recognizes that at-risk interventions can still advance mitigation goals if the use of associated credits is appropriately targeted. Implementing these principles does not require coordination between market participants, but we stress their complementary nature. Correctly applying principle 1 will be essential to the proper application of principle 3, while principle 2 provides an important restriction and safeguard on the overall implementation of our framework.

Principle 1: When the design of a nature-based intervention implies market leakage risks, upper-bound estimates of potential leakage should be used

There is widespread agreement that accounting methods for market leakage should be conservative (i.e., biased toward overestimating leakage effects).[15] We present evidence which strongly suggests that the opposite is true in practice. In the absence of reliable, low-cost methods for market leakage accounting, third-party certification standards have been forced to rely on ad hoc approaches with mixed (often low) evidential standards. Since research-quality estimates are costly and are highly context specific, ensuring the use of upper-bound estimates is a conservative design-based alternative. Some steps have been taken in this direction (e.g., the current verified carbon standard [VCS] "Agriculture, Forestry, and Other Land Use" requirements apply a 100% discount factor to calculate leakage in some cases), but the use of arbitrarily low estimates of possible leakage appears widespread.

To assess whether current crediting practices are conservative, we reviewed a small random sample of credited projects from the most important nature-based offset methodologies (by issued credit volumes). All-time issuances for the selected methodologies are about 480 Mt, or roughly 2 years' worth of the annual reductions Canada needs to hit its 2030 emissions target. All the methodologies we reviewed are for forest-based interventions, and all adjust issuances for market leakage by applying a discount factor at the project level. The range of possible discount factors included in a methodology defines minimum and maximum potential leakage rates for credits issued under that methodology; these ranges were from 10% or 20% up to a maximum of 70% in our review (Table 1, column 8). In our random sample, the discount factors selected and applied by projects (Table 1, column 9) were almost always the minimum possible value. For Verra-registered projects, additional data showed a similar phenomenon in projections of total (market + activity) leakage for sampled projects (median values: VM0007 11%, VM0009 10%, AR-ACM0003 0%, VM0015 6%, VM0006 4%; not reported in Table 1). A recent study[28] of avoided forest conversion or degradation projects corroborates our results, with 26 out of 68 projects claiming no leakage and 28 deducting expected leakage at a median rate of just 6%.

These results contrast sharply with research estimates of market leakage from forest-based interventions, which are typically above 70% (and can reach >100%; see "the problem with market leakage"). Since the methodologies we reviewed include a range of interventions and market contexts, why are the leakage rates allowed by standards and applied by projects uniformly so much lower than those suggested by the research literature? One explanation relates to technical complexity in market leakage accounting. Because accuracy is difficult and therefore costly, standards must negotiate a compromise between scientific rigor and financial viability (see work by Cashore and colleagues[80,81] for related political economy concerns). However, the compromises that have been made in practice can seriously distort carbon accounting systems. Consider the general exclusion of difficult-to-measure leakage beyond country borders (unwarranted in light of research results,[42,49,50] but in alignment with international norms in carbon accounting). One randomly sampled project (#1175 on the Verra Registry) applied this principle to rule out leakage effects from the 87% of foregone output destined for export. An alternative explanation for low leakage rates is expediency. Leakage deductions can make or break the financial case for an offset project and are a key concern for project developers.[82] Once rules are in place, project proponents are financially incentivized to apply the lowest possible discount factor, and there are minimal controls on strategic behavior. The evidential standard for selecting a discount factor is weak (typically subjective assessment of likely leakage location, expert opinion, and/or selective appeal to research literature), and the effectiveness of auditing is limited by a lack of external sources of information and potential conflicts of interest.[20]

Refinements to leakage accounting are unlikely to solve the problem of achieving accuracy in practice. Consider efforts to develop tractable leakage estimation formulas,[56,57,83] which aim to approximate the adjustment of an economic-ecological system toward a new equilibrium using a limited set of parameters. The formula of Murray et al.[36] (Box 1) is the best known and is widely positioned as the most rigorous option for project-level

Table 1. Market leakage in third-party forest carbon standards

Registry	Methodology	Project type[a]	Volume (Mt)[b]	Trigger	International leakage	Approach	Possible range	Median value[c]
Verra (verified carbon standard)	VM0007 v1.6 (framework) (VMD0011 v1.1)	multiple (REDD+)	145.7	reduction of wood products supply (to markets >50 km from project area)	no	discount factor (*wood products*) or VMD0037	20%–70% of foregone supply (timber) 40% of foregone supply (fuelwood/charcoal)	0% (0%–40%)
	VM0009 v3.0 (VMD0037 v1.0)	AC (forest, grassland)	102.78	reduction in commodity supply	no	discount factor (*wood products*) or VMD0037	10%–70% of foregone supply (discount factor) ≪30% of foregone supply (VMD0037 approach)	0%
	AR-ACM0003 v2.0	A/R	14.86	market leakage is not monitored				
	VM0015 v1.1	A(U)C (forest)	73.2	market leakage is not monitored				
	VM0006 v2.2 (VCS AFOLU Requirements v4.1)	A(U)C (forest), A(U)D (forest)	10.9	reduction in wood products supply	no	discount factor (*per pool*)	20%–70%	20% (0%–20%)
Gold Standard	Afforestation/ Reforestation v1	A/R	0.46	market leakage is not monitored				
American Carbon Registry	IFM, US Non-Federal v1.3	IFM	6.66	reduction in wood products supply (>5%)	no	discount factor (*total credits*)	10%–40%	40%
	A/R Degraded Land v1.2 (AR-TOOL15 v2.0)	A/R	3.69	market leakage is not monitored				
	US Forest Projects v1 (compliance protocol)	A/R, IFM, AC	121.84	reduction in wood products supply	no	discount factor (*wood products*)	20%	20%
In development	ART-TREES v2.0	REDD+	NA	subnational scale	no	discount factor (*total credits*)	0%–20%	NA
	BC Forest Carbon v2.0 (compliance)	A/R, IFM, AC	NA	reduction in wood products supply	yes	discount factor (*total credits*)	47.37%–71.89% (default)	NA

Italic text in "Approach" indicates which carbon pool is discounted to adjust crediting for leakage. Median values fall below possible ranges when projects report no market leakage. Median values are based on *ex ante* projections.
[a]A(U)C, avoided (unplanned) conversion; A/R, afforestation/reforestation; IFM, improved forest management; REDD+, multiple forest pathways.
[b]Issuances on public registries, all-time.
[c]Mean value (range), based on a random sample of five or ten registered projects. Ranges are not reported where all values were identical.

Box 1. A leakage calculation formula

Murray et al.[61] provide a widely used formula for estimating market leakage from foregone forest harvest, which approximates the adjustment of an economic-ecological system toward a new equilibrium:

$$\text{Leakage }(\%) = \frac{100 * e * \gamma * C_N}{[e - E(1+\gamma * \varphi)]C_R}.$$

The physical subsystem is represented by C_R and C_N, the carbon "footprints" of harvest in a reserved and non-reserved forest area, respectively. The size of the supply restriction is represented by $\varphi \in [0,1]$ (i.e., the fraction of total supply restricted by the offset). The adjustment of the economic subsystem is captured by the substitutability of timber from the reserved and non-reserved area $\gamma \in [0,1]$, the price elasticity of supply e (the percent change in supply caused by a percent change in price), and the price elasticity of demand E (the percent change in demand caused by a percent change in price).

This simple approach clearly demonstrates the core mechanics of market leakage for a good experiencing a supply restriction. Market leakage will be higher when production is displaced to a location with a higher carbon "footprint" ($C_N > C_R$), when suppliers are more responsive to changes in price ($|e|$ large), or when demanders are less responsive ($|E|$ small). It will be smaller when foregone output is less substitutable ($\gamma < 1$) and proportionately larger when the supply restriction φ is small, because price increases (and hence reductions in demand) will be less.

leakage accounting in both voluntary and compliance methodologies. For results from applications of this formula to be accurate, the parameter estimates used must correctly describe the measured system. This is not a trivial problem,[67] not least because key economic parameters (e.g., the price elasticities of demand and supply, which describe consumer and producer behavior) are not stable over space or time[39,84] and are difficult to estimate.

To recognize the uncertainty in this approach (and thus the need for upper-bound estimates), consider the following example. A forest conservation project (Verra Registry #607) issues carbon credits based on reducing lumber output in southern British Columbia (BC), Canada. Applying the Murray et al. formula yields a leakage estimate of about 69% (in contrast, project documents indicate a discount factor of 20% and an actual deduction of about 11% on recent issuances, with 2.9 Mt retired so far). This estimate employs default regional parameters provided by BC's draft forest carbon protocol (row 12 in Table 1). Varying the elasticity parameters (e and E in Box 1) by 25% to approximate reasonable confidence intervals yields estimates ranging from 58% to about 78%. This sensitivity is a problem: regionally specific estimates of these parameters reported in the literature span two orders of magnitude[85] and vary markedly over time.[84] In less data-rich contexts (for example, many developing countries) the market data necessary to estimate these parameters are unlikely to be available, forcing proponents to apply estimates out of context.

Given the potentially systematic underestimation of market leakage suggested by our evidence, the lack of low-cost and accurate methods for leakage estimation, and high inherent uncertainty in leakage estimates, we argue that mandating the use of upper-bound possibilities for projects including market leakage in their design is essential to build conservativeness into the accounting system. In practice, this may often mean the application of leakage rates approaching 100% for high-risk interventions. Since both theory and evidence suggest that the risk of leakage from market-exposed nature-based offsets is generally high, the burden of proof ought to be on project proponents to credibly demonstrate low rates. This requires a reasonably complete model of the economic system (including international markets, if implicated) and context-specific parameterization. In general, it will be preferable to design interventions that avoid market leakage from the start.

Principle 2: Nature-based credits which include market leakage risk in their design should not substitute for avoided emissions in compliance settings

The integrity of nature-based offset schemes as a mitigation strategy depends on the accuracy of offset accounting methods. The relationship between additionality and leakage outlined in our conceptual framework implies that some degree of market leakage is inevitable when additionality results from altering economic behavior and market linkages extend beyond project accounting boundaries. Accounting for market leakage is most risky in compliance settings (e.g., in cap-and-trade markets), where nature-based offsets substitute on a one-to-one basis for avoided emissions in meeting policy objectives. Substituting uncertain offsets for certain emissions reductions risks decoupling measured progress toward policy targets from physical changes in stocks of atmospheric greenhouse gases, but a design-based approach can circumvent the problem by avoiding additionality claims that rest on leakage-generating market interventions.

To substantiate our concerns about leakage in compliance settings—and illustrate the implicit relationship between leakage and additionality articulated in our framework—we present a global assessment of forest cover loss and protected areas in Earth's tropical forest biomes (Figure 3). Our calculations show that, over the last two decades, steady increases in protected forest areas have not been associated with falling forest cover loss (Figure 3A). This pattern of non-declining forest cover loss despite ongoing protection raises the possibility of widespread leakage—or, following the duality we highlight, the possibility of widespread non-additionality. Credits could be issued if it could be shown that forest cover loss would have been higher in the absence of protection, but doing so would require a credible counterfactual baseline (and a robust leakage estimate).

Figure 3B illustrates several challenges in teasing out market leakage from "background" economic activity. Zonal statistics

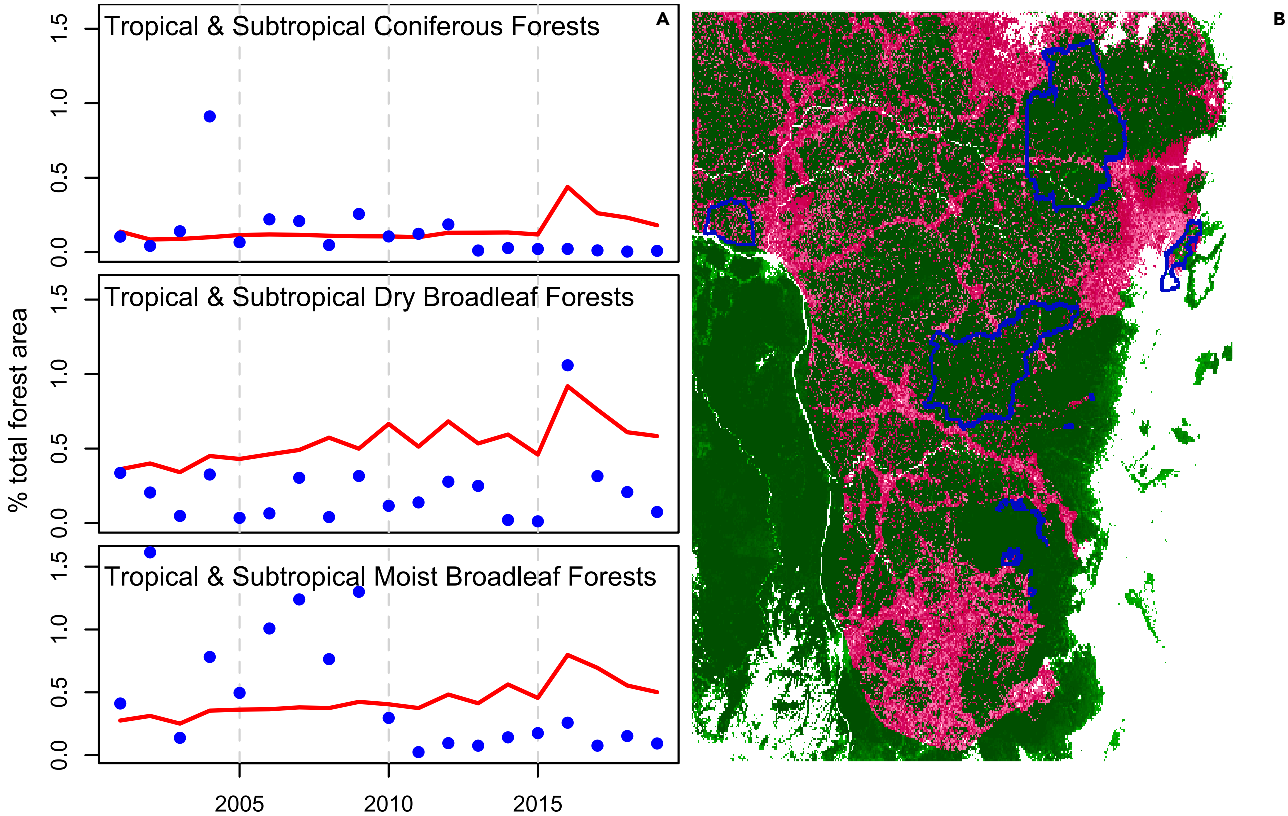

Figure 3. Forest cover loss and area protected in Earth's tropical forest biomes

(A) Summaries by biome of annual area protected (blue dots) and forest cover loss (red lines).

(B) Colorblind palette shows part of one ecoregion-level calculation (n = 279) used to generate the biome-level summaries, which illustrates challenges to leakage accounting (see main text). For each ecoregion, we tabulated annual changes in area protected as well as forest cover loss (pink shading; darker is more recent) outside protected areas (blue outlines) in forests with similar canopy closure (green shading; darker is higher closure).

Aggregating results at the biome level (A) reveals non-declining cover loss despite steady annual increases in forest protection, and a simple panel regression (not reported) of cover loss on area protected at the ecoregion level confirmed the lack of a significant relationship. Zooming in on loss in one randomly selected ecoregion (pink shading in B) shows the difficulty of teasing out leakage effects around protected areas from the economic "background" of landscape-level forest cover loss.

(e.g., using a fixed-width buffer around protected areas) require making assumptions about where leakage occurs, and leakage estimates will clearly vary with these assumptions. Quasi-experimental methods require pseudo-controls, and since all ecologically similar forests exhibit cover loss which may be due to leakage, the independence of these is doubtful. Measuring leakage by modeling the behavior of economic agents requires rich microdata, which are unlikely to be available in our example (the Northeast Congolian lowland forest ecoregion, located mostly within the Democratic Republic of the Congo). The insight provided by our framework is that because protection reduces the supply of forested land, anywhere that protection is additional is also at high leakage risk by design—thereby raising the stakes for accurate leakage estimation. Because measuring this leakage risk accurately is extremely difficult, credits from such projects are highly uncertain.

Principle 2 offers a conservative design-based solution to irreducible uncertainty about the true impact of an intervention (such as forest protection), by prohibiting high-risk carbon credits from being used as offsets in compliance settings. In effect, principle 2 can be viewed as an extension of principle 1, which requires application of a 100% leakage rate in circumstances where the costs of incorrect leakage estimates are high. Given the high rates of market leakage estimated in the literature for at-risk projects and that any attempt to justify lower leakage rates will necessarily rely on uncertain estimation practices, the cost of allowing real emissions for uncertain offsets in compliance settings is simply too great. In practice, this means prohibiting prominent nature-based interventions, likely including many current-generation REDD+ projects, from being used as offsets to meet legally required climate targets. However, our underlying conceptual framework reveals that—contrary to prior concerns[86]—avoiding high-risk projects does not cut all nature-based interventions off from compliance financing. Non-economic interventions can still qualify, as can interventions that reduce aggregate demand, and market-exposed interventions (such as REDD+) can be designed to minimize or avoid leakage risk.

Current efforts to avoid introducing uncertain credits into carbon accounting simply rule out broad project categories (both the Gold Standard and the European Emissions Trading Scheme exclude REDD+ credits, in part because of uncontrolled leakage risks[21]). In contrast, our framework implies that specific additionality claims within these project categories can be allowed when projects are designed to credibly avoid the leakage problem. REDD+ projects, for example, could be designed to maintain the supply of goods and services resulting from deforestation or degradation by improving landscape-level production efficiencies (thereby shifting the additionality claim from "reducing supply" to "increasing C efficiency" in Figure 2). However, such efforts must carefully consider the mechanics of market leakage and should be cautious about exceptions (such as relying on claims of future production increases to disregard leakage risks from current supply restrictions).

Implementing our principle 2 is likely to increase the average cost of nature-based offsets in compliance settings. Applying our framework to a well-known global estimate[10] (see https://doi.org/10.5281/zenodo.7924179) suggests that 59%–70% of low-cost mitigation potential from nature should be classified as high leakage risk because the associated additionality claims are based at least partly on reducing supply to markets. However, accurate prices are essential to enable efficient market-based mitigation solutions, maintain the integrity of these systems, and provide incentives for low-carbon innovation. The importance of these outcomes argues strongly for avoiding uncertain offsets. If allowed to substitute for avoided emissions in compliance settings, highly risky offsets reduce the cost of compliance, thereby substituting for more reliable (but potentially more costly) offsets and other emissions reduction solutions, while also reducing incentives to invest in R&D to drive innovation in new low-carbon solutions.

Principle 3: In non-compliance settings, the level of uncertainty that is acceptable in a (nature-based) offset should be set by the action for which it substitutes

When used as offsets, carbon credits substitute for alternative mitigation actions by definition. This substitution is premised on fungibility: in a carbon accounting system, a credit used as an offset is deemed equivalent to a unit of foregone emissions. We have argued that uncertainty about market leakage breaks this equivalence for specific categories of nature-based additionality claims, and on this basis have proposed prohibiting the substitution of highly uncertain offsets for relatively certain regulated emissions (principle 2). Our final principle focuses on the underlying substitution dynamic to guide market design in non-compliance settings. Where credits are used for a variety of purposes with uncertain mitigation effects, accounting integrity can be preserved by matching credits to actions on the basis of comparable certainty. Put simply, an uncertain credit should not substitute for a certain emission—but it can substitute for an uncertain one (for example, as part of corporate branding initiatives in voluntary markets or standard systems).

Operationalizing matching on uncertainty requires understanding why firms purchase non-compliance credits, as well as significant advances in how purchases are claimed and monitored—issues which are currently the focus of multiple governance initiatives in voluntary carbon markets. We suggest two possible approaches. First, if different categories of substitution can be identified, markets can be stratified such that carbon credits substitute only for comparably uncertain mitigation actions. A simple version of this approach is already in use by The Science-Based Targets initiative, which allows highly uncertain "avoidance" credits to be applied only to offset beyond-value-chain emissions. Further stratification could potentially unlock other sources of finance for uncertain nature-based interventions, for example by allowing their use in sustainability claims that demonstrate commitment but do not assert progress toward net-zero targets. Growing interest in designing biodiversity offset markets argues strongly for exploring the possibilities of market stratification now, since the true fungibility of such non-carbon interventions is also likely to be very uncertain.

One important potential application of stratification is de-risking investments in innovation. Firms or governments already invest in portfolios of low-carbon innovations, the ultimate impact of which is uncertain. Matching these investments with purchases of uncertain nature-based offsets provides a hedge against failure, increasing the chances of achieving mitigation goals. Following our principle, such purchases would substitute for the uncertainty in innovation outcomes, with market stratification providing for a pool of lower-cost, but less certain, emission offsets. Where a low-carbon transition strategy involves some probability of failure, access to such a lower-cost pool of uncertain offsets could be beneficial.

A second approach is possible when uncertainty can be quantified (as risk) or resolved over time. Risky offsets can be combined into portfolios, reducing volatility[87] and creating mitigation assets whose expected value is more certain. If the true effect of interventions can be tracked over time (and carbon accounting updated accordingly[88]), a portfolio approach could unlock significant financing for nature-based interventions without jeopardizing mitigation incentives. Making portfolios work for leaky offsets requires pinning leakage down to known ranges, which would require a considerable amount of further research into approaches to estimate the potential leakage associated with novel nature-based interventions and geographic settings. We therefore suggest our third principle as a general guide to future market development, and emphasize the urgency of implementing our first and second principles immediately to control leakage in rapidly growing offset markets.

CONCLUSION AND OUTLOOK

Nature-based offsets can play a vital role in enabling deeper and cheaper net emissions reductions, but only if credited offsets are real. Scaling up nature-based solutions is challenged by the continued lack of an accurate and cost-effective method for measuring market leakage. Current approaches appear to significantly underestimate the likely magnitude of market leakage effects, introducing a risk of silent failure into nature-based offset regimes. To correct this course, we present a conceptual framework for avoiding market leakage by design and identify three principles that can be put into practice now. Our first principle can be implemented by project developers alone, while our second and third principles depend on the use to which offsets are put and should be applied by the buyers of nature-based offsets and the designers of offset schemes.

Prior work[15,19,30,55,89,90] has suggested similar "design-based" options to reduce or mitigate leakage, for example by avoiding leaky interventions, reducing demand, substituting foregone livelihoods or output, or constraining leakage agents. These suggestions have been inconsistently applied and lack an underlying conceptual framework, significantly reducing their potential for broader implementation to control market leakage from nature-based offsets. In this article, we have aimed to establish a more consistent and robust basis for understanding market leakage that helps to resolve the problem. As we have shown, decades of economic research have not produced a reliable and low-cost approach to estimating the leakage associated with a particular offsetting intervention, leading most third-party standards to instead apply discount factors to account for potential market leakage by rule of thumb. Table 1 provides evidence suggesting that this system is not working, as actual leakage estimates applied in practice appear to diverge sharply from peer-reviewed estimates of market leakage in nature-based offsets.

Early proponents of nature-based offsets have tended to see inaccuracy as acceptable given the need to pioneer new financing models or achieve urgent conservation objectives (e.g., reduced tropical deforestation[21]). Our criticisms rest on the observation that more than 30 years after the first nature-based offset projects[23] (and 28 years since the concept of leakage from them was introduced[24]), a robust and low-cost method for market leakage accounting has not yet been found. As nature-based offsets take an increasingly central role in critical near-term mitigation efforts, it is time for a new approach.

We acknowledge that our proposals would prohibit important categories of (uncertain, highly leaky) nature-based offsets from substituting for reduced emissions. Some may see this as throwing the nature-based offsets "baby" out with the bathwater, but this need not be the case. High uncertainty[91] and a lack of credible leakage accounting[18,20] are major barriers to scaling up nature-based mitigation. In the words of the CEO of the International Emissions Trading Association,[92] "a market without trust will never be successful." We have argued that controlling market leakage via carbon accounting cannot deliver credible leakage estimates, primarily because of the difficulty of obtaining accuracy in practice. Abandoning inaccurate accounting in favor of a conservative design-based approach is a necessary step to building trust and, therefore, to boosting demand for credible nature-based offsets. We are trying to help the "baby" grow.

One objection to our proposals is that (correctly) applying high discount rates may make projects uneconomic. This misunderstands the premise of market-based mitigation schemes, which require accurate information to deliver economically efficient outcomes. Allowing bad offsets depresses prices and crowds out good projects. Such price dilution appears to be widespread today (in the past, fears of it have cut off nature-based solutions from offset-based finance[21,93]). Prices for forestry and land-use offsets in voluntary markets continue to hover around US$5 per ton[5] and roughly scale[4] inversely with leakage risk. True carbon prices are much higher: Paris-consistent prices were estimated at US$40–80 per ton in 2020,[94] and the median internal carbon price employed by corporations was US$25.[95] Estimates of the social cost of carbon (used in national policy-making) range higher still.[96] Building trust in the credibility of nature-based offsets can unlock these higher prices, potentially making more nature-based mitigation available and unleashing innovation to identify lower-cost mitigation solutions.

A second objection is a lack of alternatives. For example, Streck[21, p.849] argues that "concerns about leakage cannot be an excuse for inaction [on tropical forest loss]," and nature-based offsets are often presented as most suitable for difficult-to-abate industrial emissions. We agree with these views but contend that bad accounting is not the solution. The choice is not between current practice and nothing; it is between credible and non-credible interventions. Taking a conservative approach to avoiding market leakage will direct finance toward projects that actually deliver claimed mitigation while appropriately pricing offsets, which in turn can help to drive innovation in emissions-intensive sectors and leaky project categories. Conservativeness is particularly urgent because problems stack: the additionality of offsets is extremely difficult to demonstrate,[97] and recent work has highlighted high-profile cases of non-additional issuances.[12,13,98,99] By contrast, a design-based approach can credibly avoid the market leakage problem.

Finally, we stress that our concern with market leakage is most acute in the current context of decentralized implementation of many (relatively) small interventions. Coordinated actions and large-scale implementation can provide market substitutes or mobilize the resources necessary for accurate accounting. However, timing matters: believing that complementary actions will occur in the future is not sufficient for ignoring market leakage now (nor can a national program ignore international effects if consistent accounting approaches do not yet exist). We hope that our conceptual framework helps resolve such misunderstandings about how and where market leakage matters, but the outline we have provided is necessarily incomplete. Wealth effects, the rebound effects of intensification, and long- vs. short-run equilibrium dynamics deserve more consideration within our framework. A deeper exploration of the problems we note with quasi-experimental statistical methods is also warranted, given rapidly growing applications in offset monitoring and verification. Nevertheless, our framework and principles for a design-based approach would contribute to improving the credibility of nature-based offset markets, helping this important set of mitigation strategies to realize their potential.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Inquiries should be directed to the lead contact, Ben Filewod (b.filewod@lse.ac.uk).

Materials availability

This study did not generate new unique materials.

Data and code availability

Figure 3 was generated using publicly available datasets pre-loaded on the freely available Google Earth Engine GIS. The Earth Engine script used to process these datasets is available at https://doi.org/10.5281/zenodo.7924179. Data on leakage rates presented in column 9 of Table 1 are drawn from publicly available offset registries as explained below. The random sample we report is available from the lead contact upon request.

Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

Global assessment of tropical forest cover loss

We used high-resolution data on global forest cover (Global Forest Change[100]) and a database of protected area boundaries (World Database on Protected Areas[101]; polygons only) to analyze forest cover loss in protected forests and ecologically similar areas, as illustrated in Figure 3. We used the Google Earth Engine GIS for analysis, structuring processing by ecoregion (RESOLVE Ecoregions[102]) to facilitate parallelization. We preserved original data resolutions (raster data) and did not allow error margins in vector analysis; for one raster operation (percentile calculations) we allowed Earth Engine to rescale resolution on-the-fly to avoid resource limits.

We report aggregate results for n = 279 tropical forest ecoregions (i.e., those located within tropical and subtropical forest biomes in the RESOLVE database). For each ecoregion, we obtained and merged the spatial boundaries of "Designated," "Established," and "Inscribed" protected areas in management categories prohibiting resource extraction ("Ia," "Ib," "II," "III," "IV," and "Not Reported"), and calculated the 10th and 90th percentiles of the pixel-level distribution of (year 2000) forest canopy closure for the resulting area. We applied these percentiles to all forest cover calculations to increase comparability between protected and non-protected forest. We then calculated start-of-period (year 2000) forest area and protected area per ecoregion, and forest cover loss and total area protected for each year from 2001 to 2019 (inclusive). We applied a medium-resolution fire mask (MODIS CCI Burned Area, v5.1[103]) within each annual calculation to reduce the inclusion of non-anthropogenic forest cover loss in our analysis. We differenced annual totals to obtain year-by-year changes and generated Figure 3 using R.

The resulting data provide an approximate view of forest area protected and forest cover loss in ecologically similar forests for Earth's tropical forest biomes. This is a demonstrative analysis, with important limitations affecting accuracy: Global Forest Change data do not detect small-scale disturbances (e.g., selective logging), comparison of changes over time is complicated by differences in Landsat sensor technology and data processing, not all non-anthropogenic disturbance is due to fires (and pixel size artifacts prevent full fire masking in our approach), the choice of a 10th–90th percentile constraint is arbitrary, and incomplete fields in the World Database on Protected Areas may cause true area protected to be overstated due to filtering (conversely, unknown management effectiveness implies that effective protected area may be overstated).

Analysis of leakage in issued nature-based carbon offsets

We downloaded public registry data on credit issuances from Verra (https://registry.verra.org/) Gold Standard (https://registry.goldstandard.org/), and the American Carbon Reserve (https://americancarbonregistry.org) in April/May 2022, and selected the nature-based offset methodologies with the most issuances (per registry) for analysis, as reported in Table 1. We include two methodologies currently in development (no issuances) for comparison. We used the most up-to-date version of each methodology, noting that the issued volumes we report include credits issued according to earlier versions. We analyzed methodologies and reported the conditions under which market leakage must be assessed (Table 1, column "Trigger"), whether international leakage is considered (column "International leakage"), the approach used to account for leakage (column "Approach"), and the range of market leakage values possible under the methodology (column "Possible range").

To assess average market leakage values in practice (column "Median value"), we took a pseudorandom sample of five unique project identifiers for each methodology in R using sample_n {dplyr}. We took ten samples for VM0007. For each project, we obtained or calculated market leakage values using best available information from public documents linked on the relevant registry. We used *ex ante* data (i.e., projected mitigation and leakage from project design documents). For total leakage from VCS (main text), we report *ex ante* estimates of cumulative total leakage (typically given over a 30-year horizon) divided by the claimed emission reductions (baseline emissions minus project emissions). We note that issued credits are based on *ex poste* values, which may differ from the *ex ante* data we report if methodologies require ongoing monitoring (e.g., of a designated leakage zone) to calculate discount factors. However, *ex ante* estimates are typically conservative (in the sense of reflecting the upper bound of project proponent's views on the market leakage deductions they may incur); in several cases, project documents asserted proponents' views that *ex poste* leakage values would be lower.

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AUTHOR CONTRIBUTIONS

Conceptualization, B.F. and G.M.; investigation and methodology, B.F.; writing – original draft and writing – review & editing, B.F. and G.M.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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