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Avoiding leakage from nature-based offsets by design

Ben Filewod[1*] and Geoff McCarney[2]

Abstract

Leaky offsets are old news. As the world embraces nature-based solutions as a core strategy for critical near-term climate change mitigation, transactions of nature-based offsets in both compliance and voluntary markets reflect an underlying assumption that current approaches to managing leakage at the project level are working. We argue that this is not the case: leading third-party certification standards appear to vastly understate leakage compared to the research literature, and the tools available for project-level crediting cannot deliver the accuracy needed in practice. We propose an alternative, conservative, approach for avoiding leakage by design, based on understanding the 'duality' between additionality and leakage in a system at equilibrium. We then identify three principles that offset developers, certifiers, and consumers should implement at the project level now to improve the credibility of nature-based offset markets, while also allowing for increasing ambition and investment in nature-based solutions.

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1. Introduction

Amidst 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 offsets are central to corporate net-zero pledges[3]. Driven by corporate commitments[4], voluntary offset markets neared USD$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.

If nature-based offsets are to play a role in critical near-term mitigation efforts, they must provide a credible alternative to emissions reductions. In this paper we argue that one well-known threat to credibility, market leakage, remains uncontrolled – and that ongoing refinements to project-level leakage accounting methods will not solve the problem. Our proposed solution is novel, but awareness of market leakage is longstanding. Concern rapidly followed the first forestry offset projects in the early 1990s[9–11], and three decades of work have thoroughly explored the problem (several reviews exist[12–14], with research interest remaining high[15–17]). Scaling-up accounting systems is a frequently suggested fix[18–23], and a number of 'leakage mitigation' strategies have been identified[19,24], but how to deal with leakage remains a controversial issue[21,25]. Nevertheless, many view leakage as a tractable problem for which "sophisticated and robust tools"[2 (p.17)] and "policy levers to manage risks" [7 (p.934)] are available, and nature-based offsets continue to be transacted on the premise that project-level leakage accounting is sufficiently accurate[26–28].

In what follows, we review the theoretical and empirical literature on market leakage to argue that project-level accounting is not sufficiently accurate, and present evidence that suggests market leakage is widely underestimated in current offset issuances. Incomplete accounting decouples measured progress from actual emissions, introducing the risk of silent failure into mitigation efforts. If market leakage cannot be accounted for in today's decentralized (i.e., project-by-project) offset schemes, alternate approaches must be found. We propose a design-based solution, based on a simple conceptual framework for understanding and identifying market leakage from nature-based offsets. Drawing on this framework, we identify three actionable principles for controlling leakage now, which provide a robust basis for avoiding leakage by design at the project level. Critically, our contribution helps clarify ongoing misunderstandings about when and how market leakage matters in a nature-based context.

2. The problem with market leakage

A nature-based offset is an intervention that alters the state of a coupled economic-ecological system. Leakage occurs when some effects of the intervention fall outside the offset developer's accounting boundary (e.g., an action causing emissions reductions in one place may also cause increases elsewhere). Classifications[10,14,15,24,29] of this phenomenon now include leakage via connected ecological systems[24], information, motivation, and institutions[10], or spatial interactions[30]. Here, we refer to two canonical types involving economic agents: 'Direct' or ‘activity’ leakage arises when economic agents targeted by an offset shift activities outside of the accounting boundary, whereas ‘market’ leakage arises when non-targeted agents adjust their behaviour 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 behaviour is due to this response depends on unobservable motivations.

Scaling up the accounting boundary to include all relevant economic agents partly solves the problem, but nature-based offsets commonly impact globalized markets – and internationally consistent carbon accounting remains elusive. Nature-based offset programs therefore adjust credits using an estimate of market leakage effects. This is a challenging but critical task. We illustrate the issues in Figure 1, which summarizes annual forest area protected and forest cover loss in ecologically similar forests across Earth’s tropical biomes. Increased protection has not led to falling forest cover loss, suggesting that forest cover loss in non-protected areas may have changed as a result of protection (or that protection is not ‘additional’[31], in the sense that it does not affect the causes of forest cover loss). Cover loss could have been even higher if no forest had been protected, and this ‘baseline’ must be modelled to identify gains. Critically, cover loss outside of protected areas has multiple causes. Treating observed cover loss as leakage requires assuming that other causes of cover loss in monitored forests were insignificant, and no loss was displaced beyond the monitored area.

While there are several approaches to estimating market leakage, each have their limitations. Accounting-based approaches (e.g. input-output analysis or material flow analysis) can provide compelling circumstantial evidence of leakage effects[32,33] but cannot separate out the causal impact of a specific intervention. Partial- or general-equilibrium models (which simulate the actions of a large set of economic agents) are arguably a more appropriate approach because they are developed specifically to capture market interdependencies (i.e., equilibrium effects). However, the underlying parameters that guide agent behaviour in these models must also be estimated, and subtle changes in parameter assumptions can substantially alter results[34]. Simple zone-based methods (e.g., Figure 1, which can also be viewed as a form of accounting), are widely used to quantify activity-shifting leakage from protected areas[35,36] but require assuming that leakage occurs within known areas which are unaffected by ‘background’ economic incentives – an untenable premise in the well-functioning and large-scale markets where indirect effects are of most concern. Quasi-experimental econometric techniques, the current standard for policy impact evaluation, are limited by underlying assumptions about the independence of pseudo-controls that are violated by the presence of leakage effects (and leakage estimates from such studies tend to be zone-based[37,38], although recent work[39] is beginning to explore alternatives). There is, in short, no perfect ruler.

The evidence on leakage in nature-based offset projects from these lines of inquiry is mixed, and methodological choices must be carefully scrutinized. Thus far, model-based assessments of market leakage from nature-based interventions have focused on “stop-harvest” forest mitigation projects, frequently leveraging established partial equilibrium models. Leakage estimates for developed countries from these models are typically *at least* 70-80% of reduced output, measured either as forestry production[40–44] or carbon stocks[45]. Lower estimates (50% or less) have been found for the specific case of a global carbon price[46], or in a developing country context when international leakage is deemed negligible[47] (Kuik[48] estimates 0.5%-11.3% market leakage from large national supply restrictions in developing countries, but this result depends on methodological choices and is contracted by other evidence[39]). Afforestation scenarios may produce lower leakage than avoided conversion (e.g. ≤43% vs ≤92% in one estimate[49]) because of productivity differences or the availability of under-utilized land.

Carbon leakage from non-forest interventions is less well studied. Kim et al[50] find about 15% leakage from crop conversion, while econometric studies of leakage from conservation reserves (also known as 'slippage') suggest that leakage occurs but is typically low[51]: estimates include 4% activity leakage (measured as forest cover loss)[37] and 20% market leakage (measured as farm area[52]; although criticisms of this estimate[53–55] highlight measurement challenges). Further econometric evidence is available for forest to agriculture conversion in Brazil[39,56,57], with leakage estimates ranging from insignificant to essentially all program gains. It has been noted, however, that the lower estimates for some non-forest interventions should be weighed against the potential for 'weak additionality' of the associated interventions[58], which typically occur on under-utilized farmland. A growing literature also considers carbon leakage associated with unilateral adoption of various climate policies, 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, market leakage from nature-based solutions can be very high, potentially up to 100% of claimed mitigation (e.g., as in [40]). We return to this point in Section 4, where we summarize the theoretical conditions for high and low leakage rates. Second, leakage estimates are context-specific, and not easily transferable between projects. Results from a particular offset project (or averages of prior estimates[60]) are not a good measure of market leakage from another intervention[61], which suggests project-level leakage estimation will remain difficult and costly (as discussed in Section 3). The problem with market leakage is thus a problem of measurement: achieving a defensible estimate of low leakage (and hence net mitigation) from a market-exposed offset project is not a simple task.

3. Project-level measurement

The technical complexity of market leakage accounting introduces challenges to the integrity of nature based offset systems. Among specialists, these problems are well known and long established. For example, Richards and Andersson[62:53] argued that both theoretical and practical challenges prevent the accurate measurement of leakage at the project level, concluding that "either the reliability of project analysis will be low or the costs of analysis will be high, and quite possibly both". Research has repeatedly highlighted the extreme difficulty of measuring leakage[15,24], and current accounting methods (i.e., adjusting credited mitigation using a leakage discount factor) have been acknowledged to be insufficiently rigorous "in the long run"[14:329]. Nevertheless, today's voluntary and compliance offset markets routinely transact nature-based issuances that claim to have accounted for leakage at the project level.

In practice, project-level accounting and certification by a third-party standard is the primary tool used to manage market leakage. Table 1 summarizes accounting approaches by leading third party forest carbon standards, using the most important nature-based offset methodologies (by issued credit volumes) and a small random sample of credited projects. The combined issuances of these methodologies (all time) are about 480 Mt (for context, this is roughly double 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. In stark contrast to the research results reviewed above, we found the possible ranges of market leakage discount factors (column 8) tends to range from 10% or 20% to 70% while, in our randomly selected sample, the discount factors actually selected (column 9) usually fall at the bottom of the identified range. For Verra-registered projects, additional data (not reported in Table 1) show a similar phenomenon in projections of total (market + activity) leakage in sampled projects (median values: VM0007 - 11%, VM0009 – 10%, AR-ACM0003 – 0%, VM0015 - 6%, VM0006 - 4%). A recent study[16] of avoided forest conversion/degradation projects corroborates these results (26/68 projects claim no leakage, and 28/68 subtract leakage emissions from expected mitigation at a median rate of 6%).

The standards in Table 1 include a range of interventions and market contexts. So why are the values in Table 1 so low? One explanation relates to technical complexity in market leakage accounting: since accuracy is difficult and therefore costly, standards must negotiate a compromise between scientific rigour and financial viability (see work by Cashore and others[63,64] for related political economy concerns). However, the compromises made may distort project-level accounting outcomes. Consider the general exclusion of difficult-to-measure leakage beyond country borders (unwarranted in light of research results[33,40,41], but in alignment with international norms in climate policy): in one randomly sampled project, #1175 on the Verra Registry, the calculation for market leakage begins by excluding possible effects from the 87% of foregone output expected to be exported. Another explanation is expediency: leakage deductions can make or break the financial case for an offset project, and are a key concern for project developers[65]. Once rules are in place, project proponents are financially incentivized to apply the lowest possible discount. There are minimal controls on strategic behaviour, as the evidential standard for selecting a discount factor is weak (these include: subjective assessment of likely leakage location, expert opinion, 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[25].

From the perspective of methodology developers, part of the problem is surely a lack of options. Decades of economic research have not produced a reliable, low-cost approach to leakage assessment. Accurate measurements require a rich data environment and highly skilled personnel. Standards therefore tend to apply discount factors by rule-of-thumb because more accurate estimates are out of reach. One response by researchers has been to derive tractable formulas for applied use[48,50,66], of which Murray et al[49] is the best known (Box 1). The aim of these formulas is to approximate the adjustment of an economic-ecological system towards a new equilibrium, using a limited set of parameters. Nevertheless, for the result to be accurate, the parameter estimates used to apply these formulas 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 behaviour) are not stable over space or time[34,68] and are non-trivial to estimate.

To see the resulting uncertainty for project-level measurement, consider the following example. A forest conservation project (Verra Registry ID#607) issues carbon credits based on reducing lumber output in southern British Columbia (B.C.), 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 is obtained using default regional parameters provided by British Columbia'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*[69] and vary markedly over time[68]. 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.

Early proponents of nature-based offsets have tended to see this potential 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 29 years after the first nature-based solutions offset projects[9] (and 27 since the concept of leakage from them was introduced[10]) a robust and low-cost method for project-level leakage accounting has not yet been found. In the absence of alternatives, current initiatives to improve offset quality (e.g. the Integrity Council for the Voluntary Carbon Market, or the Voluntary Carbon Markets Integrity Initiative) are now faced with the challenge of endorsing project-level accounting methods without clear options to address these concerns. As nature-based offsets take an increasingly central role in critical near-term mitigation efforts, it is time for a new approach.

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 towards a new equilibrium:

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

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 $\phi \in [0,1]$ (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, since price increases (and hence reductions in demand) will be less.

4. Designing out project-level market leakage

Prior work[14,19,24,47,70,71] has suggested '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. However, these suggestions have been inconsistently applied and lack a conceptual framework, significantly reducing their potential to control market leakage from nature-based offsets. In the remainder of this article we aim to outline a viable conceptual framework, and thereby establish a more consistent and robust basis for project-level accounting that helps to resolve the market leakage problem. In this section we elaborate our framework for designing out project-level market leakage, while in the following section we present three principles to operationalize our approach.

The defining feature of market leakage is information transmission through price. In an economic model of a single market equilibrium, reducing output from one producer causes prices to rise, incentivizing other producers to increase output but causing consumers to demand less (see Figure 2). The net result of such equilibrium adjustments in interconnected markets is complex, but some general statements are possible[43,61]. All else equal, 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 (see Box 1). These conditions explain why estimates of market leakage are often high: nature-based offsets typically operate within globalized 'food, fuel, and fiber' commodity markets in which products are highly substitutable, demand is relatively inelastic with respect to price[34,72,73], and markets are very large relative to the size of the intervention.

Our conceptual framework is based on the insight that, when nature-based solutions are used as offsets, the solution space is bounded by the need to *simultaneously* satisfy the three well-known criteria for real offsets of permanence, additionality, and (no) leakage. In contrast, recent debate[74–80] around the biophysical potential of nature-based mitigation has tended to consider these issues separately. Within this solution space, designing out market leakage depends on recognizing the potential for 'duality' between leakage and additionality. When leakage occurs, this by definition reduces the additionality of a project (potentially up to 100%, as demonstrated in the review above). Yet, at the same time, when a nature-based offset claims additionality based on interventions that affect markets, some leakage is likely inevitable (unless market effects are fully contained within the project boundary). The strength of this potential additionality-leakage 'duality' depends on the extent to which the offset's claim to mitigation depends on altering market equilibria.

Recognizing these criteria as simultaneous and inter-dependent (as opposed to independent) constraints can therefore help to clarify the overall potential of nature-based offsets while avoiding market leakage. We begin by considering offsetting interventions in ecosystems alone (i.e., no economic implications; dashed box in Figure 3). The primary way such interventions deliver mitigation is by increasing sequestration, which requires transitioning ecosystems to higher carbon states. If the new higher carbon state is naturally occurring, it may be a later successional stage (e.g. shrubland to forest). Since succession would have occurred anyway, the offset is additional in time and baseline dynamics must be netted out in crediting (if baseline succession is slow, accelerating succession can still deliver useful mitigation). If the new state is not naturally occurring (e.g. shrubland to non-native plantation), non-carbon values (e.g., biodiversity) restrict large-scale deployment.

However, ecosystems can exist in multiple naturally occurring stable states[81] (e.g. savannah/closed forest, rock/kelp). Both active processes (i.e. abiotic or biotic disturbance agents, such as fire or grazing megafauna[82]) and the effects of past actions (path dependency) can cause ecosystems to exist in stable low-carbon states. Additionality from removing the most important active processes (fire, pests, pathogens) is unlikely to be permanent (and accurately modelling baselines is extremely challenging). Removing 'ecosystem engineers' such as large grazers is constrained by ecological leakage if relocated or non-carbon values if eliminated. Conversely, if low carbon stable states exist due to 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 risk of leakage. Restoring degraded but abandoned land is the most prominent example.

Re-introducing economic effects of offsets (and the potential for market leakage) complicates this set-up. Where economic activity is either a source of ecosystem emissions or a cause for maintaining ecosystems in low-carbon states (i.e., preventing sequestration), an additional offset necessarily disturbs the existing market equilibrium, producing price changes that transmit information throughout the connected economic system – unless very specific conditions are met. A standard economic model of supply and demand (e.g. Figure 2) illustrates that the simultaneous constraints of (supply-side) additionality and (no) market leakage can only be satisfied when flows of ecologically-derived goods into economies remain unchanged or no substitutes exist (in the former case, price changes do not occur; in the latter, they are irrelevant). When neither condition is met, reducing market leakage below 100% requires that alternative output is only available at higher prices, causing quantities demanded to fall. This assumption is a problem for (relatively) small projects without market power, a category which arguably encompasses most nature-based offsets issued to date.

However, 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 efficiency) can deliver economic additionality without leakage (since market equilibriums can remain unchanged), and remains an important mitigation strategy[83] . 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). Note that to avoid the leakage measurement problem, these efficiency gains must be demonstrated *within* the credited project (in contrast to some recent studies[84–86] which assume strong spatial and temporal coordination *between* project classes to model mitigation potential).

The final option is to reduce demand, which can avoid emissions or reduce sequestration without causing negative effects outside the accounting boundary. General equilibrium effects must still be considered whenever markets beyond the accounting boundary are implicated: reduced demand can suppress prices and incentivize increased consumption elsewhere, and increases in efficiency can lead to increased production via price reductions or firm entry (i.e., rebound effects[12]). What matters for leakage is the connection between interventions and markets beyond the accounting boundary. For example, rebound effects from culturally specific changes in resource management are less likely, while rebound effects from transferable technological innovation are more likely.

We have argued that both theoretical and empirical expectations of market leakage from market-exposed nature-based offsets are high, and that accurate project-level measurement faces serious practical barriers. Nature-based interventions and offsets schemes should therefore be designed to minimize or avoid the conditions under which market leakage arises. In this section we have summarized those conditions and sketched a conceptual 'simultaneous constraints' framework for understanding how leakage arises within the set of possible nature-based additionality claims. Figure 3 provides a visual summary. For 'ecosystem only' projects, which do not generate market leakage by definition, our framework highlights the importance of interventions that transition ecosystems between path-dependent stable states. Where intervening in economies is part of a project-level additionality claim, avoiding market leakage means focusing on interventions that decarbonize production (but are not transferable) or reduce demand (within local markets). If interventions in economies reduce the supply of goods to formal or informal markets, project proponents must find sufficient resources to obtain credible leakage estimates or exclude the associated mitigation.

5. Three principles to avoid leakage by design

The simultaneous constraints framework we sketch in the prior section aims to clarify how and why market leakage arises from a given nature-based additionality claim. Applying this framework at the project level can allow project proponents to zero in on problematic additionality claims and avoid market leakage by design, but this requires understanding the related theory. To simplify application, we now synthesize the insights of this framework with the preceding review to identify three core principles for avoiding market leakage by design.

Principle 1. Nature-based offsets which reduce supply to markets should not substitute for avoided emissions

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

We demonstrate in Figure 3 that, contrary to prior concerns[87], avoiding additionality claims based on market interventions does not preclude all categories of nature-based offset projects. Focusing on the source of additionality provides a fine-filter alternative, but a sound understanding of leakage mechanics is essential. For example, forest management projects that reduce or defer harvest (as implemented in California's cap and trade scheme; see row 10 in Table 1) derive additionality from reducing market supply. If projects are (relatively) small and products substitutable, the associated mitigation is probably spurious. However, projects that maintain output while reducing emissions or increasing sequestration are at low leakage risk. This suggests the possibility of 'internalizing' market leakage effects, either by scaling up the accounting boundary or by identifying opportunities to increase or maintain outputs while reducing the emissions 'input'. Such strategies may be best suited to large-scale interventions, such jurisdictional approaches to Reducing Emissions from Deforestation and forest Degradation (REDD+).

Our focus on additionality claims supports wider deployment of nature-based solutions than prior efforts to avoid leakage by prohibiting offsets from broad classes of interventions (e.g., both the Gold Standard and the European Scheme Emissions Trading Scheme exclude REDD+ credits due to uncontrolled leakage risks). Yet some may see this principle as too strong, and it is therefore important to anticipate arguments for ignoring market leakage risks in certain project categories. In particular, evidence from non-forest interventions is very scarce and low estimates of market leakage have sometimes been found. Revisiting the 'duality' between leakage and additionality helps show why such estimates should be approached with caution: if the theoretical conditions for market leakage are met but leakage measurements are low, additionality is suspect. This is the case for the very low estimates from conservation reserve programs[37,52] noted in Section 3. Such programs incentivize the enrollment of economically marginal land (selection bias), implying that some claimed gains would have happened anyway.

Principle 2. The standard of certainty for avoiding market leakage risk should be set by the nature of the substituted action

When nature-based offsets rely on additionality in markets, our review (sections 2 and 3) demonstrates fundamental uncertainty in estimating the potential for market leakage risk – but that it is likely high. It is on this basis that Principle 1 advocates for avoiding the use of high-risk offsets as substitutes for emissions reductions in compliance settings.

Distinguishing nature-based offsets by market leakage risk could led to stratification in offset markets by allowing higher-risk offsets (or those subject to greater uncertainty of leakage risk) to only be applied in restricted circumstances. In a stratified market, nature-based offsets at higher leakage risk can retain a role in reducing risks in transition plans and in a portfolio approach to corporate ESR branding, provided the high-risk nature of offsets is fully acknowledged and transparently reported. We note that such careful attention to labelling is a strength of third-party certification schemes, and that current governance initiatives are trending towards differentiation.

Such stratification would have several important implications. First, in compliance settings, agents would have access to a more restricted pool of higher quality (low leakage risk) offsets – likely driving up the price of emissions substitution and providing stronger incentives to invest in clean innovation and other forms of direct emissions reductions. Access to such pools of higher quality offsets is essential to meet emissions reductions goals for hard-to-abate sectors, but integrity must be assured. Since the emissions resulting in these sectors are physical phenomena that can be measured with precision (e.g., industrial fuel consumption), only offsets without market leakage risk should be allowed.

The situation is more nuanced in a voluntary setting, where nature-based offsets are used to make sustainability claims primarily to reduce transition risks or as part of corporate environmental and social responsibility (ESR) claims. Access to a lower cost pool of risker offsets could be beneficial in specific circumstances: for example, in cases where a low carbon transition strategy involves some probability of failure (provided that risk is proportional to the leakage risk in the offset), or as part of a portfolio of measures that provide other sustainability co-benefits (provided the leakage risk is properly and transparently reported). In such cases, we propose that the nature of the associated claim must be carefully scrutinized. In the case of a 'net zero' claim, for example, the offset is presented as a substitute for reduced emissions and should be held to a correspondingly high standard of certainty.

Principle 3. When risk of market leakage is present in nature-based offset projects, upper-bound estimates should be used.
There is widespread agreement that accounting methods for market leakage should be 'conservative' (i.e., biased towards over-estimating leakage effects)[24], but our analysis in Section 3 suggests that in practice the opposite is true. 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 estimates vary and are highly context-specific, ensuring the use of upper-bound possibilities is a conservative design-based alternative. Some steps have been taken in this direction (e.g., the current 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 upper bounds on possible leakage appears widespread (Table 1).

The theoretical and empirical evidence reviewed above suggests that upper-bound possibilities for market leakage are generally high, putting the burden of proof on the project proponent to credibly demonstrate low market leakage rates. Projects which cause a small reduction in supply of an undifferentiated product are of particular concern, as leakage rates may reach 100%. This is true even when many such small projects are anticipated to occur, both because many small projects may still be a negligible fraction of a globalized market and because projects must occur proximately in time to act as a single (larger) market shock. To arrive at a credible alternate estimate requires a reasonably complete model of the economic system (including international markets, if implicated) and context-specific parameterization. In our view, these conditions exceed resource availability for most nature-based offset projects (and particularly small ones), favoring application of a design-based approach via our first principle. If interventions in markets are unavoidable, the specific portion of mitigation relying on a market additionality claim should generally be tried according to our second principle, with upper-bound leakage adjustments applied to maintain accounting integrity.

6. Conclusion

Nature-based offsets can play a vital role in enabling deeper and cheaper net emissions reductions – but only if credited offsets are real. We argue that scaling up nature-based solutions is challenged by the continued lack of an accurate and cost-effective method for measuring market leakage at the project level. 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 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 and second 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. Our third principle can be implemented by project proponents alone.

Our proposals would prohibit important categories of (uncertain, highly leaky) nature-based offsets from substituting for reduced emissions (following the logic in Figure 3, we would classify 59-70% of estimated global low-cost mitigation potential from nature[85] as high leakage risk; see Supplemental Information). Some may see this as throwing the nature-based offsets 'baby' out with the bathwater, but this need not be the case. High uncertainty[88] and a lack of credible leakage accounting[25,28] are major barriers to scaling up nature-based mitigation. In the words of the CEO of the International Emissions Trading Association[89:5], "a market without trust will never be successful". We have argued (Section 3) that controlling market leakage via project-level accounting cannot deliver credible leakage estimates, primarily because of the difficulty of obtaining accuracy in practice. Abandoning inaccurate project-level 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 nature-based solutions off from offset-based finance[21,90]). Prices for forestry and land use offsets in voluntary markets continue to hover around USD $5/ton[5] and roughly scale[4] inversely with leakage risk. True carbon prices are much higher: Paris-consistent prices were estimated at USD $40-80/ton in 2020[91], and the median internal carbon price employed by corporations was USD $25[92]. Estimates of the social cost of carbon (used in national policy-making) range higher still[93]. 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[21:849] 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 hard-to-abate industrial emissions. We agree with these views, but note that bad accounting is not the solution. The choice is not between current practice and nothing; it is between credible and not credible projects. Taking a conservative approach to avoiding market leakage will direct finance towards projects that actually deliver claimed mitigation while appropriately pricing offsets so as 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[94], and recent work has highlighted high-profile cases of non-additional issuances[95,96]. 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 small offset projects. Coordinated actions and large-scale implementation can provide market substitutes or mobilize the resources necessary for accurate accounting. But 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 ‘simultaneous constraints’ framework helps resolve such misunderstandings about how and where market leakage matters, but the sketch we have provided is necessarily incomplete. Wealth effects, the rebound effects of intensification, and long- versus short-run equilibrium dynamics deserve more consideration within our framework. A deeper exploration of the problems we note (Section 2) 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 realize their potential.

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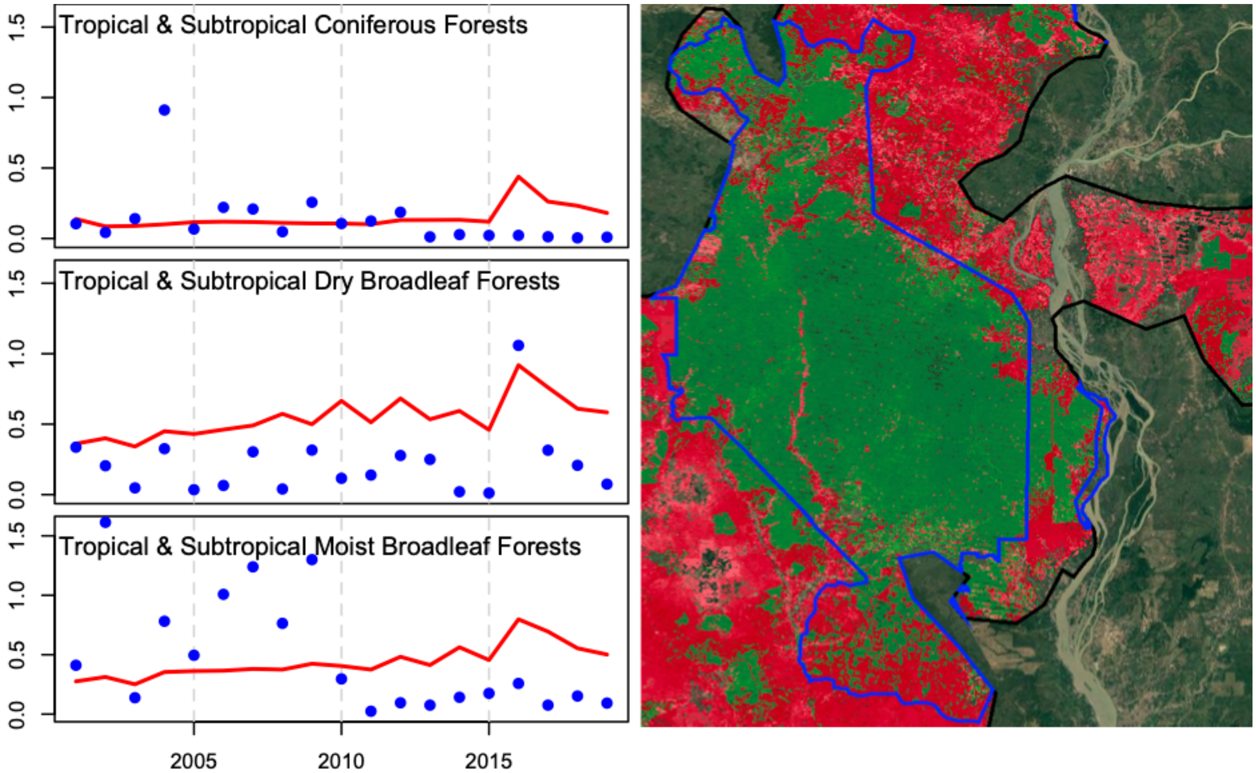

Figure 1. Forest cover loss and area protected in Earth's tropical forest biomes. Left panes show annual area protected (blue dots) and forest cover loss in ecologically similar areas (red lines), expressed as a percent of total forest area in each biome. Right pane shows an example of the underlying ecoregion-level calculations (see Experimental Procedures) in the dry evergreen forests of Cambodia (black outline). For each ecoregion and year, we calculated the increase in forest area protected (blue outline), identified forests within the same ecoregion and with similar canopy closure (green shading; darker is higher closure), and, within these similar forests, calculated the area of forest cover loss (red shading; darker is more recent). Non-declining forest cover loss despite ongoing protection raises the possibility of leakage, but simple zone-based analyses of this sort do not accurately identify market leakage effects without extremely strong assumptions (see main text).

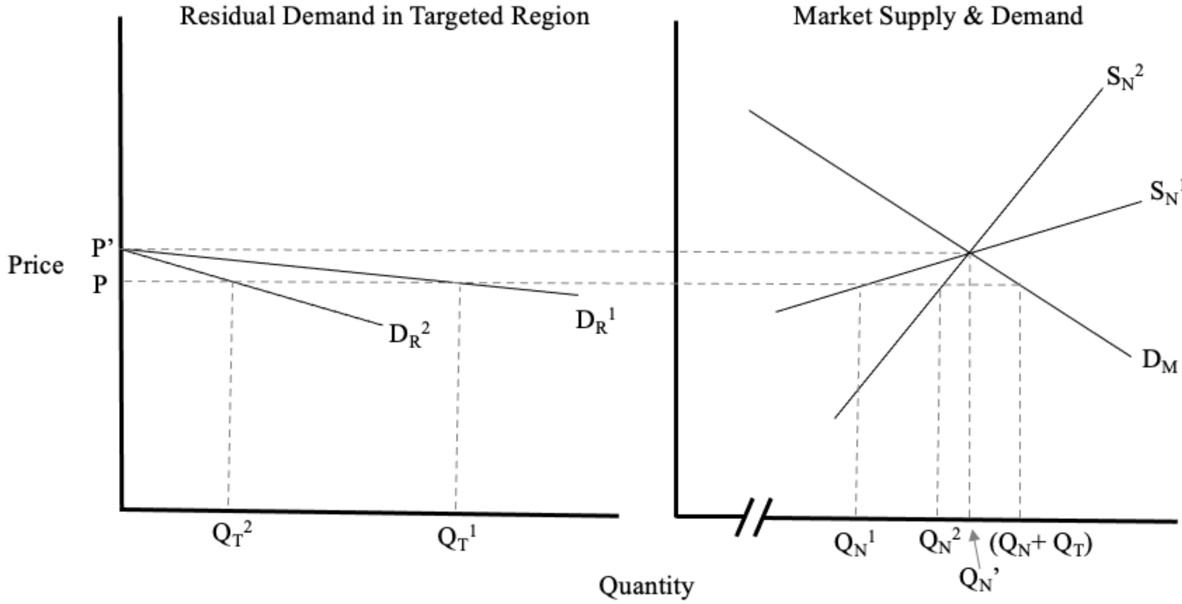

Figure 2. Market leakage occurs because price signals induce agents outside a targeted region to change behaviour. We depict market supply and demand for a common good (right panel) and residual demand for a supply area which will be targeted by an offset program (left panel). S_N is supply from all 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 and Targeted areas. An intervention resulting in Q_T=0 will cause 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.

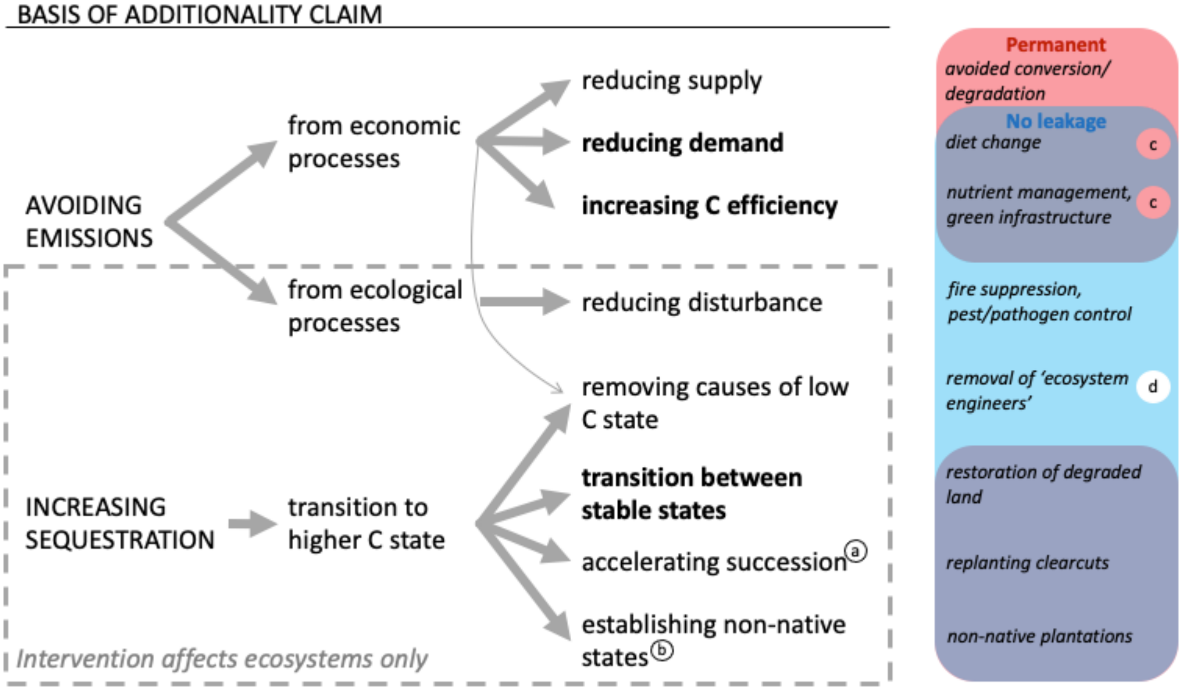

Figure 3. Possible additionality claims in nature-based offsetting. Colors on right indicate sets of overlapping constraints (red: permanence, blue: (no) leakage). Following main text, (a) is additional in time only and (b) is constrained by non-carbon values (not shown). Exceptions to set assignment are possible within the broad categories shown here: (c) both reducing demand and increasing carbon efficiency can cause market leakage under some circumstances, (d) removing causes of low carbon states can produce ecological leakage. Bold font indicates preferred additionality claims for nature-based offsets identified in Section 4; thin arrow indicates economic additionality resulting in increased sequestration in abandoned ecosystems.

Table 1. Leakage in third-party forest carbon standards. Italic text in the '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.

Registry	Methodology	Pathway[a]	Volume (Mt)[b]	Trigger	Int'l 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 >50km 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 Req'mnts** 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, U.S. 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*				
	U.S. 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
	B.C. 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

[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 5 or 10 registered projects. Ranges are not reported where all values were identical

Experimental Procedures

Resource Availability
Lead contact:
Ben Filewod: b.filewod@lse.ac.uk

Materials availability:
This study did not generate new unique materials.

Data and code availability:
Figure 1 was generated using publicly available datasets which are pre-loaded on the freely available Google Earth Engine GIS. The Earth Engine script used to process these datasets is available on request and includes data identifiers. 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 (Figure 1)
We used high-resolution data on global forest cover (Global Forest Change[97]) and a database of protected area boundaries (World Database on Protected areas[98]; polygons only) to analyze forest cover loss in protected forests and ecologically similar areas. We used the Google Earth Engine GIS for analysis, structuring processing by ecoregion (RESOLVE Ecoregions[99]) 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. located within Tropical & 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 10^{th} and 90^{th} 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 2001-2019 (inclusive). We applied a medium-resolution fire mask (MODIS CCI Burned Area, v5.1[100]) 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 1 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 does not detect small-scale disturbances (e.g., selective logging), not all non-anthropogenic disturbance is due to fires (and pixel size artefacts prevent full fire masking in our approach), the choice of a 10^{th}-90^{th}

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 current universe of nature-based carbon offsets (Table 1)
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. 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 5), whether international leakage is considered (column 6), the approach used to account for leakage (column 7), and the range of market leakage values possible under the methodology (column 8).

To assess average market leakage values in practice (column 9), we took a pseudorandom sample of 5 unique project identifiers for each methodology in R using sample_n {dplyr}. We took 10 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 standards (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 less 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 proponent's views that *ex poste* leakage values would be lower.