Title: The value of impermanent carbon credits

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Abstract: A new framework linking economics with remote-sensing means impermanent carbon reduction can be directly compared with permanent drawdown.

One-Sentence Summary: A new framework linking economics with remote-sensing means impermanent carbon reduction can be directly compared with permanent drawdown.

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*). Alongside this there is an urgent need for scaling-up nature-based solutions (NBS), such as cutting deforestation or restoring forests or wetlands (*2-4*). 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. Natural climate solutions are also critically important for slowing deforestation and averting the extinction crisis, and can also benefit rural communities. Yet growth in investment in robust NBS-derived offsets is insufficient to meet the financing needs of project developers (*5*).

Impermanence as a problem

We believe this is in large measure because many would-be buyers are not convinced by current assessments of the additionality and permanence of NBS offsets, and struggle to make like-for-like comparisons of diverse offsetting products (*6*). Nature-derived credits consequently attract discouragingly low prices. There have been significant advances in quantifying the additionality of NBS projects by estimating how far observed outcomes would have happened in their absence using experimental or statistical counterfactuals (*7-8*). On the other hand offset impermanence – the release of carbon to the atmosphere through fires, drought, etc. (*9*) after a credit has been issued - presents a significantly greater challenge.

As evidenced by the low price of NBS compared with non-NBS offsets, existing approaches to quantifying and addressing such reversals are problematic, in several ways. Current techniques (*10-12)* variously deal with only very short-term releases, are not easily integrated with assessment of counterfactual outcomes, neglect advances in understanding the costs of emissions, or are not readily applied across project types (for discussion, see SM). The most widely used approach allocates a fraction of the additional carbon generated by a project to a not-for-sale buffer pool to be drawn from in the event of reversal. But this procedure is intrinsically flawed because after the project ends both monitoring and access to the buffer pool cease – so all credits issued are effectively assumed to be permanent after that point. This in turn places an unequitable expectation on future stakeholders to not allow releases from past credits in excess of the buffer pool. To address these substantial limitations we have developed a framework for characterising NBS projects which combines cutting-edge econometric and remote-sensing methods for quantifying additionality with an economically robust approach to impermanence, and a transparent, self-correcting protocol for addressing the uncertainty of predicting post-credit reversals.

Our proposal – Permanent Additional Carbon Tonnes

Most of us would value even one extra year of life. Likewise although all carbon drawdown or emissions reduction achieved through NBS should be viewed as impermanent, it nonetheless has value (*10,11*). The most robust economic device for conceptualising that value is the Social Cost of Carbon (SCC) - 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 (*13*). 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 cost of the damage caused by the subsequent release of that carbon, which can be estimated from the SCC at the time of the release. In present-day 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, δ (for proof see SM). 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 (or EP) of the offset. In combination with corrections for additionality and leakage, EP can then be used to inform prospective offset buyers how many impermanent credits constitute what we call a Permanent Additional Carbon Tonne (or PACT), with the same present-value climate benefit as a fully additional, permanent credit.

The figure summarises how this approach can be operationalised (for detail see SM). Imagine a simplified, 20-year deforestation-reduction scheme (top left; 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 been additional. A corresponding carbon credit is issued, with an EP estimated by linking the Social Cost of Carbon to an *ex ante* schedule (bottom left) which conservatively assumes the credited carbon is subsequently released to the atmosphere at half the observed counterfactual rate over the remainder of the project, rising to the counterfactual rate thereafter.

Continued *ex post* monitoring 10 years later allows correction for the inevitable uncertainty in predicting credit reversals (top right). In our example the project has continued to cut deforestation and (because of the deliberately conservative release schedule) lost less previously-credited carbon than expected. The release that has occurred lowers project additionality over this second interval, but its social costs have already been accounted for in the EP calculation for the first credit. So that the project is not penalised twice for this release, and to compensate for anticipated releases that did not happen, this second decade's credit is calculated as the sum of its observed additionality plus the release of the previous credit that was predicted for this interval. This new credit is assigned a lower EP (bottom right), as the project is now ending, so reversals might reasonably be expected to accelerate.

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 performance increases the size and EP value of future credit issuances (see SM). If however already-credited carbon is released more rapidly than expected, this 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; Fig. S1). But adopting deliberately conservative release schedules means 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 equity concerns about dealing with impermanence.

Broad applicability

Buyers clearly need to make direct comparisons across a diverse array of NBS and other offset classes. The PACT framework enables this by explicitly and transparently capturing differences in the performance of projects and in the durability of the net drawdowns they generate. To illustrate the scheme's flexibility, consider three archetypal NBS projects, set out as above, but lasting for 40 year and with more plausible yet still purposely pessimistic schedules of credit accumulation and reversal (see Fig. S2). The first again involves reduced deforestation and assumes previously credited carbon is lost at one-tenth the counterfactual rate until the project ends, and at the counterfactual rate after that. The second involves reforestation, with credited carbon released from a fast-growing plantation when it is harvested for timber. The final example describes a restored native woodland that is damaged by a major fire.

Given these carbon fluxes, a mid-range discount rate of 3%/year and an SCC growth schedule derived from an analysis embedded in an Integrated Assessment Model, Equivalent Permanence values for these projects' first round of credits, if issued *ex post* today, would range from 0.20 to 0.40. Combining these EP estimates with headline prices for similar NBS offsets, adjusted for additionality and leakage, in turn suggests that PACTs derived from such schemes might typically cost in the order of $80-160. Importantly, 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 (which reportedly average $140/ tonne CO_2e [*6*], but vary widely, with some currently selling at ~$1000/tonne CO_2e [https://climeworks.com/subscriptions]). Note that this conclusion is reasonably robust to plausible changes in discount rate, SCC schedule, release schedule and time horizon (see SM sensitivity tests). Hence despite the impermanence of their effects, nature-based interventions, which of course can provide important biodiversity and rural livelihood benefits as well, appear at present likely to 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 potential that the PACT framing offers for transparently addressing significant concerns about credit reversals into assessments of NBS (and other impermanent interventions), allowing low-risk portfolios of comparable offset products to be assembled. We think our scheme has the potential to facilitate project comparability, promote buyer confidence and hence boost sales of NBS offsets to existing and new customers. Such increased demand should encourage many 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 should also enhance project additionality, reduce risks of leakage of forgone production and hence emissions elsewhere, and improve local livelihoods. Last, our proposal for continued monitoring and *ex post* repayment for lower-than-anticipated releases should help incentivise project stakeholders to continue to safeguard already-credited carbon into the future.

The emerging 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 socio-economic drivers change, understanding of climate feedbacks improves, 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 (*14*). Methods for estimating permanence will need updating as understanding of release schedules improves and as threats to emissions drawdowns change (*9*). 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 (*15*). The dynamic accounting central to our 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 (4). Moreover, while NBS schemes may be more vulnerable to impermanence than some other offset classes, they can and do mitigate 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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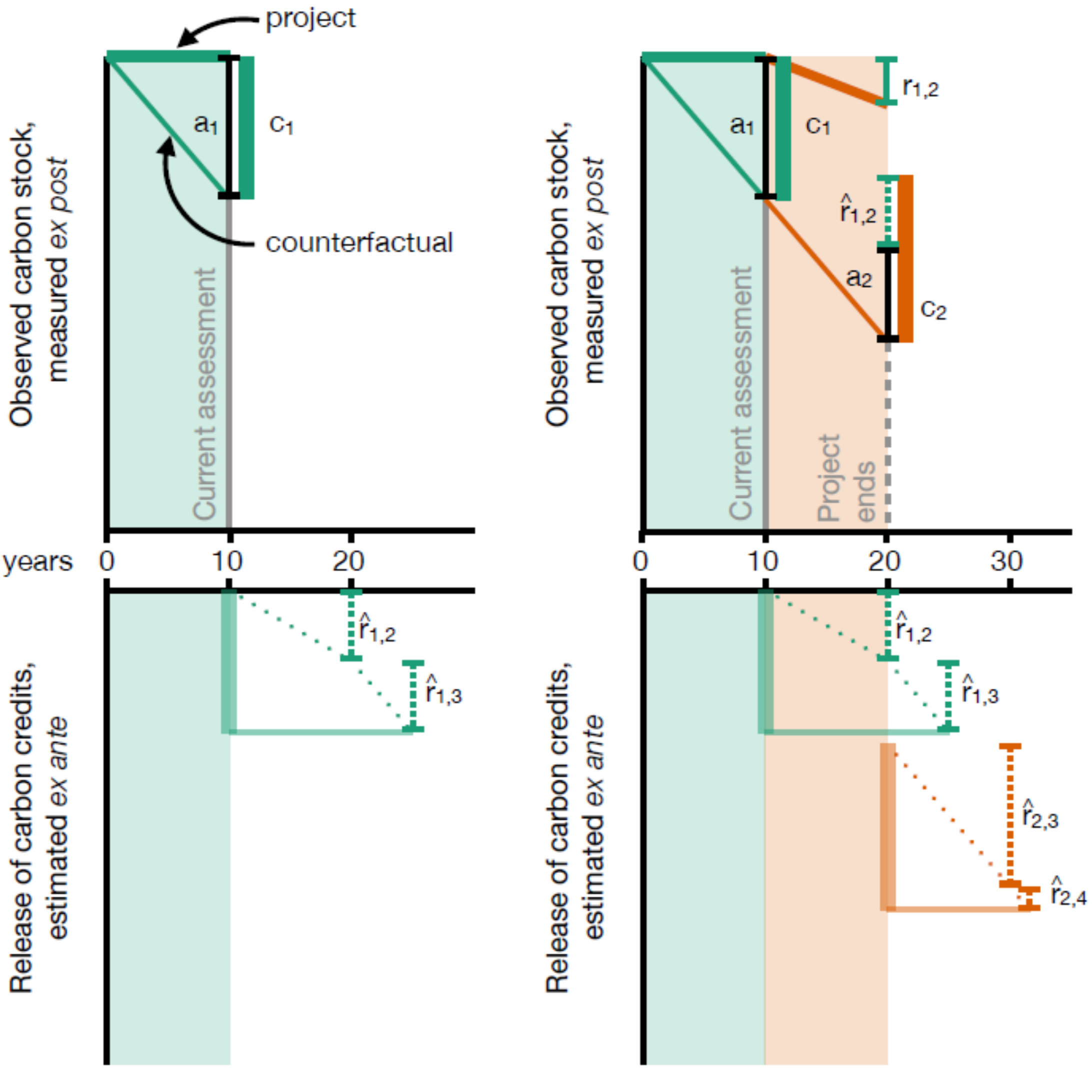
Supplementary Materials
Limitations to current approaches to addressing offset impermanence
An operational framework for valuing impermanent offsets
Application of PACT framework to diverse NBS interventions
Sensitivity analyses
Tables S1 to S2
Figs. S1 to S8

References (*16-26*)



Left panel, top: Summary of how PACT works, for a stylised 20-year reduced-deforestation project (see also Fig. S1). Over its first decade (green) it reduces deforestation to zero. Additionality (a_1) is estimated *ex post* as the difference in change over the interval in the carbon stock of project and counterfactual sites (thick and thin lines, respectively). Credit c_1 is issued. *Bottom:* 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), then at the counterfactual rate once project ceases (releasing $\hat{r}_{1,3}$ over decade 3); all of c_1 is anticipated to be released. This release schedule is used to derive an EP value for c_1. *Right panel, top:* Over decade 2 (orange) the project continues to perform well relative to the counterfactual. Some of c_1 ($r_{1,2}$) is actually released, so project additionality over the interval (again, calculated as the difference between the project and counterfactual in how their carbon stock changes) is reduced (a_2 is < a_1). Credit issued (c_2) is the sum of this new additionality a_2 and the release of c_1 that was anticipated over the interval ($\hat{r}_{1,2}$). Note that if the actual release of the first credit ($r_{1,2}$) is smaller, a_2 and hence c_2 are greater, and vice versa. *Bottom:* c_2 is conservatively estimated *ex ante* to be released at the counterfactual rate, as project activities now cease. Again all of c_2 is released, with the costs of the release accounted for via the EP value for credit c_2, calculated based on this schedule.

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Limitations to current approaches to addressing offset impermanence

The central premise of the PACT framework is that even impermanent carbon gains benefit society and that robustly estimating the future value of gains achieved now is key to incentivising nature-based interventions. This point is not new (*11, 12, 16*), but we believe it bears repetition. We contend, however, that existing approaches to quantifying and addressing project impermanence are flawed in several important ways, which undermines confidence in NBS and other impermanent solutions.

The *tonne-year approach* uses a model of the biophysical dissipation of CO_2 from the atmosphere (*11*), linked in some iterations with discounting (e.g. *17*), 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. 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, and so cannot capture the consequences of gradual, long-run releases likely to arise from avoided deforestation or reforestation.

The *sequestration-effectiveness approach* (*10*) estimates the economic cost of long-run releases of a credit and uses that to calculate 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 (*10*). We instead show 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 (see SM Sensitivity Tests below). 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 counterfactual analysis of what might have happened in the absence of a project.

To our knowledge neither of these conceptual framings has been widely operationalised beyond considerations of short-term delays in timber harvesting. Instead certifiers have adopted a third 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 (*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 adverse weather. The impact of that future release needs to be accounted for whenever a credit is issued from an NBS scheme. An additional 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, the PACT system is, we suggest, better grounded in climate science and the economics of climate damages; is closely 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 very largely addresses the 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 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 sequestration. 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 Table S1.

Table S1. 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 sequestration in 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 τ
$D(\tau, T(\tau))$	Damage due to a tonne of carbon being released into the atmosphere during period τ with a background temperature *T* [*13*]
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
δ	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*) (for worked example see [*18*]). 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 adverse weather events. (Note that steady-state turnover of carbon through respiration and photosynthesis 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 sequestration of one tonne of carbon is the same as the Social Cost of Carbon (SCC) (see main text) [*13,19,20*]. 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 $T(\tau)$ [*15*]. 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:

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

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

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

Equation 4 sums the SCC from each year's release, discounted to interval t, when this computation is carried out. Equation 5 substitutes Equation 3 into Equation 4, and Equation 6 simplifies the expression.

The net benefit from the impermanent sequestration 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 δ. 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 (*21*). 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 (*22-24*). 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 sequestration. The smallest value of EP is 0, when the sequestration in year 0 is also released in year 0 (i.e., no sequestration 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 sequestration 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) sequestration. This bundle of 5 impermanent credits would then be equivalent to a single PACT.

Observation 3: 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 at shorter assessment intervals.

Observation 4: 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 sequestration 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 market evidence 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 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. 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. Providing the anticipated release rate of these credits (in tonnes/year) is unchanged, larger credit issuances will of course 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 (Fig. S1A,B). In cases of extreme underperformance this may not be true, and credits will thus be negative (Fig. S1C). 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.

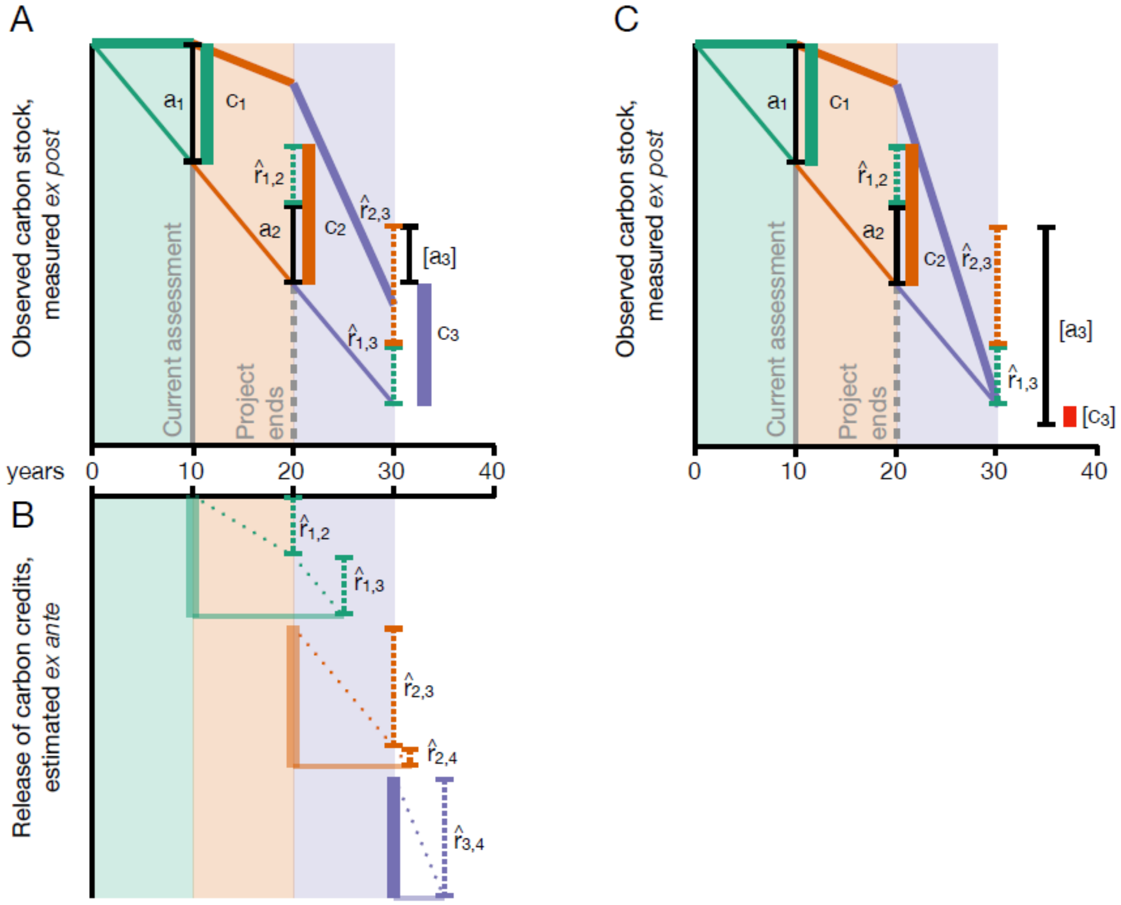

Fig. S1 A, In the decade (blue) following the end of the simplified deforestation-reduction project portrayed in our main figure, monitoring of project and counterfactual sites continues. A combination of the release of some previously credited carbon c_1 and c_2 and an increase in deforestation means 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 (indicated by square brackets). But even more carbon was anticipated to be released from c_1 and c_2 over this interval, so the sum of this negative additionality and the anticipated release of c_1 and c_2 over the interval $(\hat{r}_{1,3} + \hat{r}_{2,3})$ is positive. Hence a credit c_3 is issued. 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 the carbon loss in the project site (thick line) is much faster than in the counterfactual (thin line). Additionality a_3 is now strongly negative, and exceeds the amount of carbon anticipated to be released from c_1 and c_2 over this interval $(\hat{r}_{1,3} + \hat{r}_{2,3})$. The net negative change in carbon stock (a_3, note square brackets) could be compensated for by a withdrawal from a portfolio-wide insurance pool of carbon credits, even though the project has ended.

Application of PACT framework to diverse NBS interventions

In this section we demonstrate the flexibility of the PACT approach by illustrating its application to three very different types of NBS project - a deforestation-reduction scheme, the creation of a fast-growing plantation to be cut after 40 years, and the restoration of native woodland in a fire-prone biome (Fig. S2). Although we suggest the PACT framework would best be deployed over short, iterated assessment intervals (under 5 years), for graphical clarity we focus here on a single assessment made a decade into each project.

Each release schedule describes the complete release of all credited carbon, and is used to derive an EP value for the first round of credits, assuming they are issued in 2021, a discount rate of 3%/year and a representative IAM-coupled SCC growth schedule (*25*). We also suggest plausible headline prices for impermanent credits of this type, adjusted for additionality and leakage, and then combine these with our EP figures to estimate the resulting cost of a Permanent Additional Carbon Tonne for each hypothetical project. Note that existing Project Design Documents may commonly give unreliable estimates of project additionality and/or leakage (*8*), so that adjusting the headline prices of offsets may often be necessary in estimating the cost of a PACT.

In each of our cartoon examples NBS-derived PACTs appear competitively priced compared with wholly additional, completely permanent geological offsets – a conclusion which is relatively insensitive to plausible changes in discount rate, SCC schedule, release schedule and time horizon (see below). Note that if *ex ante* release schedules are revealed *ex post* to have overestimated release rates, subsequent issuances would probably carry higher EP values, so PACT prices would fall.

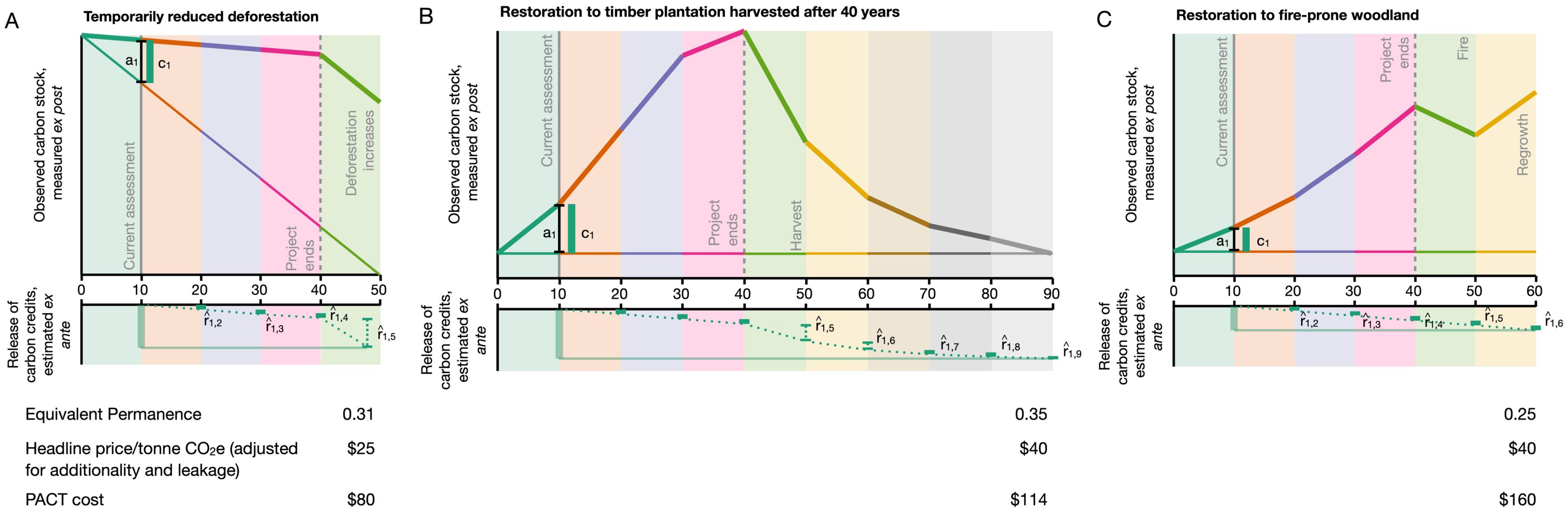

Fig. S2 Application of the PACT framework to three archetypal 40-year NBS projects. *Upper plots*: carbon stock in the project and counterfactual sites (thick and thin lines respectively). *Lower plots*: release schedules for credited carbon for the current credit c_1, issued 10 years into the project. *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 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 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.

Sensitivity analyses

The EP and PACT values presented above and in our main text are for imaginary 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. In the main text we focus on a discount rate of 3%/year, which approximates the findings of a recent expert survey [*26*]. 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 (Fig. S3). 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 (*6*; https://climeworks.com/subscriptions).

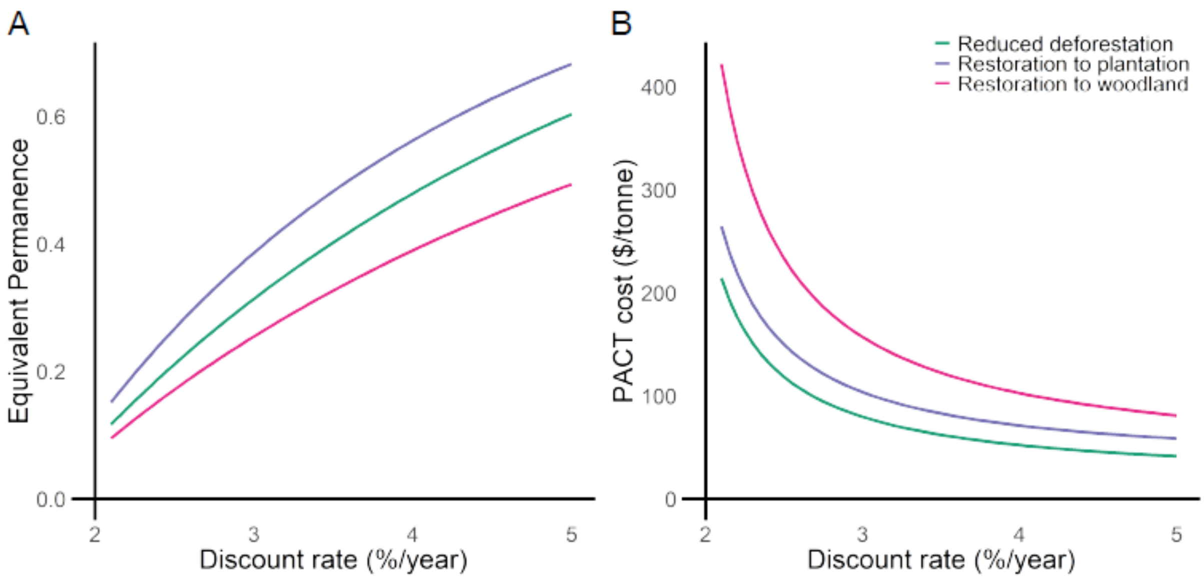

Fig. S3. The sensitivity to discount rate (%/year) of A, Equivalent Permanence (EP) and B, the resulting price of a Permanent Additional Carbon Tonne, for each of our three examples.

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. Based on these assumptions we obtain the growth rates for SCC_t^{CV} shown in Table S2.

Table S2. 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)	2021	2025	2030	2035	2040	2045
Quadratic total damages	2.2%	2.0%	2.0%	1.9%	1.9%	1.9%
Cubic total damages	2.3%	2.2%	2.1%	2.0%	1.9%	1.9%

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 (Table S2), and using this alternative schedule for SCC_t^{CV} has very little effect on our EP and PACT estimates for our three projects (Fig. S4).

As a second sensitivity test we examine the effects of assuming different emissions pathways (Fig. S5). 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.

A crucial claim in the main text, which the calculation of EP relies on, 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}, the present value of SCC_t^{CV}. The SCC is typically defined in present value terms as follows:

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

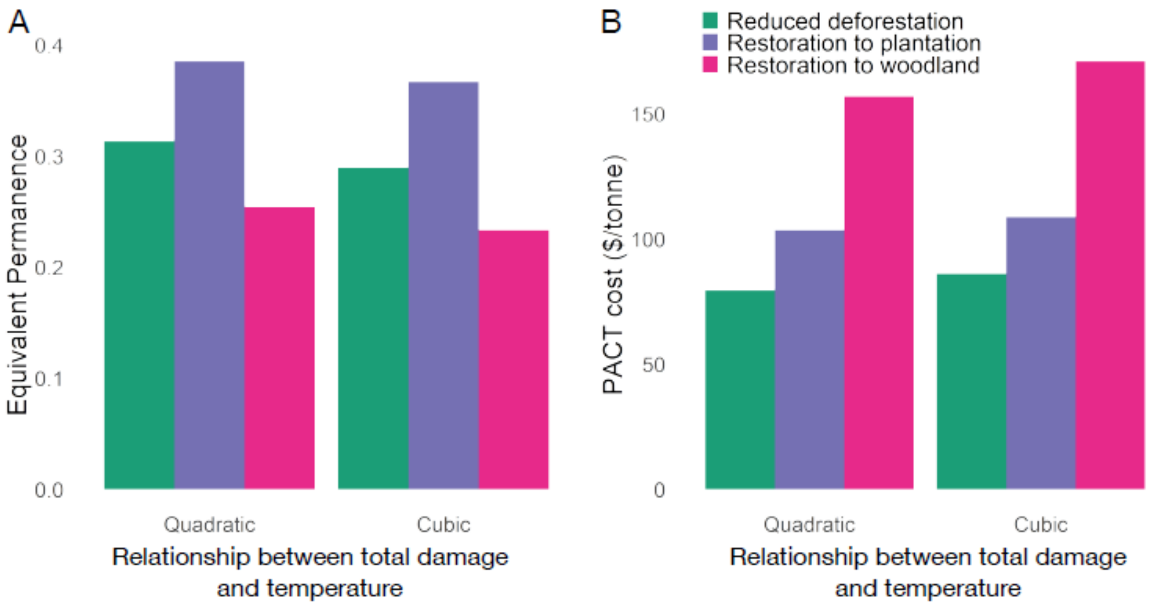

Fig. S4. The sensitivity of A, Equivalent Permanence (EP) and B, the resulting price of a Permanent Additional Carbon Tonne, to whether the SCC growth schedule assumes total damages are quadratic or cubic with respect to temperature (see also Table S2).

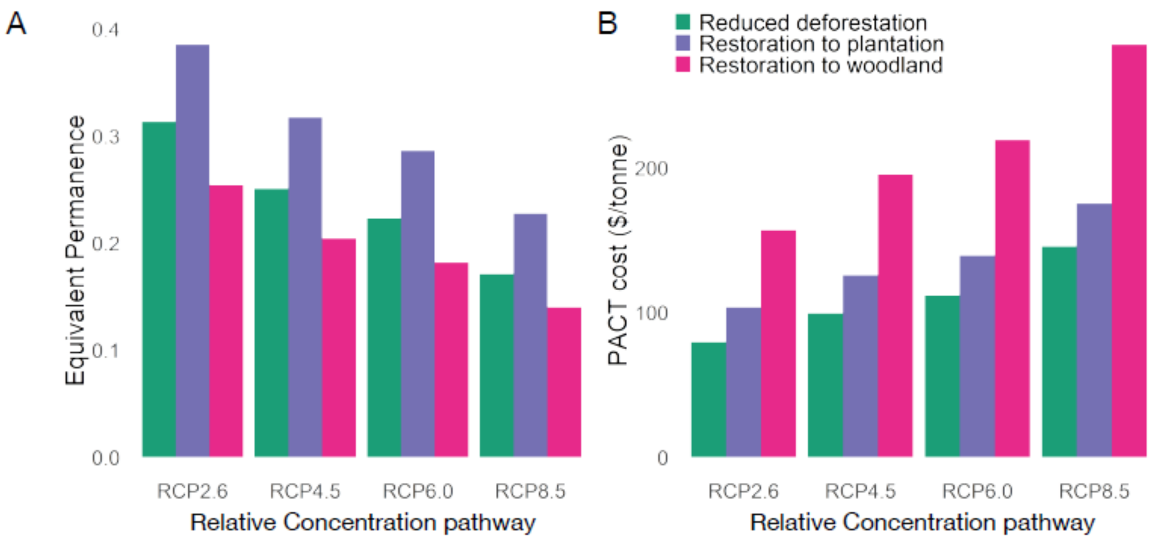

Fig. S5. The sensitivity of A, Equivalent Permanence (EP) and B, the price of a Permanent Additional Carbon Tonne to changes in the assumed emissions pathway, for each of our three examples.

where $MargDamage_\tau$ is the marginal damage arising from a unit of emission at time τ. 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 (Fig. S6). 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 and reduction in PACT prices as projects progress (see main text).

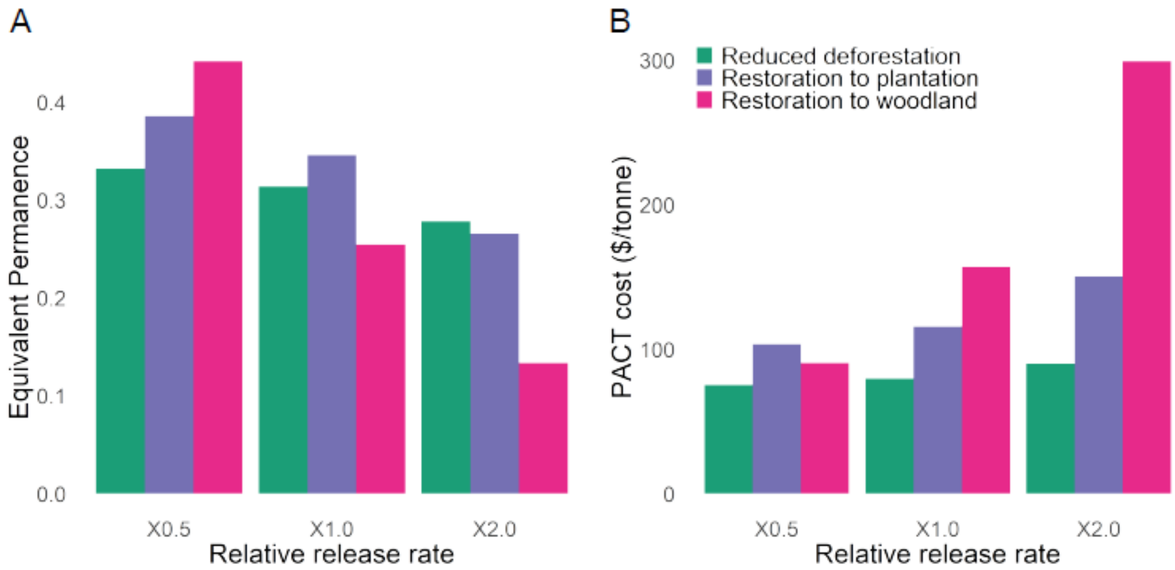

Fig. S6. The sensitivity to anticipated release rate (as a multiple of the rate assumed in Fig. S2) of A, Equivalent Permanence (EP) and B, the resulting price of a Permanent Additional Carbon Tonne, for each of our hypothetical NBS examples.

TIME BEFORE MAJOR REVERSAL

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 (Fig. S7). The effects on both outcome variables are broadly similar to those of changing assumed rates of carbon release.

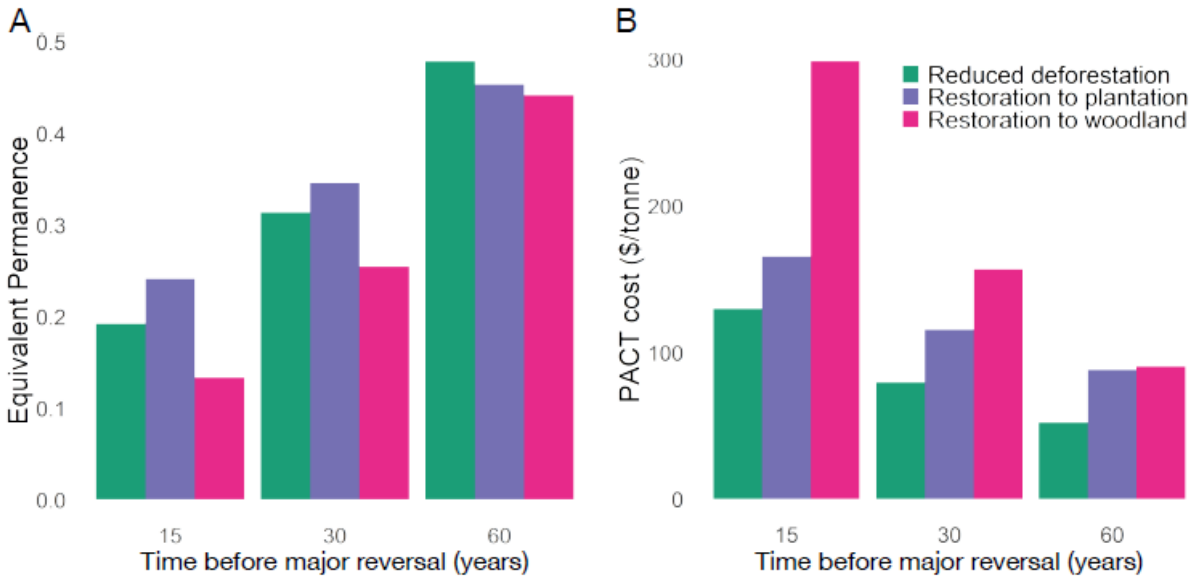

Fig. S7. The sensitivity to the anticipated time before major reversal occurs of A, Equivalent Permanence (EP) and B, the resulting price of a Permanent Additional Carbon Tonne, for each of our three hypothetical NBS examples.

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 (Fig. S8). Short time horizons act to truncate the long-run damages associated with an emission and lead to an overvaluation of impermanent carbon credits.

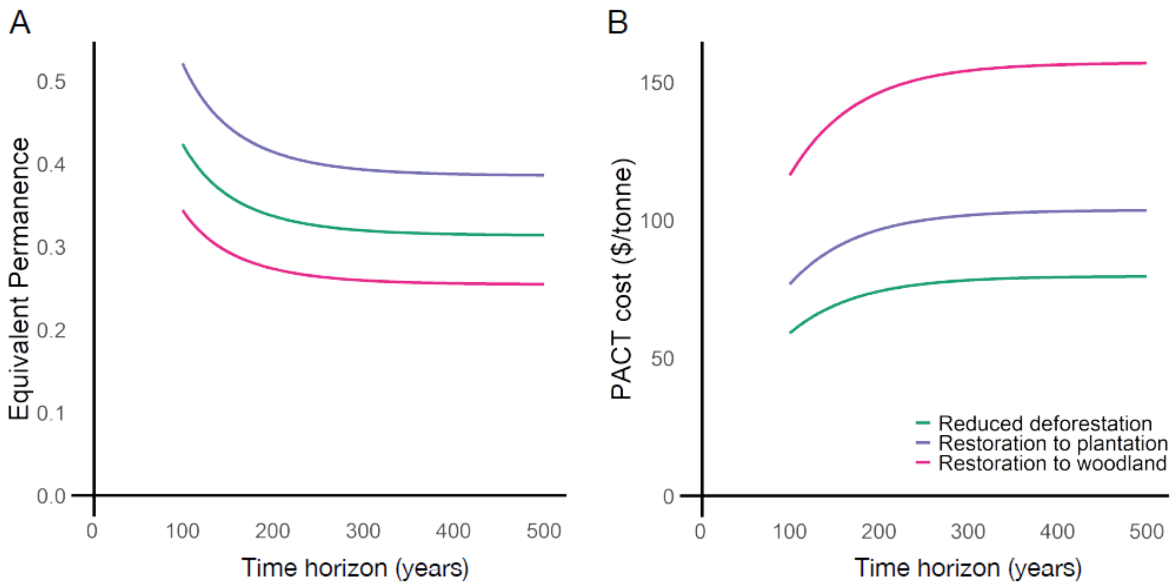

Fig. S8. The sensitivity to the time horizon over which the SCC is evaluated on A, Equivalent Permanence (EP) and B, the resulting price of a Permanent Additional Carbon Tonne of our three hypothetical NBS examples.