# Realising the social value of impermanent carbon credits

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**Efforts to avert dangerous climate change by conserving and restoring natural habitats are hampered by widespread concerns over the credibility of methods used to quantify their net long-term benefits. We develop a novel, flexible framework for estimating the long-run social benefit of impermanent carbon credits generated by nature-based interventions which integrates three substantial advances: (1) the conceptualisation of the permanence of a project's impact as its additionality over time (relative to a statistically-derived counterfactual); (2) the risk-averse estimation of the social cost of future reversals of carbon gains; and (3) the deployment of post-credit monitoring to correct for errors in deliberately pessimistic release forecasts. Our framework generates incentives for safeguarding already-credited carbon while enabling would-be investors to make like-for-like comparisons of diverse carbon projects. Preliminary comparisons suggest that after fully adjusting for the impermanence of their effects, nature-based interventions may offer less costly ways of reducing climate damages than more technological solutions.**

Ambitious net-zero commitments made at and since COP26 highlight the imperative of slashing greenhouse gas emissions as swiftly as possible, but also underscore the growing need for credible carbon offsets [1]. In parallel there is an urgent need for scaling-up nature-based solutions (NBS), such as slowing deforestation or restoring forests or wetlands [2–5]. These are widely recognised as essential to avoiding dangerous climate change, especially over the next two or three decades while more technological approaches such as various forms of Direct Air Capture and Storage (DACS) become affordable. NBS are also critically important for slowing deforestation and averting the extinction crisis, and can benefit rural communities [3,5].

Yet investment in robust NBS-derived offset schemes is grossly insufficient to meet the financing needs of project developers [6]. We believe this is in large measure because many would-be buyers of credits are not convinced by current assessments of the additionality of NBS projects – how far they deliver climate benefits that would not have arisen in their absence – nor by reassurances that credit issuances have been fully corrected for the impermanence of those gains. Consequently purchasers struggle to make like-for-like comparisons of diverse offsetting products [7], and NBS credits attract discouragingly low prices.

To assess additionality, NBS credit issuers have primarily relied on comparing changes in the carbon stored in project areas with historical trends or with events in reference areas identified by project proponents [8]. But researchers in other sectors such as public health and international development have found these sorts of approaches result in biased estimates of project performance, and so have instead developed quasi-experimental methods to generate more reliable estimates of counterfactual outcomes [9,10]. Recent results from applying these techniques to estimate the additionality of deforestation-reduction schemes consistently suggest that the effects of such projects are more mixed and typically far smaller than estimates from comparisons with historical trends or reference areas [11–13]. Although more work is needed to improve the robustness of econometric counterfactual estimation there is now a strong case for its widespread adoption across the NBS carbon-crediting sector [14].

Addressing the impermanence of nature-based carbon storage through the release of carbon to the atmosphere via fires, deforestation, disease or severe weather events [15,16] presents a further challenge. The approach most widely used in the offsetting industry is to allocate a fraction of the additional carbon sequestered (or not emitted) because of a project to a not-for-sale buffer pool. In the event of reversal, credits are drawn from this pool [8]. However we consider this procedure to be intrinsically flawed because after the project ends monitoring ceases and all project credits in the buffer pool are cancelled. This means that all credits issued are effectively assumed to be permanent after that point. Moreover up-front allocation to a buffer pool places an unequitable expectation on future stakeholders to not allow releases from past credits in excess of the pool, yet provides them with no incentive to do so. Other approaches [17–20] variously deal with only very short-term releases; are not readily applied across different project types; do not include climate change physics; overlook advances in understanding the costs of emissions; or are not easily integrated with assessment of counterfactual outcomes (for further details see Supplementary information).

Here we attempt to address these substantial limitations by presenting a new dynamic accounting method for quantifying the long-run social benefits of impermanent NBS-derived carbon credits. Our Permanent Additional Carbon Tonne (or PACT) framework comprises three interlinked advances: understanding the permanence of a project's impacts as its additionality – relative to a statistically-derived counterfactual – through time; creating a robust economic framework to derive a risk-averse forecast of the likely social cost of the impermanence of carbon gains, which in turn enables purchasers to make like-for-like comparisons across diverse offset products; and ongoing correction of errors in deliberately pessimistic forecasts of post-credit releases, based on long-term monitoring. Our method is intended to be transparent, capable of readily accommodating future advances in methods for estimating additionality and the social costs of climatic change, and applicable to a wide variety of NBS and indeed other credit-generating projects.

## Permanence as additionality through time

Our starting point is to adopt the conservative view that all NBS-derived credits are likely to be impermanent. We distinguish short-term fluctuations in carbon stock, such as through deciduous leaf fall or the death of individual trees, from the directional release of carbon previously sequestered (or not emitted) as a result of an intervention, such as through the resumption of deforestation, a major disease outbreak or a change in the fire or climate regime. Impermanence is about directional loss, and can helpfully be conceptualised as the loss of additionality over time.

To illustrate this point, consider a stylized deforestation-reduction project (Fig. 1; note that the approach is generalizable to other NBS interventions and to different methods for constructing counterfactuals). The project's additionality is assessed at the end of each of three time intervals by comparing the change in its stock of carbon with the change in stock of a counterfactual set of areas, matched to the project site in terms of initial carbon stock, exposure to drivers of deforestation and variables (such as governance) likely to predict adoption of conservation actions.

Over the first time interval the counterfactual pixels lose half their carbon while the project area loses none. Difference-in-difference analysis thus indicates that the project has generated additionality $a_1$. Over the second interval the counterfactual pixels lose all their remaining carbon while the project ceases to be effective at slowing deforestation and so loses carbon at the same rate. Because changes in carbon stock are the same in the counterfactual and project pixels no further additionality is generated ($a_2$=0) and the overall additionality of the project is unchanged. Impermanence emerges over the final interval, when the counterfactual pixels lose no carbon (as by now they have none to lose), while the project loses its remaining stock; hence project additionality over this interval ($a_3$; the difference in the change of the project and the counterfactual carbon stock) is $-a_1$, and the additionality generated previously is fully released. The relative permanence of a credit can thus be assessed by considering whether the additionality it was based on is reversed, and when any such release occurs.

## Social value and Equivalent Permanence

The next stage of the PACT framework links this additionality-based understanding of when impermanence arises with an assessment of the value of impermanent reductions in atmospheric greenhouse gases. One view is that if the policy goal is to achieve a time-bound target for limiting temperature increases, any drawdowns of carbon which reverse completely before that target date will not affect temperature at that point and so have limited value (except perhaps in helping the development of more permanent storage technologies) [21]. We take a different position [22]. To see this, imagine a health policy with a target of increasing the life expectancy of people born in 2050 to 100 years. Interventions which extend the lifespan of people alive today won't directly help meet the target. But most of us alive now would value even one extra year of life, so those interventions have social value. Our focus here is on the analogous social value of impermanent reductions in the damages incurred by climate change [17–19,22,23].

The economic device we use for characterising that value is the Social Cost of Carbon (SCC) [24] - the cumulative long-run cost of the damage caused by releasing one additional tonne of $CO_2e$ into the atmosphere, discounted into present-day terms. It follows that one tonne of $CO_2e$ permanently withdrawn from (or not emitted to) the atmosphere as a result of an offsetting intervention has an equal but opposite effect, and hence a present value ($V_{perm}$) which is identical to the SCC. For an impermanent offset, by comparison, the value of a one tonne drawdown is the SCC of a permanent drawdown minus the present-day cost of the damage caused by the subsequent release of that carbon, estimated from the SCC at the time of the release [19]. In today's terms this damage cost will be less than the value of the initial drawdown because the rate of increase of the SCC is always less than the discount rate, $\delta$ (for proof see Supplementary information). If the release schedule can be estimated, the damage cost ($D_{tot}$) can be subtracted from the value of the initial drawdown to derive the present value of the impermanent offset ($V_{imp} = V_{perm} - D_{tot}$). We can then calculate the ratio of this value to that of the permanent drawdown of one tonne of $CO_2e$ ($V_{imp}/V_{perm}$) to derive the Equivalent Permanence (EP) of the offset. The inverse of EP (i.e. 1/EP) can then be used as a multiplier to decide how many present-day impermanent NBS credits need to be purchased to be comparable in welfare terms to geological sequestration.

These ideas are summarised diagrammatically in Fig. 2, for the same stylized project as Fig. 1. In terms of changes in carbon stock (panel a), the project successfully stops deforestation over the first time interval so there is net drawdown of carbon, $a_1$. However, this additionality is fully released over the third interval ($a_3$). In terms of social value (panel b), the present value of the project ($V_{imp}$) is the value of the initial drawdown ($V_{perm}$) minus the cost of the damage caused by the release of additionality over interval 3 discounted to its value at the end of interval 1 ($D_{tot}$). The Equivalent Permanence of the additionality achieved by the project is then the ratio of this impermanent value ($V_{imp}$) to that of an equally additional but fully permanent drawdown ($V_{perm}$).

Fig. 3 sets out in greater depth how this approach can be operationalised (for details see Supplementary information). Imagine a simplified, 20-year deforestation-reduction scheme (panel a; in practice release schedules would be described probabilistically and assessed over shorter time intervals). After a decade, *ex post* comparison of trends in carbon stock in the project and in a set of statistically-derived counterfactual sites confirms that the project has generated additionality $a_1$. A corresponding carbon credit $c_1$ is issued, with an EP ($EP_1$) based on an *ex ante* release schedule (panel b). It is important the release schedule does not overestimate the value of impermanent credits – so this schedule starts by conservatively assuming that for the remainder of the project it loses 1.5 times as much carbon as do the counterfactual sites. This means that the loss of additionality (the difference in amount of carbon lost in the project and the counterfactual sites; Fig. 1) is half the amount lost in the counterfactual case (because 1.5 – 1.0 = 0.5). Once the project ends, the schedule then assumes that the project loses carbon stock even faster – losing double the amount lost in the counterfactual sites – so additionality now decreases at the same rate as in the counterfactual (as 2.0 – 1.0 = 1.0) and is dissipated entirely by year 25. Two further considerations are important at this point. First, the derivation of EP should in principle also include the value of the drawdown realised over the assessment interval (the triangle to the left of $a_1$ in Fig. 3a); to aid interpretation we have omitted this complexity. Second, one can also make conservative corrections for leakage – the increase in emissions as a result of forgone food, timber or mineral production being displaced to non-project areas [25,26]. Combining any leakage correction with EP, one can then inform prospective offset buyers how many impermanent credits constitute a Permanent Additional Carbon Tonne: a bundle of credits which is estimated to have at least the same present-value climate benefit as a fully additional, permanent credit.

## Correction for forecasting errors

A third key element in the PACT framework is continued monitoring after a credit has been issued, to allow for *ex post* correction for the inevitable uncertainty and conservative bias in predicting credit reversals. Returning to our example, suppose the project is re-assessed 10 years after the first credit issuance (Fig. 3 panel c). Imagine that while deforestation in the counterfactual sites has continued, the project has done far better than our pessimistic forecast and none of the anticipated deforestation has occurred. In this case the project will have generated further additionality, denoted $a_2$. However, the credit issued for this interval, $c_2$, should also include an amount equal to the release previously expected to occur during this interval, because its social cost has already been accounted for in the EP value assigned to the first credit ($EP_1$). An anticipated release schedule and new EP value are then developed for this second credit ($EP_2$; panel d), which might reasonably reflect a slightly more optimistic view of likely post-project releases, given the project's better-than expected performance over the last 10 years.

An alternative, perhaps more likely outcome over years 10-20 is that carbon stocks do fall in the project area, but at a lower rate than anticipated (Fig. 3 panel e). Additionality over this second interval $a_2$ is less than $a_1$, but because net release has still not happened, this second decade's credit $c_2$ is therefore again calculated as the sum of its observed additionality over that period plus the amount of release of the previous credit that was predicted for this interval. This new credit is assigned its own EP ($EP_2$; panel f), based on the same anticipated post-project release rate as that in panel b.

In contrast to the widely-used buffer pool approach this iterative system of tracking and accounting for releases creates an incentive to safeguard already-credited carbon, because good post-credit performance increases both the magnitude of future credit issuances and their associated EP values (see Supplementary information). Importantly, however, if already-credited carbon is released more rapidly than expected, this too can be corrected through deductions from future credits, and *in extremis* by withdrawal from a portfolio-wide insurance pool of credits (even after the project ends; Supplementary Fig. 1). But adopting deliberately conservative release schedules should mean such situations will be uncommon. Conservatism also acts to reduce expectations of non-release placed on future custodians of already-credited carbon, helping to alleviate intergenerational equity concerns about dealing with impermanence.

## Broad applicability of the PACT framework

Buyers clearly need to make direct comparisons across a diverse array of NBS and other offset classes [7]. The three-pronged PACT framework enables this by explicitly and transparently expressing the performance of different types of projects in a common currency that captures variability in the durability and hence social benefit of the net drawdowns they generate. To illustrate our scheme's flexibility, consider three archetypal NBS projects, set out as in Fig. 3, but lasting for 40 years and with more plausible yet still purposely pessimistic schedules of additionality generation and reversal (see Fig. 4). To ensure timely corrections for post-credit performance we suggest the PACT framework would best be deployed over short, iterated assessment intervals (under 5 years,), but for graphical clarity we focus here on a single assessment made a decade into each project.

The first project (column a) again involves reduced deforestation and anticipates previously credited carbon is lost at 10% of the counterfactual rate until the project ends, and at the counterfactual rate after that. The second (column b) involves a fast-growing timber plantation. In this case we anticipate 1% of credited carbon is lost each year because of disease, that half of the remainder is lost as a result of wastage at harvesting, and that the wood products generated then last a further 40 years.  The final example (column c) describes a restored native woodland in a fire-prone biome, where a conservative release schedule reflects a 2% chance of it being lost entirely each year.

Each of these schedules describes the anticipated complete release of the carbon credited after the first decade, and is used to derive an associated EP value assuming a 3%/year discount rate and an SCC schedule derived from an analysis embedded in a representative Integrated Assessment Model [27] (Supplementary Fig. 3). Under these assumptions Equivalent Permanence values for these projects' first round of credits, if issued *ex post* today, would range from 0.26 to 0.39 (Fig. 4). Combining these EP estimates with headline prices for similar NBS offsets, themselves adjusted for likely overestimation of additionality and underestimation of leakage [11–13,26], in turn suggests that PACTs derived from our archetypal projects would cost in the order of \$80-160 (Fig. 4).

Significantly, while this indicates that fully offsetting emissions through NBS is substantially more expensive than current market prices suggest, such schemes still appear competitively priced when compared with wholly additional, permanent, geologically-sequestered offsets. These reportedly average \$140/tonne $CO_2e$ [7], but vary widely, with some currently selling at ~\$1000/tonne $CO_2e$ (https://climeworks.com/subscriptions). This conclusion is insensitive to plausible changes in SCC schedule, release schedule and time horizon, although the cost of NBS-derived PACTs would increase substantially at very low discount rates (<2%/year; see Supplementary information Sensitivity tests and Supplementary Figs 2 and 4-8). Hence despite the impermanence of their effects, nature-based interventions, which can also provide important biodiversity and rural livelihood co-benefits, may offer less costly ways of reducing climate damages than many more technological solutions.

## Engaging with impermanence

We suggest that more important than the direction of these preliminary findings, though, is the ability of the PACT framing to integrate significant concerns about credit reversals into assessments of NBS (and indeed of those technology-based offsets at risk of reversal [28]). This facilitates project comparability and has the potential to promote buyer confidence. This may in turn boost sales of NBS offsets to existing and new customers, although the higher cost of

PACTs compared with unadjusted NBS credits may discourage buyers who are satisfied with low-integrity offsets. If demand for robust credits does grow, this should encourage more NBS projects to enter the carbon offset market – a critical policy goal.

In addition, tailoring and revising the estimation of EP according to the recent performance of a project (and others like it) should incentivise project providers to implement actions likely to increase permanence, such as improving land tenure and reducing the opportunity costs experienced by local communities. If successful, these actions would enhance project additionality, reduce risks of leakage of forgone production and hence emissions elsewhere, and improve local livelihoods. Continued monitoring would also enable separate, ongoing accounting of the physical climate impacts of projects (essential for tracking progress towards temperature-based goals [21]). Crucially, this monitoring – if linked, as we propose, with *ex post* repayment for lower-than-anticipated releases –incentivises project stakeholders to continue to safeguard already-credited carbon into the future.

The increasing availability of near-time remote-sensing data will be key in continuously updating the information provided to offset purchasers about what they are buying. Procedures for estimating NBS additionality will need regular revision as counterfactual estimation techniques improve, socio-economic drivers change, and new national and sectoral commitments to stopping deforestation are made. Some NBS and indeed technology-based schemes will also become less additional if their costs fall so that they become financially viable without offset payments [29]. Methods for estimating permanence will need updating as our ability to forecast release schedules improves and as threats to emissions drawdowns change [15]. And techniques for estimating leakage will require further work, especially as trade expands such that carbon-emitting production, forgone as a result of project activities, becomes increasingly likely to be displaced far away from intervention sites [25,26]. The dynamic accounting central to the PACT framework means that it is readily capable of accommodating such new procedures and information.

Investors face trade-offs in deciding which offsets to buy. Well-designed NBS projects present singular opportunities for benefitting biodiversity and rural livelihoods [5]. Moreover, while NBS schemes may be more vulnerable to impermanence than some other offset classes, they can and do mitigate the social costs of climate change considerably. Our novel, generalisable and scalable formulation suggests how this contribution can be valued, enabling the direct comparison of nature-based and technological offset options for progressing towards net zero.

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## Author contributions

AB, SK, FV, DC, BG, AM, and TS conceived the initial idea, AB, SK, FV, BG, and TS developed the method, TS created the figures, AB, SK and TS wrote the manuscript and all co-authors revised it.

## Competing interests

The authors declare no competing interests.

## Data and materials availability

All data are available in the main text or the supplementary materials. The code for producing carbon release schedules and calculating equivalent permanence is available on request.

## Supplementary information

The PACT framework compared with current approaches to addressing offset impermanence
An operational framework for valuing impermanent offsets
Sensitivity analyses
Tables S1 to S2
Figs. S1 to S8
References

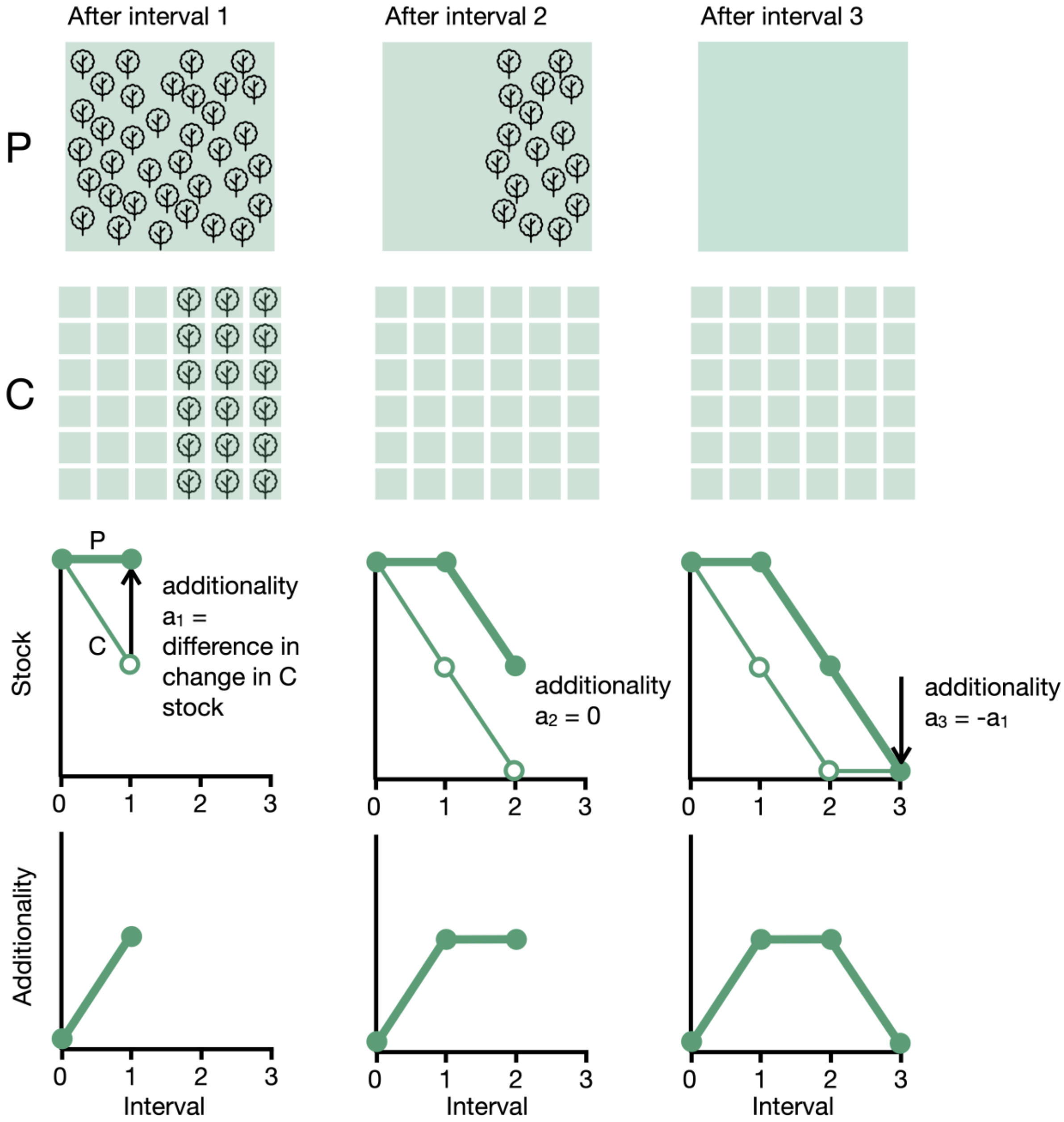


**Fig. 1 │Permanence as additionality through time, illustrated for a stylized deforestation-reduction programme.** First and second rows: the carbon stock in project area P and in a counterfactual set of areas C, assessed after three successive time intervals. Third row: the additionality *a* of the project over each interval is measured as the difference in change in carbon stock between the project and counterfactual areas, and so is positive after interval 1, zero over interval 2, and negative over interval 3. Bottom row: cumulative additionality of the project over the three intervals, showing that the additionality generated over interval 1 becomes impermanent and is completely dissipated over interval 3.

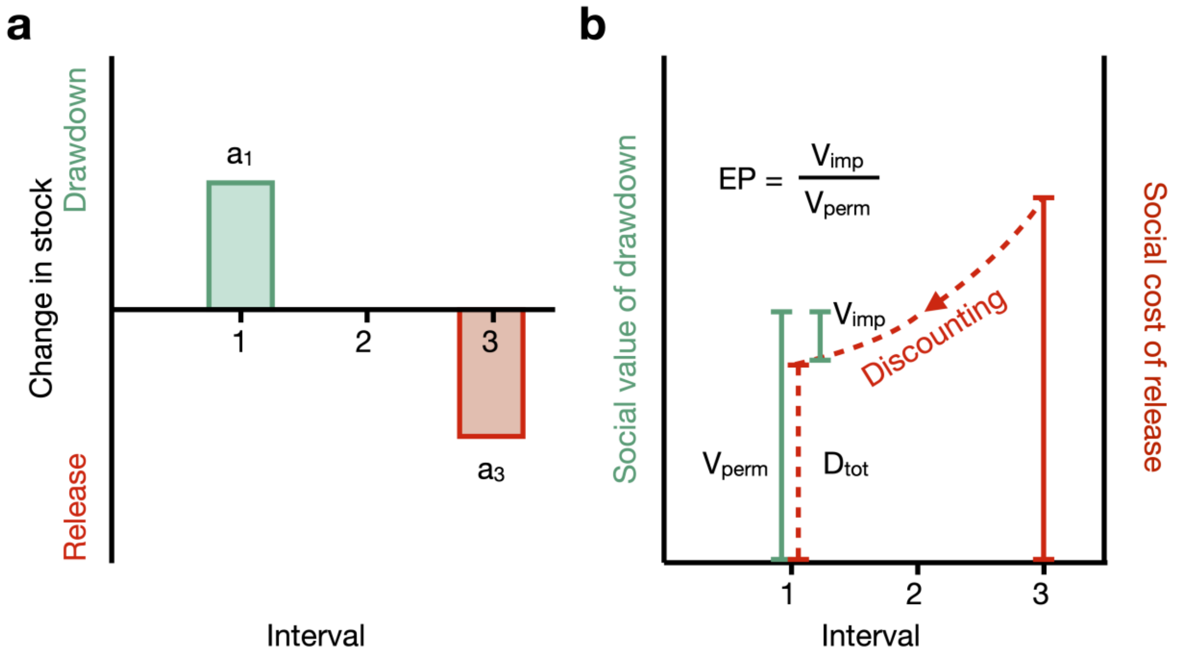


**Fig. 2 │Derivation of Equivalent Permanence (EP), for the same stylized programme as Fig. 1.** **a,** Comparison of changes in carbon stock in the project and counterfactual areas shows the project results in the net drawdown of carbon over interval 1 ($a_1$) and its complete release ($a_3$) over interval 3. **b,** The social value of the project at the end of interval 1 ($V_{imp}$) can then be estimated as the social value of a permanent drawdown of the same size as that achieved over interval 1 ($V_{perm}$) minus the cost of its future release over interval 3 discounted to its value at the end of interval 1 ($D_{tot}$). Note that because the Social Cost of Carbon (SCC) is likely to increase over time, the cost of the damage when it occurs exceeds the value of the drawdown when it occurs. However because the growth rate of the SCC is always less than the discount rate, $V_{imp}$ is always positive (for proof see Supplementary information). EP is then estimated as the ratio of the impermanence-adjusted value of the drawdown to that of a fully permanent drawdown of the same size

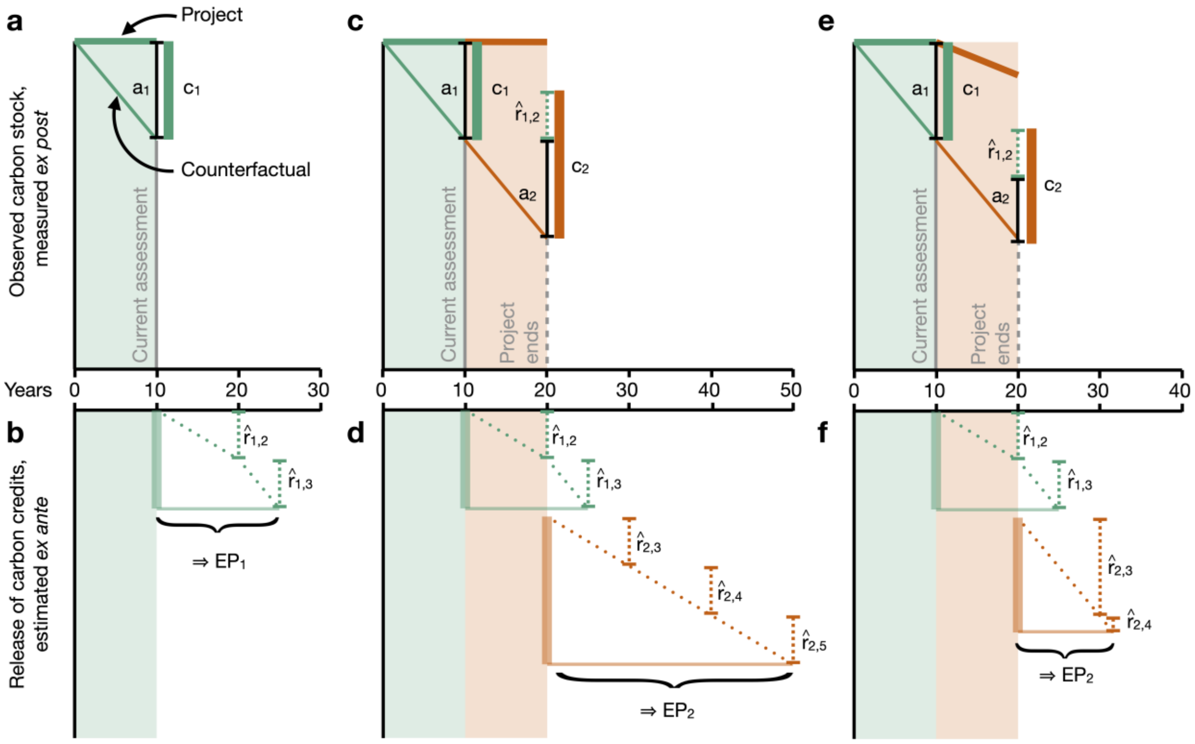
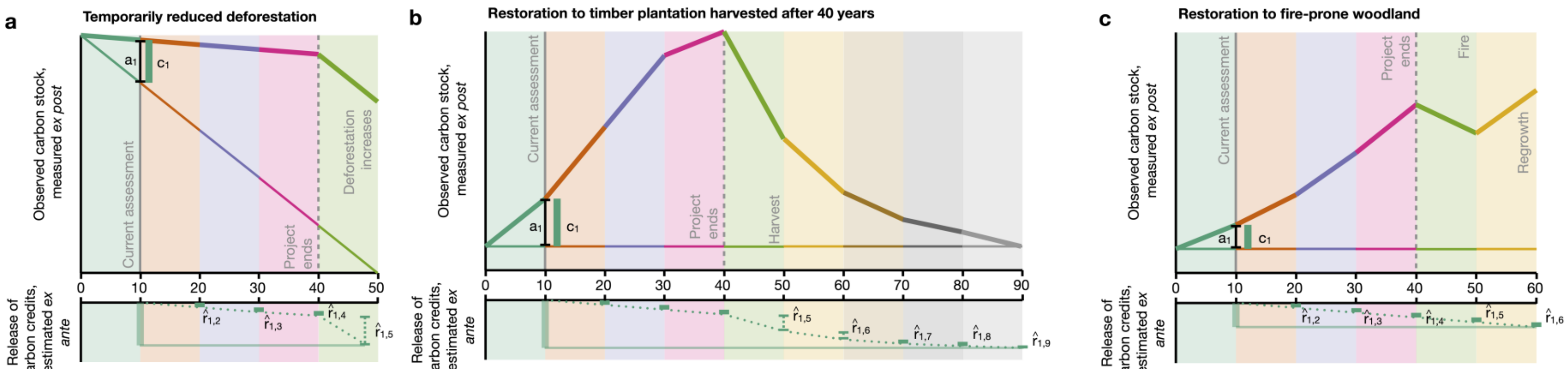


**Fig. 3 │Forecasting a release schedule and correcting for forecasting errors, for a stylized 20-year reduced-deforestation project. a,** Over its first decade (green) the project reduces deforestation to zero. Additionality ($a_1$) is estimated *ex post* as the difference in change over this interval in the carbon stock of project and counterfactual sites, and credit $c_1$ is issued. **b,** $c_1$ is very conservatively estimated *ex ante* (dotted line) to be released at half the rate observed in counterfactual sites over the next decade (releasing $\hat{r}_{1,2}$ over decade 2, with the 'hat' indicating this is a forecast), then at the counterfactual rate once the project ceases (releasing $\hat{r}_{1,3}$ over decade 3; see explanation for text). All of $c_1$ is anticipated to be released over these two decades. This anticipated release schedule is used to derive $EP_1$, the Equivalent Permanence value for $c_1$, as outlined in Fig. 2. **c**, Over decade 2 (orange) the project performs better than conservatively anticipated. Deforestation remains at zero, and additionality $a_2$ is generated (calculated again as the difference between the project and counterfactual in how their carbon stock changes over the interval). Because the release of the previous credit ($c_1$) which was anticipated for this decade ($\hat{r}_{1,2}$) did not happen, the credit issued after decade 2 ($c_2$) is the sum of the new additionality $a_2$ generated plus $\hat{r}_{1,2}$ (so $c_2 = a_2 + \hat{r}_{1,2}$). **d**, $c_2$ is estimated *ex ante* to be released at a slightly lower rate than was anticipated for $c_1$, given the project's better than anticipated performance. Again all of $c_2$ is expected to be released, with the costs of the release accounted for via $EP_2$, the EP value derived from this schedule. **e**, An alternative outcome over decade 2 is that carbon is lost from the project area but at a slower rate than pessimistically anticipated in the release schedule for credit $c_1$. Additionality $a_2$ is less than $a_1$, but because additionality is still positive (i.e. release has not occurred) this second decade's credit $c_2$ is again calculated as the sum of the additionality over the period plus the release of the previous credit that was predicted for this interval ($c_2 = a_2 + \hat{r}_{1,2}$). **f**, This new credit is assigned its own EP assuming the same anticipated post-project release schedule as panel b.



| | a | b | c |
|---|---|---|---|
| Equivalent Permanence | 0.31 | 0.39 | 0.26 |
| Headline price/tonne $CO_2e$ (adjusted for additionality and leakage) | \$25 | \$40 | \$40 |
| PACT cost | \$80 | \$103 | \$154 |

**Fig. 4 │ Application of the PACT framework to three archetypal 40-year NBS projects.** *Upper plots*: carbon stock in the project and counterfactual sites (thick and thin lines respectively). *Lower plots*: release schedules for credited carbon for the current credit $c_1$, issued 10 years into the project; note that steady-state turnover of carbon through respiration, photosynthesis and decomposition is not considered relevant. *Bottom row*: EP values for $c_1$ issuances based on these release schedules; plausible headline prices for impermanent credits of this type, adjusted for additionality and leakage; and the resulting cost of a Permanent Additional Carbon Tonne (PACT) for each hypothetical project. **a**, Hypothetical deforestation-reduction scheme which reduces deforestation to 10% of the counterfactual rate. The release schedule anticipates that already-credited carbon is also lost at 10% of the counterfactual rate, rising to 100% when the project ends. **b**, Hypothetical reforestation project involving a fast-growing plantation, cleared for timber (as scheduled) after 40 years. Anticipated release of the credited carbon $c_1$ involves 1% loss of carbon each decade prior to harvesting to allow for possible disease outbreak, 50% loss of the remainder through wastage at harvesting, and then release of half of the carbon in harvested timber each decade, starting 10 years after harvest, with complete loss 40 years later. **c**, Hypothetical woodland restoration project in a fire-prone biome. The project is severely impacted by a fire releasing 25% of its additional carbon in the decade after the project ends. A fire was predicted however, with a conservative release schedule assuming a 2% chance of it being lost entirely each year.

# Supplementary Information for

## Realising the social value of impermanent carbon credits

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**This document includes:**

## The PACT framework compared with current approaches to addressing offset impermanence

The central premise of the PACT framework is that even impermanent reductions in atmospheric greenhouse gases benefit society and that robustly estimating the present-day value of those future gains is key to incentivising nature-based interventions. This point is not new [1–4], but we believe it bears repetition. We contend, however, that existing approaches to quantifying and addressing project impermanence have important limitations (and in some cases serious flaws) that undermine confidence in NBS and other impermanent solutions. Here we summarise our concerns about four existing frameworks.

The *tonne-year approach* uses a model of the biophysical dissipation of $CO_2$ from the atmosphere [1], linked in some versions with discounting [3], to estimate the benefit of delaying for a short period the emissions arising from an action such as harvesting a forest. This approach is used in new short-term carbon-offset contracts (e.g. by NCX Inc.; https://ncx.com). But it doesn't take into account thermal inertia of the climate system, the saturation of carbon sinks, or the convex shape of damage functions. As a result it is not suitable for capturing the long-run consequences of gradual releases likely to arise from credits generated by avoided deforestation or reforestation projects.

The *sequestration-effectiveness approach* [3] estimates the economic cost of long-run releases of carbon used to derive a credit, and from that calculates how many impermanent credits need to be purchased to have the same economic benefit as a permanent drawdown of the same size. However the method takes a cost-*effectiveness* rather than cost-*benefit* approach, and rests on hypothetical trajectories of how carbon prices change into the future rather than grounding the value of the offset in the framework of the Social Cost of Carbon (SCC), as we do. On a cost-effectiveness path, the carbon price will be different from the SCC and will increase at the discount rate. This results in zero value for temporary absorption of carbon [7]. We instead show (in Sensitivity tests, below) that when damages are taken into account, the SCC will always increase at a slower rate than the discount rate and hence the value of a temporary drawdown of carbon cannot be zero. Moreover the sequestration-effectiveness approach has not been generalised to a wide range of release schedules, has no system of correcting for inevitable errors in *ex ante* predictions of reversals, and is not integrated with additionality – i.e. with counterfactual analysis of what might have happened in the absence of a project.

The closest approach to date to our framework is the idea of *equivalence trading ratios* [4]. This approach, like ours, uses an SCC schedule to estimate the present-day value of future damages, and proposes as we do that buyers purchase additional impermanent credits to achieve the same social benefit as buying a single, fully permanent credit. However, as set out [4] the approach only deals with complete, instantaneous reversal, rather than complex release schedules; does not consider how results might differ under different SCC schedules; is not integrated with considerations of additionality; and most importantly, does not allow for *ex post* corrections for errors in *ex ante* release schedules, and so does not lend itself to situations where there is substantial uncertainty about what the future holds.

To our knowledge none of these conceptual framings has been widely operationalised beyond considerations of short-term delays in timber harvesting. Instead certifiers have mostly adopted a fourth practice – dealing with impermanence-prone offsets by allocating a proportion of the additionality generated by a project to a not-for-sale *buffer pool*, to be drawn from when some of the carbon issued as a credit is later released to the atmosphere [10–

[12]. However we consider this approach and related insurance schemes to be intrinsically flawed, because the buffer pool can only be drawn on for the lifetime of the project. Hence all additionality remaining after that period is effectively assumed to be permanent. We instead anticipate that all additional carbon stored in the biosphere will eventually be released to the atmosphere through reversals such as deforestation or fire. The impact of that future release needs to be accounted for whenever a credit is issued from an NBS scheme. An additional and important concern is that the buffer pool approach effectively places an unequitable and unenforceable burden on future custodians of already-credited carbon to not allow releases in excess of the size of the buffer pool.

In contrast to these approaches, we suggest that the PACT system is better grounded in climate science and the economics of climate damages and better able to deal with changes in our understanding; is directly integrated with considerations of how project additionality changes through time; accepts that all NBS drawdowns are impermanent but that estimating their future release is intrinsically uncertain; and rather than imposing an unequitable burden on future generations instead actively rewards safeguarding already-credited carbon. As a result it addresses many of the key shortcomings of existing procedures.

## An operational framework for valuing impermanent offsets

This section sets out our approach for assigning a permanence value to a carbon drawdown (sequestration or emissions reduction) project when the underlying project is impermanent and can suffer from some degree of lack of additionality. The key idea is to compute the Equivalent Permanence (EP) of the additional carbon temporarily sequestered in a project as the ratio of its social value to the social value of permanent drawdown. When combined with estimates of project additionality and leakage we can then identify the number of impermanent credits required to completely offset an emission – a bundle of credits which we term a *Permanent Additional Carbon Tonne* or PACT. The analysis uses the notation in Supplementary Table 1.

**Supplementary Table 1 │Notation.**

| Term | Meaning |
|---|---|
| $S_t^p$ | Carbon stock measured in a project pixel at the end of interval *t* |
| $S_t^c$ | Median carbon stock measured in a set of matched counterfactual pixels at the end of interval *t* |
| $F_t^p$ | Carbon flux in a project pixel during interval *t* |
| $F_t^c$ | Median carbon flux in a set of matched counterfactual pixels during interval *t* |
| $a_t$ | Net carbon drawdown or emissions reduction by a project during period *t* taking additionality into account |
| $c_t$ | Credit issued at the end of interval *t* |
| $\hat{r}_{t,\tau}$ | The number of tonnes of carbon additionally sequestered in interval *t c* conservatively expected to be released into the atmosphere in interval $\tau$ |
| $D(\tau, T(\tau))$ | Damage due to a tonne of carbon being released into the atmosphere during period $\tau$ with a background temperature $T$ (Nordhaus 2014) |
| $L$ | Lifetime of temperature impact of carbon dioxide emissions |

| | |
|---|---|
| $K$ | The number of years after $t$, over which carbon sequestered in time interval $t$ is released |
| $\delta$ | Discount rate |
| $SCC(t)$ | Social cost of releasing a tonne of carbon in time interval $t$ |
| $V_{perm}(x,t)$ | Value of permanently sequestering $x$ tonnes of carbon in time interval $t$ |
| $V_{imp}$ | Value of impermanently sequestering carbon given the damages arising from anticipated future releases |
| $EP$ | Equivalent Permanence |

We divide time into contiguous disjoint intervals, not necessarily of equal length, indexed by $t$. Carbon credits are issued at the end of each interval, with a dynamic baseline, so that additionality and permanence of the issued carbon credits are periodically reassessed and corrected as necessary.

To ensure additionality, each pixel in the project under consideration (referred to as a *project pixel*) is matched with one or more pixels from control areas (referred to as *counterfactual pixels*). Various matching procedures are available, but for one worked example see Guizar-Coutiño (2022) [13]. Let the carbon stock measured in a project pixel at the end of interval $t$ be $S_t^p$ and the median carbon stock measured in the set of matched counterfactual pixels at the end of interval $t$ be $S_t^c$. Then, the flux (change in carbon stock) in the project pixel is $F_t^p = S_t^p - S_{t-1}^p$ and the median flux in the counterfactual pixels is $F_t^c = S_t^c - S_{t-1}^c$. The additional gain in flux in the project pixel - which we attribute to project actions - is therefore $a_t = F_t^p - F_t^c$.

We next describe the computation of credits and of their permanence at the end of the first time interval, and then the corresponding computations at the end of subsequent time intervals.

## FIRST TIME INTERVAL

At the end of the first time interval ($t$ = 1), the number of credits issued is $c_1 = a_1$. We also make an *ex ante* forecast of the release of this additional flux in up to $K$ future time intervals, through habitat conversion, fire, disease or climatic change. Note that steady-state turnover of carbon through respiration, photosynthesis and decomposition is not considered relevant. In general, at the end of interval $t$ we forecast $\hat{r}_{t,\tau}$ tonnes of C additionally sequestered in interval $t$ to be released into the atmosphere during interval $\tau > t$, where $1 < \tau <= K$. This forecast might be in error (hence the 'hat'), so the credits issued in future intervals must be accordingly corrected *ex post*. We return to this point later: we first focus on computing the Equivalent Permanence of the credits issued at the end of the first time interval.

To begin with, it is evident that the social value of permanent drawdown of one tonne of carbon is the same as the Social Cost of Carbon (SCC) (see main text) [9–11]. In other words, if releasing of one tonne of carbon has a cost of SCC($t$) during interval $t$, then permanently sequestering one tonne during interval $t$ ought to have the same value. The social cost of carbon in interval $t$ is defined as the discounted sum over the time interval $[t, t + L]$ (where $L$ is the lifetime of $CO_2$ in the atmosphere, typically measured in centuries) of the damage $D(\tau, T(\tau))$ incurred to society in future time intervals $\tau > t$, with an expected background temperature of $T(\tau)$ [9]. Specifically:

$$SCC(t) = \sum_{\tau=t}^{t+L} (1+\delta)^{-(\tau-t)} D(\tau, T(\tau)) \tag{1}$$

Note that damages are exponentially discounted by a factor $0 \leq \delta \leq 1$: damages that will happen in the future are diminished.

The benefit $V_{perm}$ from permanently and additionally sequestering $c_t$ tonnes of carbon in time interval $t$ is $c_t\, SCC(t)$:

$$V_{perm}(c_t, t) = c_t\, SCC(t) \tag{2}$$

However, future release of this carbon into the atmosphere will cause damage. Specifically, the anticipated economic damage caused by a release of $\hat{r}_{t,t+\mathrm{i}}$ tonnes of carbon in some future time interval $t+i$ is:

$$\hat{r}_{t,(t+\mathrm{i})} SCC(\mathrm{t}+\mathrm{i}) \tag{3}$$

which has a present discounted value (at the end of time interval $t$) of $\hat{r}_{t,t+\mathrm{i}}\,(1+\delta)^{-i} SCC(t+i)$. Suppose this release happens over $K$ time intervals. Then, the total damage caused due to this release is given by:

$$D_{tot} = \sum_{i=1}^{K} \hat{r}_{t,t+\mathrm{i}} \quad \underbrace{(1+\delta)^{-i} SCC(t+i)}_{Present\ value\ of\ future\ damage} \tag{4}$$

$$= \sum_{i=1}^{K} \hat{r}_{t,t+\mathrm{i}}\ (1+\delta)^{-i} \sum_{\tau=t+i}^{t+i+L} (1+\delta)^{-(\tau-t-i)} D(\tau, T(\tau)) \tag{5}$$

$$= \sum_{i=1}^{K} \hat{r}_{t,t+\mathrm{i}}\ \underbrace{\sum_{\tau=t+i}^{t+i+L} (1+\delta)^{-(\tau-t)} D(\tau, T(\tau))}_{Present\ value\ of\ future\ damage} \tag{6}$$

Equation 4 sums the SCC from each year's release, discounted to interval $t$, when this computation is carried out. Equation 5 substitutes Equation 1 into Equation 4, and Equation 6 simplifies the expression.

The net benefit from the impermanent drawdown is therefore:

$$V_{imp} = V_{perm}(c_t, t) - D_{tot} \tag{7}$$

and the equivalent permanence (EP) is given by normalizing with respect to $V_{perm}(c_t, t)$:

$$EP = \frac{V_{perm}(c_t, t) - D_{tot}}{V_{perm}(c_t, t)} \tag{8}$$

We now make four important observations.

Observation 1: Our expression for EP depends only on the additional credit $c_t$, the damage function $D$ and the discount rate $\delta$. The damage function, or, equivalently, SCC (if using Equation 4), as well as the discount rate can be found in standard governmental publications, such as Valatin 2011[13–15]. Thus, the methodology detailed here is suitable for automated evaluation using publicly available datasets which now routinely track land-use change and carbon density through time [16]. This is important in enabling recurrent long-run assessment of project performance, potentially even after projects have ceased.

Observation 2: The largest value of EP is 1, when the release is zero, i.e., for permanent drawdown. The smallest value of EP is 0, when the drawdown in year 0 is also released in year 0 (i.e., no drawdown at all). Intermediate values of EP correspond to increasing levels of permanence. Thus, EP can be viewed as a multiplicative factor to compensate for impermanence. As a concrete example, if after adjusting for leakage a project pixel sequesters 1 additional tonne of carbon with an EP of 0.2, then the permanent additional drawdown is 0.2*1 = 0.2 tonnes. So, a buyer would need to buy 5 credits (1/EP) to achieve the same social benefit (measured in present-day terms) as purchasing a single tonne of fully additional, permanent (i.e. geological) drawdown. This bundle of 5 impermanent credits would then be equivalent to a single PACT.

<u>Observation 3</u>: Our formulation conservatively assumes carbon drawdown (or emissions reduction) occurs instantaneously at the point of credit issuance. Any social benefit enjoyed before this point (because additionality is accrued gradually) is not reflected in the EP associated with the credit, which is therefore underestimated. This issue becomes increasingly minor the shorter assessment intervals are relative to the length of release schedules. However, it would also be possible to include the value of drawdowns in terms of the present value of the historic SCC($t$) at the time they occurred rather than at the end of the assessment interval. Calculated in this way greater values of EP are obtained because $V_{perm}$ is increased through the capitalized value of past drawdowns.

<u>Observation 4</u>: In devising a release schedule there is a trade-off to be navigated between the risk associated with the issuance of an impermanent credit and the incentive received by the project provider. At one extreme one could take a view that all additional carbon may be released immediately. In this worst case the release schedule is $\hat{r}_{t,t+1} = c_t$ with all other values of $\hat{r}_{t,\tau}$ being 0; that is, all the net drawdown in year $t$ is released in year $t+1$. In this case the permanence-adjusted value of the credit at point of issuance would likely be insufficient to incentivise many badly-needed nature-based climate mitigation activities.

At the other extreme one could assert (as many accrediting bodies and resulting NBS Project Design Documents currently do) that all or most additional carbon is effectively permanent. However, as well as being implausible, evidence from relative prices suggests this does not persuade sceptical buyers, and hence once again means too few providers join the market.

We propose instead that EP is estimated (as in our hypothetical NBS examples below) using an intermediate but nevertheless conservative schedule to accommodate the partial, doirectional release of carbon during a project (as a result of drought, fire, pests or human activities), and its complete release over time once the project ends, based on the worst-case performance of other, similar projects. Importantly, as described next, as more information about the project and others like it becomes available the schedules are recomputed. This motivates project managers to better manage their projects and collect trustworthy unbiased observations, such as from remote sensing, that bolster their credibility as managers. In addition credits can be awarded at subsequent time intervals for anticipated releases that have not occurred.

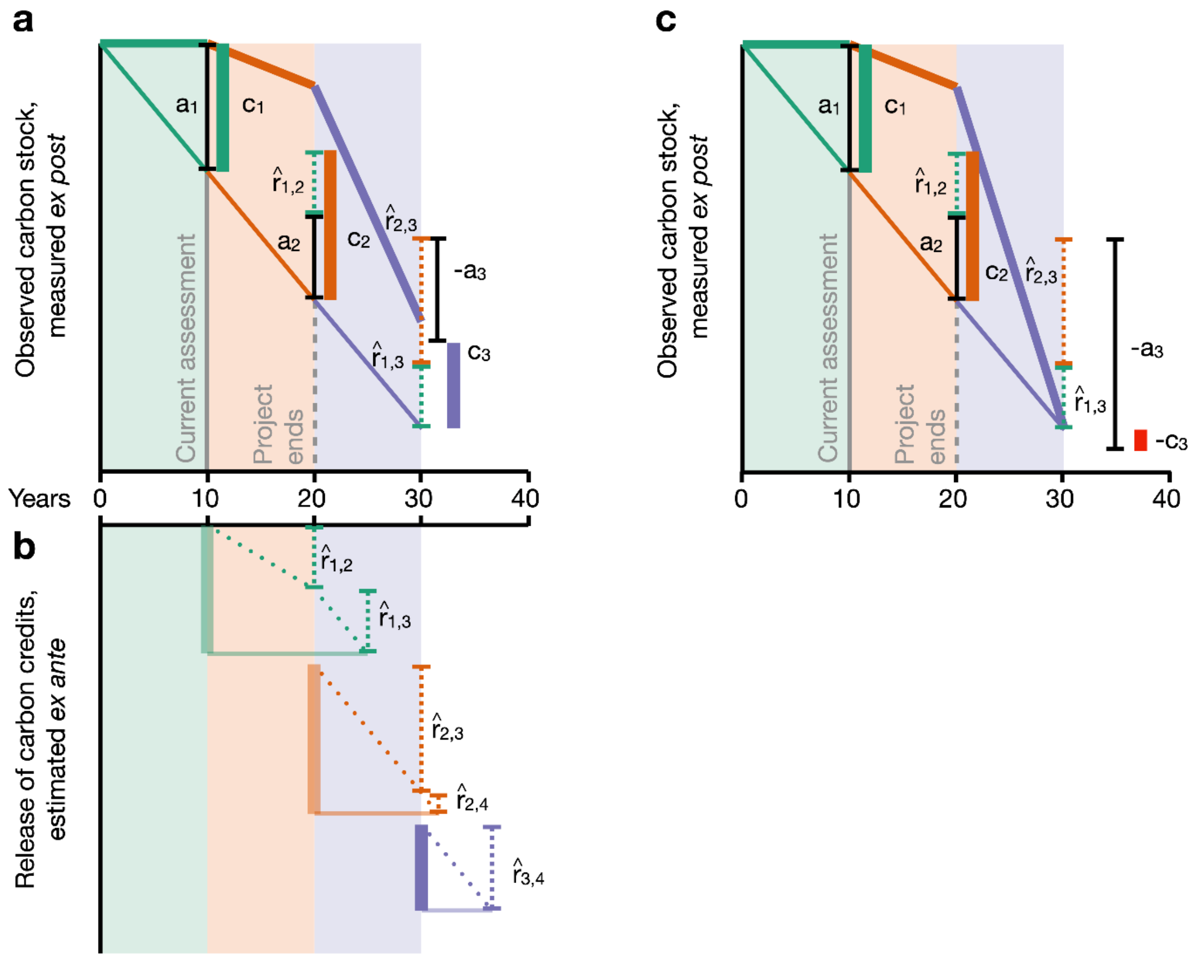
## SUBSEQUENT TIME INTERVALS

At the end of time intervals $t > 1$, we issue credits taking into account all prior *ex ante* releases forecast by setting credit $c_t = a_t + \sum_{\tau=1}^{t-1} \hat{r}_{\tau,t}$; note that $a_t$ is estimated net of actual reversals over the immediately prior interval. The justification for this equation is that the credit is issued not just for the additionality in this interval but also for any releases previously expected to occur during this interval, because the social cost of such releases has already been accounted for in the EP values of prior issuances (see main text).

Because EP is estimated conservatively, in most instances any reductions in additionality due to actual releases will be less than anticipated. The greater this better-than-expected performance (so the less that additionality over subsequent intervals is reduced by reversals), the larger the subsequent credit issuances will be. Larger credit issuances will also take longer to be fully reversed – so they will also have a greater EP. These two consequences, we suggest, will incentivise retention of past project additionality, as a result further reducing the risk of releases above the *ex ante* forecast.

It is possible, if actual releases are greater than anticipated and/or a project is performing worse than its counterfactual, that the additionality over an interval becomes negative. Credits can still be issued provided this negative additionality is less than the sum of the *ex ante* releases from prior credits anticipated for the interval (Supplementary Fig. 1a,b). In cases of extreme underperformance this may not be true, and credits will thus be negative (Supplementary Fig. 1C). To address such instances we propose that projects could potentially borrow credits from other projects that form a mutual insurance pool, under the condition that all participating credits are tracked until the end of their *ex ante* release schedules. We leave the question of pool sizing and formation to future work.

The permanence of all credits issued in subsequent time intervals can be computed using a procedure that is identical to that used for credits issued in the first time period.



**Supplementary Fig. 1 | Correction for greater than expected releases of already-credited carbon. a**, In the decade (blue) following the end of the simplified deforestation-reduction project portrayed in Fig. 3e, monitoring of project and counterfactual sites continues. A combination of the release of some previously credited carbon $c_1$ and $c_2$ and an increase in deforestation means that carbon loss in the project site (thick blue line) is now greater than in the counterfactual (thin blue line), and so additionality $a_3$ is negative. However, an even greater release during this decade ($\hat{r}_{1,3} + \hat{r}_{2,3}$) has already been accounted for in the Equivalent Permanence values assigned to credits $c_1$ and $c_2$, so to ensure the project is not penalised twice for this release, a credit $c_3$ is issued, equal to the difference between the anticipated and observed release (so $c_3 = \hat{r}_{1,3} + \hat{r}_{2,3} - a_3$). **b**, The complete release of $c_3$ is conservatively estimated *ex ante* to occur faster than the counterfactual rate, with the costs accounted for through the credit's resulting EP value. **c**, In this second, extreme example, greater than anticipated release of the carbon from $c_1$ and $c_2$ and an increase in deforestation in the project site mean that carbon loss in the project site (thick line) is much greater than in the counterfactual (thin line). Additionality $a_3$ is now strongly negative, and exceeds the anticipated releases of carbon already accounted for in the Equivalent Permanence values assigned to credits $c_1$ and $c_2$ ($\hat{r}_{1,3} + \hat{r}_{2,3}$). Hence there is net emission from the project ($c_3 = \hat{r}_{1,3} + \hat{r}_{2,3} - a_3$ is negative). This could in principle be compensated for by a withdrawal from a portfolio-wide insurance pool of carbon credits. However, conservative estimation of release schedules should make such situations uncommon.

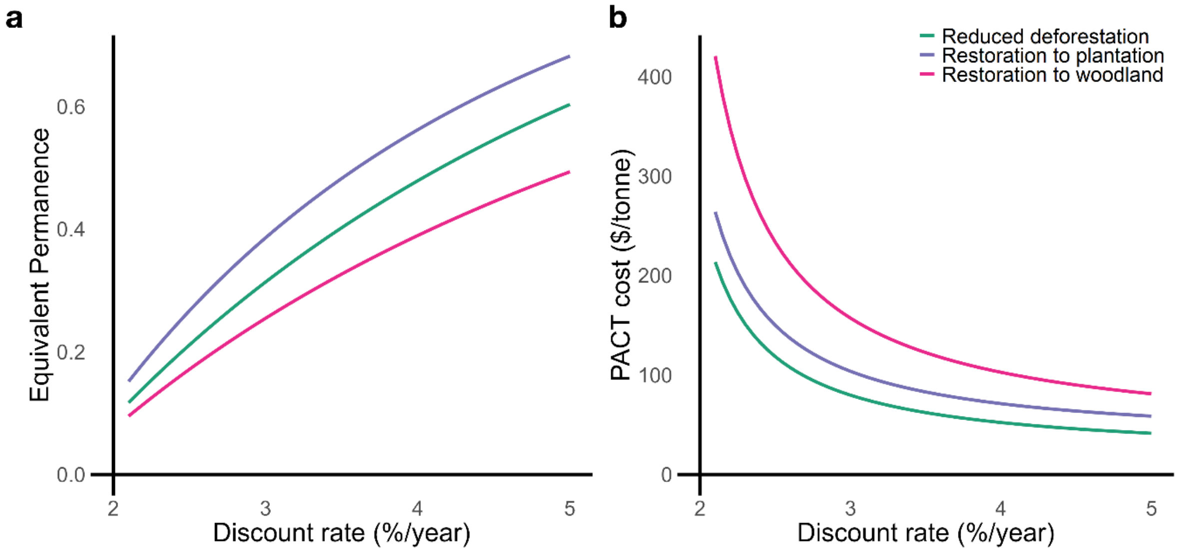
Sensitivity analyses

The EP and PACT values presented above and in our main text are for hypothetical examples of NBS projects. Below we present a series of analyses that cover a much wider variety of possible scenarios, revealing the sensitivity of our EP and PACT estimates for the first credit issued from these projects to reasonable variation in key parameters, while holding all other aspects of each example constant.

## DISCOUNT RATE

The discount rate selected for assessing the damages caused by carbon released in the future has a large effect on estimated EP (for a similar finding see [4]). In the main text we focus on a discount rate of 3%/year, which approximates the findings of a recent expert survey [16]. Below we show the sensitivity of our findings to a wider range of discount rate values.

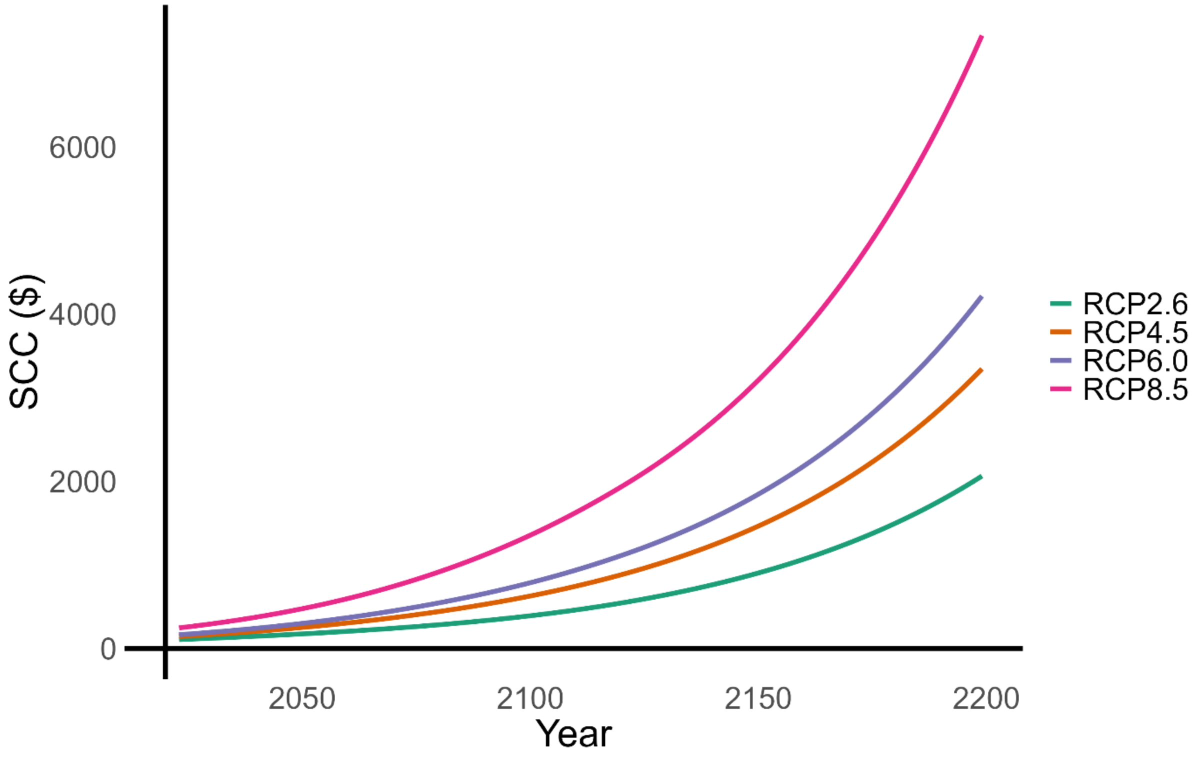
Higher discount rates are associated with attributing lower present-day value to damages incurred by future carbon releases. Consequently, EP increases and the cost of a PACT decreases with increasing discount rate (Supplementary Fig. 2). At very low discount rates the price of NBS PACTs becomes quite high, but remains below that of some geological storage schemes which offer no biodiversity or livelihood co-benefits [17]; https://climeworks.com/subscriptions).



**Supplementary Fig. 2 |** The sensitivity to discount rate (%/year) of A, Equivalent Permanence (EP) and B, the resulting price of a Permanent Additional Carbon Tonne, for each of the three examples shown in Fig. 3.

## SCC SCHEDULE

The main text and NBS examples illustrate the social value of delayed emissions in the context of growth in the current value of the SCC ($SCC_t^{CV}$ ) - the value of the SCC at the time it is evaluated. We assume that $SCC_t^{CV}$ will increase over time with the growth of the economy, that damages will be proportional to the size of the economy (GDP), and that marginal damages are linear with respect to temperature (such that total damages are quadratic with respect to temperature). Each of these are standard assumptions in coupled economy-climate Integrated Assessment Models. The precise growth rate of $SCC_t^{CV}$ depends on the economic growth rate, specific emissions path and discount rate. We assume 1.7%/year economic growth, a discount rate of 3%/year and the RCP 2.6 temperature path (Supplementary Fig. 3). Based on these assumptions we obtain the growth rates for $SCC_t^{CV}$ shown in Table S2.



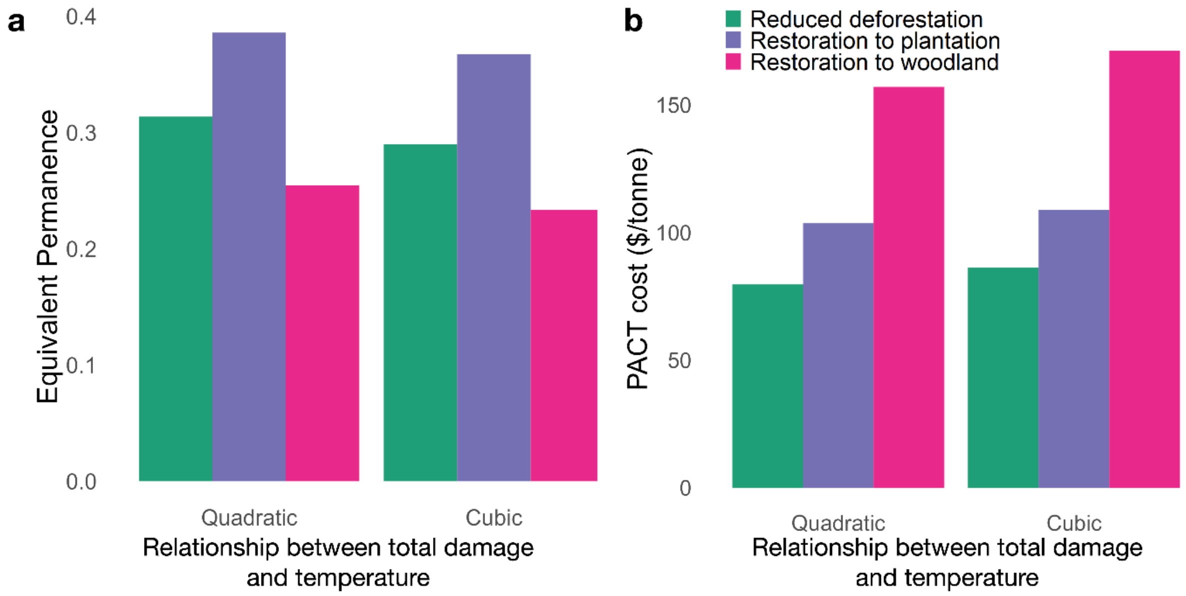
**Supplementary Fig. 3 |** The SCC schedule used in our main analysis (RCP 2.6, green line) and schedules explored in subsequent sensitivity analysis (see below) corresponding to three other Relative Concentration Pathways.

**Supplementary Table 2 |** Detailed growth rate schedule for $SCC_t^{CV}$. Note that in the long run this growth rate converges to the growth rate of production (assumed to be 1.7%/year).

| Growth in $SCC_t^{CV}$ (%/year) | 2025 | 2030 | 2035 | 2040 | 2045 |
|---|---|---|---|---|---|
| Quadratic total damages | 2.0% | 1.9% | 1.9% | 1.9% | 1.8% |
| Cubic total damages | 2.2% | 2.1% | 2.1% | 2.0% | 2.0% |

As a sensitivity test we explore the consequences of marginal damages instead being quadratic with respect to temperature (such that total damages are cubic with respect to temperature). The growth rate of $SCC_t^{CV}$ is quite similar (Supplementary Table 2), and using this alternative schedule for $SCC_t^{CV}$ has very little effect on our EP and PACT estimates for our three projects (Supplementary Fig. 4).

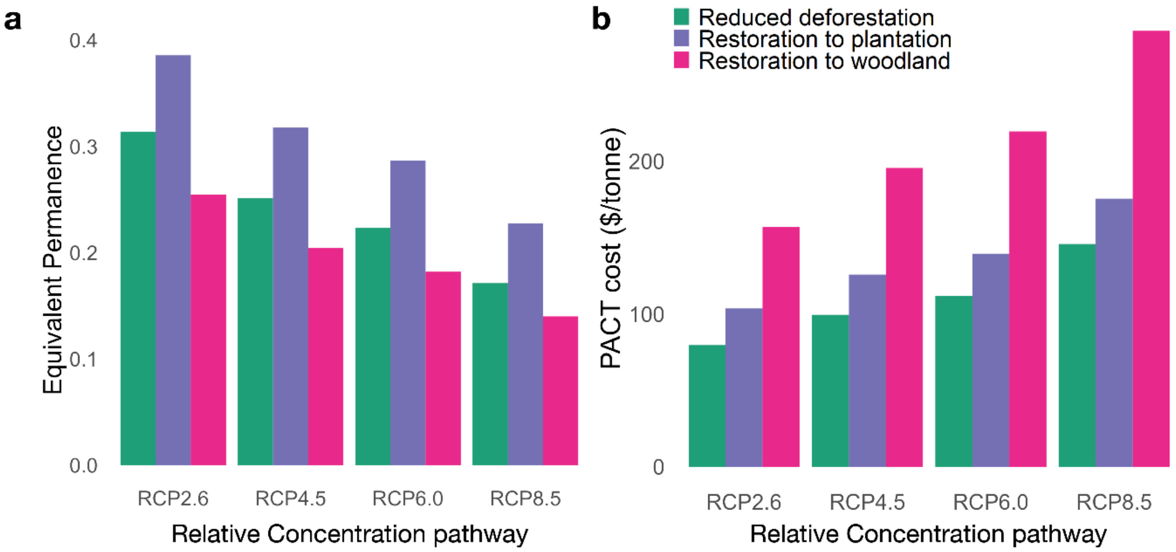
As a second sensitivity test we examine the effects of assuming different emissions pathways (Supplementary Fig. 5; for effects on SCC schedules see Supplementary Fig. 3). As one would expect, adopting less benign emissions scenarios – such that credit reversals are imposed on a warmer world – reduces the estimated Equivalent Permanence and hence increases the costs of a Permanent Additional Carbon Tonne of each project. This finding underscores the inescapable importance, beyond offsetting, of dramatically reducing greenhouse gas emissions if net-zero targets are to be met.



**Supplementary Fig. 4 |** The sensitivity of A, Equivalent Permanence (EP) and B, the resulting price of a Permanent Additional Carbon Tonne, to whether the SCC growth schedule assumes total damages are quadratic or cubic with respect to temperature (see also Supplementary Table 2).

A crucial claim in the main text, which in turn means EP is always positive, is that the rate of increase of $SCC_t^{CV}$ is less than the discount rate δ. It can be shown that this is always true where carbon emissions cause additional damages. This can be seen by taking the time derivative of $SCC_t^{PV}$, defined as the present value of $SCC_t^{CV}$. The SCC is typically defined in present value terms as follows:

$$SCC_t^{PV} = e^{-\delta\tau} SCC_t^{CV} \overset{\text{def}}{=} \int_t^{\infty} e^{-\delta\tau} MargDamage_\tau d\tau$$



**Supplementary Fig. 5 |** The sensitivity of A, Equivalent Permanence (EP) and B, the price of a Permanent Additional Carbon Tonne to changes in the assumed emissions pathway, for each of the three examples shown in Fig. 3.

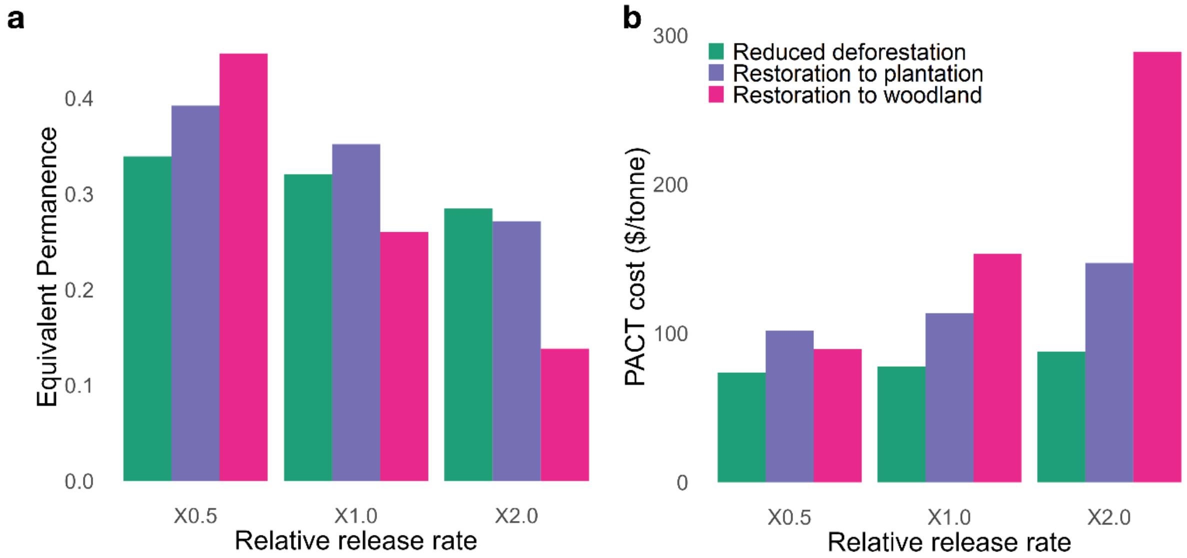
where $MargDamage_\tau$ is the marginal damage arising from a unit of emission at time $\tau$. Therefore, the derivative of $SCC_t^{PV}$ with respect to the evaluation date *t* is given by:

$$\frac{d}{dt}SCC_t^{PV} = -e^{-\delta\tau}MargDamage_t$$

which is negative if marginal damages are positive. If the present value were to remain constant over time, this derivative would be zero and $SCC_t^{CV}$ would be increasing at the rate of discount δ. The negative value reflects the fact that $SCC_t^{PV}$ is decreasing over time and $SCC_t^{CV}$ is increasing at a rate lower than the discount rate δ.

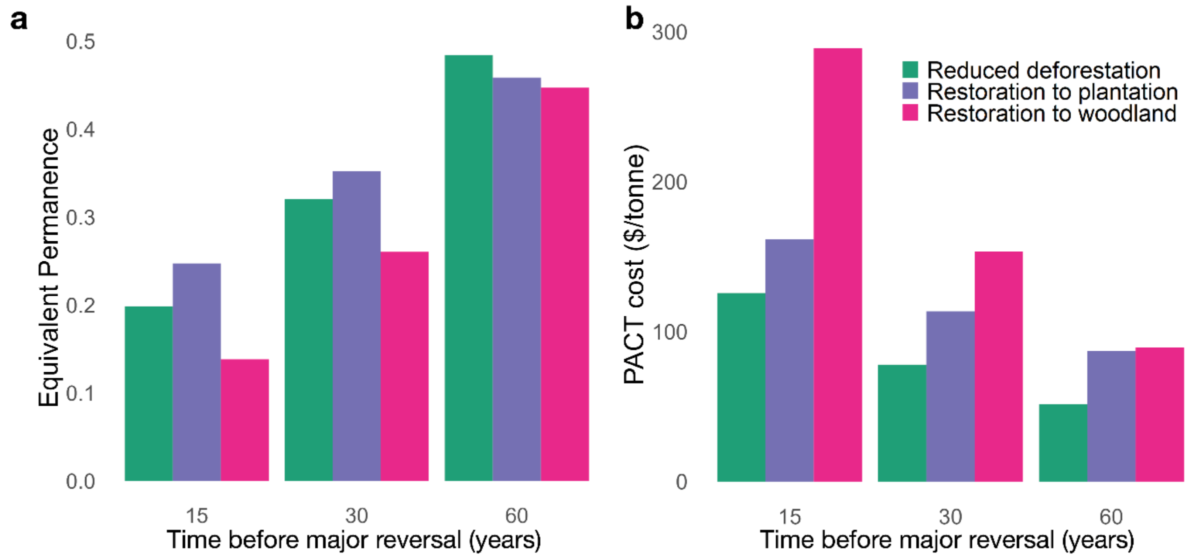
## RELEASE RATE

In this sensitivity analysis we examine the effects of halving or doubling the rates at which already-credited carbon is anticipated to be released, prior to the anticipated major reversal – the deforestation rates during the project in our reduced-deforestation example; the loss of stored carbon to disease in our plantation example; and in the woodland restoration example, the assumed annual probability of catastrophic fire. As expected, less conservative schedules (involving lower rates of reversal) increase EP values and reduce PACT costs, and vice versa (Supplementary Fig. 6). Note that all else being equal, more conservative schedules would result in a greater uplift to future credit issuances and hence an increase in EP values as projects progress (see main text).



**Supplementary Fig. 6 |** The sensitivity to anticipated release rate (as a multiple of the rate assumed in Fig. S2) of A, Equivalent Permanence (EP) and B, the resulting price of a Permanent Additional Carbon Tonne, for each of the three examples shown in Fig. 3. Note that because our hypothetical release schedules differ across the examples, their relative permanence (compared to one another) varies with the release rate chosen.

## TIME BEFORE MAJOR REVERSAL

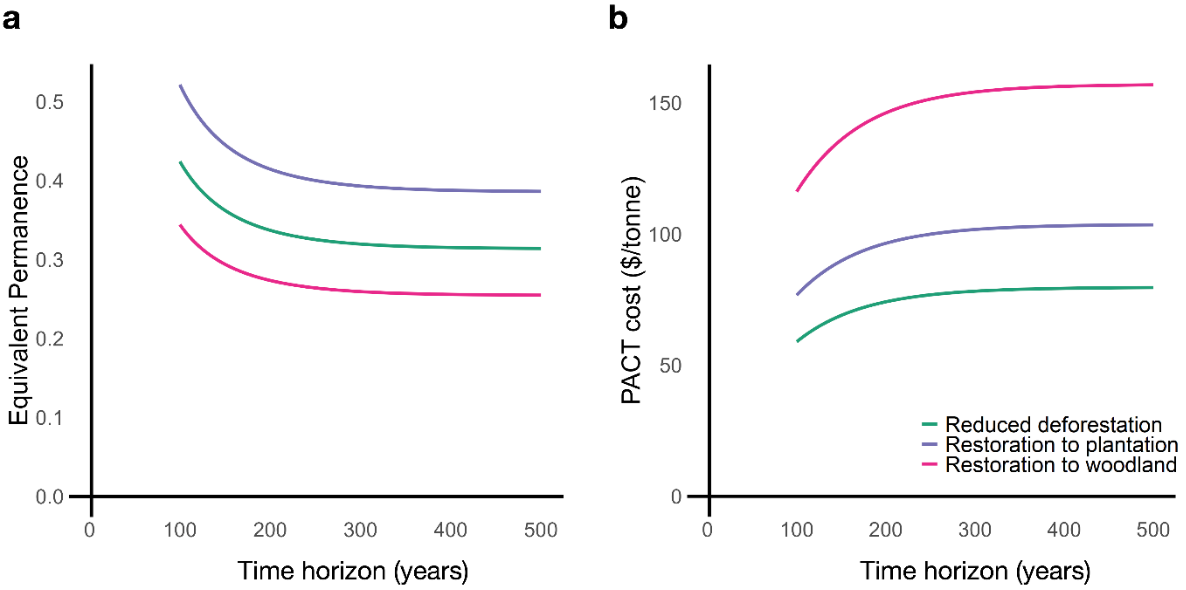


**Supplementary Fig. 7 |** The sensitivity to the anticipated time before major reversal occurs of A, Equivalent Permanence (EP) and B, the resulting price of a Permanent Additional Carbon Tonne, for each of the three examples shown in Fig. 3. Note that because our hypothetical release schedules differ across the examples, their relative permanence (compared to one another) varies with the time before major release takes place.

As well as changing the release schedule by altering the rate of post-credit carbon release, we investigate the effects on EP and PACT price of altering the anticipated time from the issuance of a credit until a major reversal – the acceleration of deforestation in our deforestation-reduction example, the timber harvest in the plantation case, and the anticipated probability of catastrophic fire in the woodland case (Supplementary Fig. 7). The effects on both outcome variables are broadly similar to those of changing assumed rates of carbon release.

## TIME HORIZON

In our final sensitivity analysis we examine the effects of truncating the time horizon (in years from the present) within which marginal damages contributing to the SCC are considered. In all other analyses we use a time horizon of 1500 years. As expected, shorter time horizons, particularly those less than 200 years, increase EP and reduce PACT costs, and vice versa (Supplementary Fig. 8). Short time horizons act to truncate the long-run damages associated with an emission and lead to an overvaluation of impermanent carbon credits.



**Supplementary Fig. 8 |** The sensitivity to the time horizon over which the SCC is evaluated on A, Equivalent Permanence (EP) and B, the resulting price of a Permanent Additional Carbon Tonne for each of the three examples shown in Fig. 3.

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