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Realizing 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 concerns over the credibility of methods used to quantify their long-term impacts. Here we develop a flexible framework for estimating the net social benefit of impermanent nature-based interventions that integrates three substantial advances: (1) conceptualizing the permanence of a project's impact as its additionality over time; (2) risk-averse estimation of the social cost of future reversals of carbon gains; and (3) post-credit monitoring to correct 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 analyses suggest nature-derived credits may be competitively priced even after adjusting for impermanence.

Ambitious net-zero commitments made at and since the 26th United Nations Climate Change Conference of the Parties highlight the imperative of slashing GHG 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 recognized 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 become affordable. NBS are also critically important for averting the extinction crisis and can benefit rural communities[3,5].

Despite these factors, project developers cannot get the financing they need to develop initiatives because investors see NBS as being too risky[6]. We believe this is in large measure because many would-be buyers of credits are not convinced that NBS projects are additional (that is, deliver climate benefits that would not have arisen in their absence) or that credit issuances fully correct for impermanence. Consequently, purchasers struggle to make like-for-like comparisons of diverse offsetting products[7] and NBS credits attract discouragingly low prices.

To assess additionality, changes in carbon storage in a project are typically compared to historical trends in reference areas identified by the project proponents themselves[8]. However, researchers in other sectors such as public health and international development have found these 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

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are drawn from this pool[8]. However, we consider this procedure to be intrinsically flawed because it assumes that future stakeholders will not allow releases from past credits in excess of the pool yet provides them with no incentive to do so. Other approaches also have notable limitations. Tonne-year accounting[17,18], for instance, deals with only very short-term releases and does not correctly model climate change physics, assuming, for example, that the climate impact of one tonne of sequestration for five years is the same as that of five tonnes of sequestration for one year. Likewise, the sequestration-effectiveness approach[19] and equivalence trading ratios[20] are not easily integrated with considerations of additionality, have not been generalized for a diversity of project types, and—most importantly—do not allow for ex post corrections of ex ante forecasts of the release of credited carbon (for further discussion see the 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 (PACT) framework allows credits to be issued and sold at the end of each time period, based on ex post determination of additionality and ex ante forecasting of reversals, and comprises three interlinked advances:

(1) Understanding the permanence of a project's impacts as its additionality—relative to a statistically derived counterfactual—through time.
(2) Risk-averse forecasting of the expected social cost of the impermanence of carbon gains, so that purchasers can make like-for-like comparisons across diverse offset products while having confidence that NBS credits have been fully adjusted for impermanence.
(3) Using long-term monitoring for the ongoing correction of errors in deliberately pessimistic forecasts of post-credit releases, so that project providers can be compensated if forecasts are overly conservative.

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.

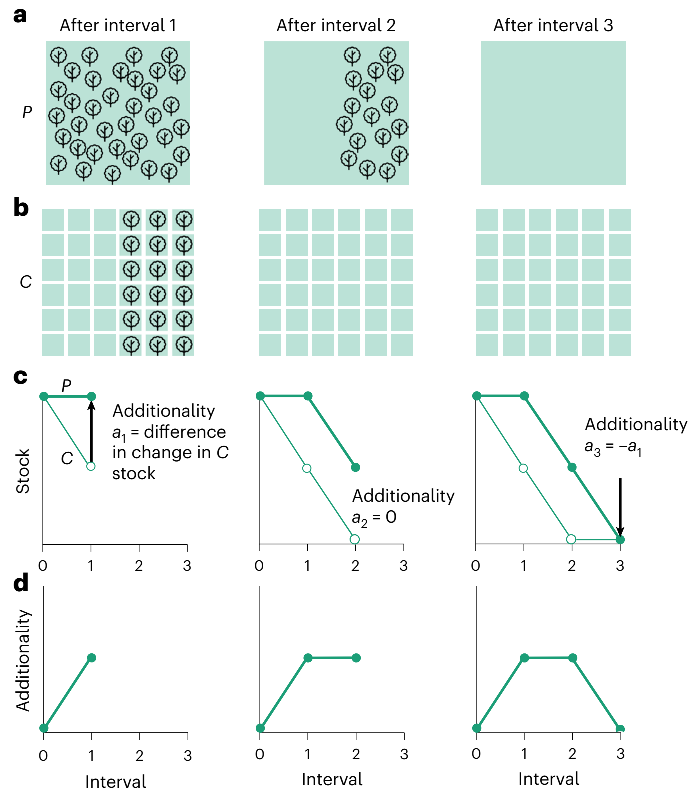

Fig. 1 | Permanence as additionality through time, illustrated for a stylized deforestation-reduction programme. a,**b**, The carbon stock in project area *P* (**a**) and in a counterfactual set of areas *C* (**b**) is assessed after three successive time intervals. **c**, The additionality *a* of the 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. **d**, 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.

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 additional carbon generated by a project, such as through the resumption of deforestation, a major disease outbreak or a change in the fire or climate regime. Impermanence is due to directional loss and can helpfully be conceptualized 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 not involved in the intervention but matched to the project site in terms of initial carbon stock, exposure to drivers of deforestation and variables (such as governance) that are 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; again, simply the difference in the change of the project and the counterfactual carbon stock) is $-a_1$. This is how much previously accrued additionality is lost—and means that in this example all additionality is released over this third interval. The relative permanence of any 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 GHG. 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 and consider temporary drawdowns as valuable[22]. To see this, imagine a health policy motivated by people's desire to live longer, and with a specific target of increasing the life expectancy of people born after 2050 to 100 years. Interventions that extend the life span of people alive today will not directly help to meet the target. But most of us alive now would benefit from even one extra year of life, so those

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interventions have social value. Our focus here is on the analogous social value of impermanent reductions in the damages incurred by climate change[17,19,20,22,23].

The economic device we use for characterizing that value is the social cost of carbon[24] (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. There are several well-known uncertainties associated with estimating the SCC[25] but we use it here as the best-known way of translating future global warming into present-day utility. If the release of one tonne of CO_2e has a value equal to the SCC, 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}) that 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[20]. This logic assumes that the project has a small effect on temperature compared to the magnitude of warming from the industrial revolution.

In today's terms, the damage cost from a release will always be less than the value of the initial drawdown because the rate of increase of the SCC is always less than the discount rate. Formal proof of this is provided in the Supplementary Information, but the intuition is as follows. An emission today results in a relatively constant and eternal small increase in temperature and an associated stream of marginal damages. The SCC is the sum of the discounted value of these marginal damages. An emission next year has an identical stream of marginal damages except that they are discounted by one year less (so the marginal damages have grown in value by the discount rate) and begin one year later (so do not include the cost of damages in the current year). Hence, while it might appear that the SCC increases by the discount rate, because the damages of the current year are now behind us and no longer included, the SCC in fact increases by less than the discount rate.

Building from the framework of the SCC, if a release schedule of additionality can be estimated, the damage cost (D_{tot}) from these releases 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 (that is 1/EP) can then be used as a multiplier to decide how many present-day impermanent credits need to be purchased to be comparable in welfare terms to geological sequestration.

These ideas can be summarized diagrammatically (Fig. 2, for the same stylized project as Fig. 1). In terms of changes in carbon stock (Fig. 2a), 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 (Fig. 2b), 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 EP 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}).

Setting out in greater depth how this approach can be operationalized, imagine a simplified, 20-year deforestation-reduction scheme (Fig. 3a; in practice release schedules would be described probabilistically and assessed over shorter time intervals; for a complementary mathematical account see the Supplementary Information). 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 (Fig. 3b). It is important that this does not overestimate the value of

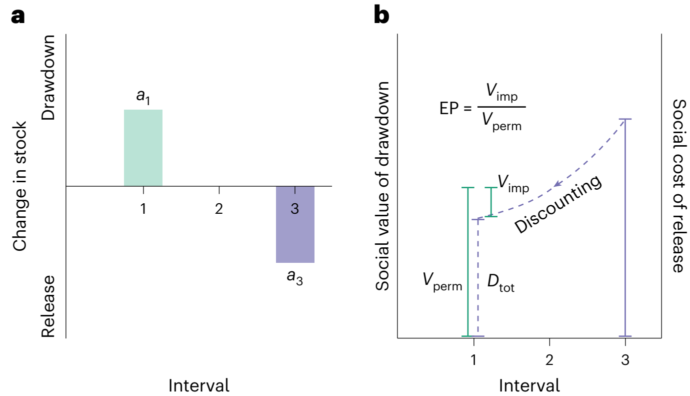

Fig. 2 | Derivation of EP for a stylized deforestation-reduction programme. **a**, Comparison of changes in carbon stock in the project and counterfactual areas shows the project depicted in Fig. 1 results in the net drawdown of carbon over interval 1 (a_1) and its complete release (a_3) over interval 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 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 the 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.

impermanent credits—so, for illustration, this particular schedule pessimistically forecasts that over its second decade the project will lose carbon stock 1.5 times as fast as the counterfactual sites. Because additionality is released at a rate equal to the difference in change in carbon stock in the project and counterfactual sites (demonstrated in Fig. 1), half of the additionality is forecast to be released over this second interval ($\hat{r}_{1,2}$, the additionality generated in period 1 which is estimated will be released in period 2; change in project stock − change in counterfactual stock = 1.5 − 1.0 = 0.5). During the third interval the project is no longer operational, so the pessimistic forecast is that the project area will now lose carbon twice as fast as the counterfactual sites. Hence the loss of additionality over this interval ($\hat{r}_{1,3}$) occurs twice as quickly as before and so, according to this pessimistic schedule, the first decade's additionality is dissipated entirely by year 25.

The ability to set realistic but conservative ex ante release schedules is central to the operation of the PACT framework. If they are too pessimistic, project providers will be deterred, but if they are too optimistic, purchasers will be deterred. In real-world applications, the forecasting of release schedules should be informed by empirical estimates of carbon fluxes over and beyond the lifetimes of comparable projects. Two further considerations are important at this point. First, the derivation of EP should in principle also include the value of the drawdown realized 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[26,27]. Combining any leakage correction with EP, one can then inform prospective offset buyers of how many impermanent credits constitute a PACT: 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 reversals.

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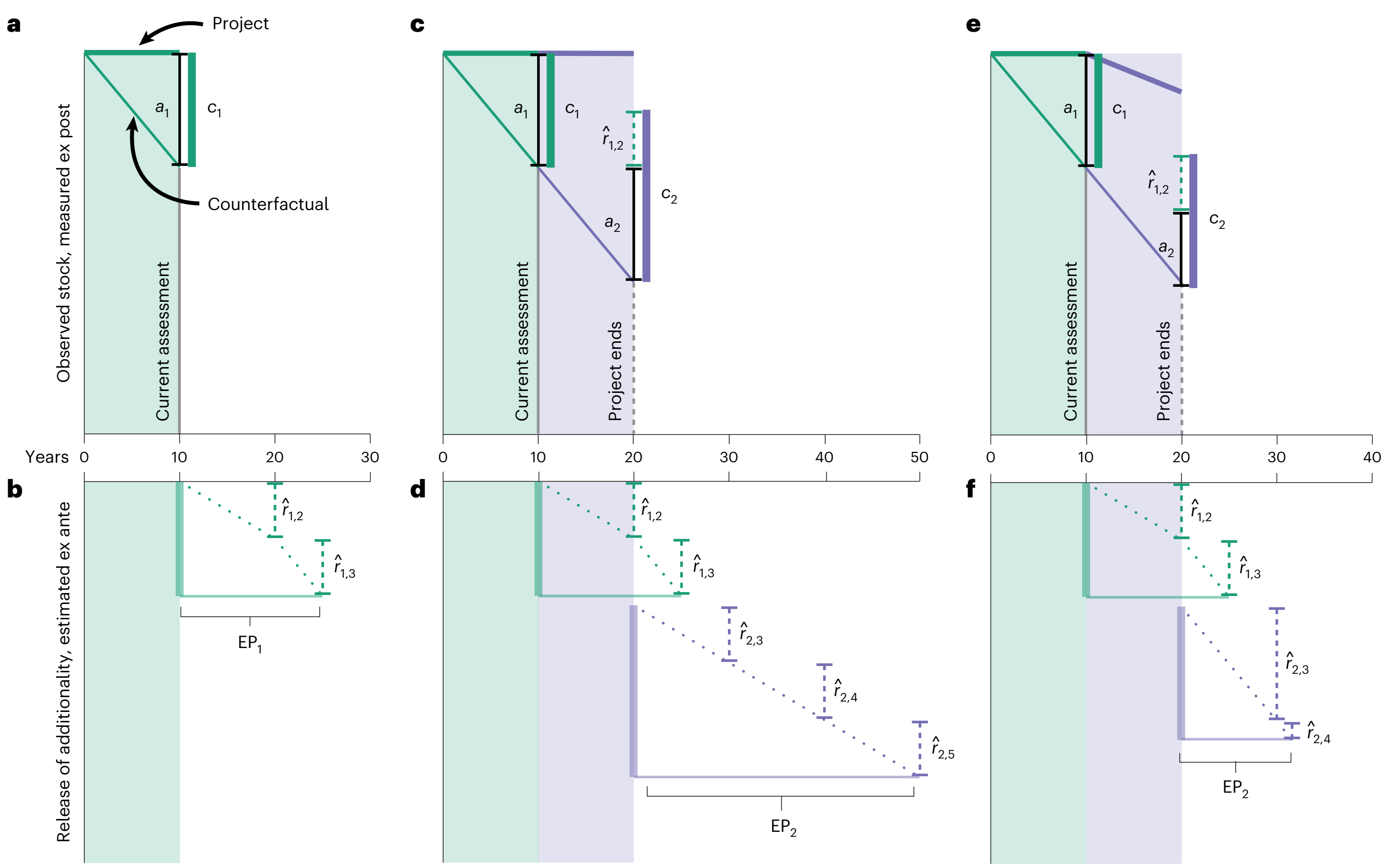

Fig. 3 | Forecasting a release schedule and correcting for forecasting errors for a stylized 20-year reduced deforestation project. a, Over its first decade (green), the project reduces deforestation to zero. Additionality a_1 is estimated ex post as the difference in change over this interval in the 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 text for explanation). All of c_1 is forecast to be released over these two decades. This anticipated release schedule is used to derive EP_1, the EP value for c_1, as outlined in Fig. 2. **c**, Over decade 2 (purple), the project performs better than conservatively forecast. 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 forecast 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 (that is, 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 forecast post-project rate of release schedule as **b**.

Returning to our example, suppose the project is reassessed ten years after the first credit issuance, as it draws to a close (Fig. 3c). Imagine that while deforestation in the counterfactual sites has continued, the project has done far better over its second decade 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 new credit issued for this interval, c_2, should also include an amount equal to the release previously expected to occur during this interval ($\hat{r}_{1,2}$), 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; Fig. 3d), 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 ten years.

An alternative and 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. 3e). 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; Fig. 3f), based on the same anticipated post-project release rate as that in Fig. 3b.

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 (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). However, 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

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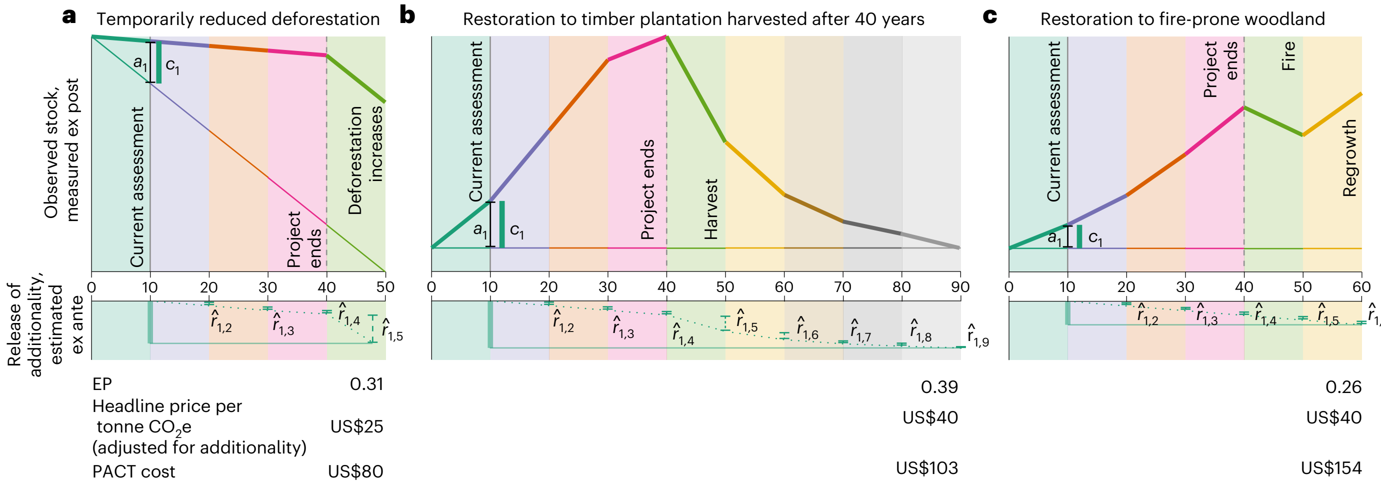

Fig. 4 | Application of the PACT framework to three archetypal 40-year NBS projects. a–c, The upper plots show carbon stock in the project and counterfactual sites (thick and thin lines, respectively) and the lower plots show release schedules for additionality of the current credit c_1, issued ten years into the project; note that steady-state turnover of carbon through respiration, photosynthesis and decomposition is not considered relevant. 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 PACT for each hypothetical project are given below the plots. The three scenarios show a hypothetical deforestation-reduction scheme that reduces deforestation to 10% of the counterfactual rate, where the release schedule anticipates that additionality of c_1 is also lost at 10% of the counterfactual rate, rising to 100% when the project ends (**a**); a hypothetical reforestation project involving a fast-growing plantation, cleared for timber (as scheduled) after 40 years, where anticipated release of the additionality of c_1 involves 1% loss of additionality 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 additionality in harvested timber each decade, starting ten years after harvest, with complete loss 40 years later (**b**); and a hypothetical woodland restoration project in a fire-prone biome which is severely impacted by a fire releasing 25% of its additional carbon stock in the decade after the project ends—a fire was predicted, however, with a conservative release schedule assuming a 2% chance of the additionality of c_1 being lost entirely each year (**c**).

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 diverse types of projects in a common currency that captures differences in the durability and hence social benefit of the net drawdowns they generate. To illustrate our scheme's flexibility, consider three archetypal NBS projects (Fig. 4), this time lasting for 40 years and with more plausible—yet still purposely pessimistic—schedules of additionality generation and reversal. To ensure timely corrections for post-credit performance, we suggest the PACT framework would best be deployed over short, iterated assessment intervals (under five years), but for graphical clarity we focus here on a single assessment made a decade into each project.

Estimating the EP values of the credits issued after this first assessment again requires developing conservative release schedules. The first project (Fig. 4a) involves reduced deforestation and, for illustration, a plausible but pessimistic release forecast that previously credited carbon is lost at 10% of the counterfactual rate until the project ends, and at the counterfactual rate after that. Our second project (Fig. 4b) is a fast-growing timber plantation. In this case the release schedule anticipates that 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 (Fig. 4c) 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% per year discount rate and an SCC schedule derived from an analysis embedded in a representative integrated assessment model[28] (Supplementary Fig. 3). Under these assumptions, EP 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 probable overestimation of additionality and underestimation of leakage[11–13,27], in turn suggests that PACTs derived from our archetypal projects would cost in the order of US\$80–160 (Fig. 4).

Significantly, while these calculations indicate 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[7] US\$140 per tCO_2e, but vary widely, with some currently selling at around US\$1,000 per tCO_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% per year; see the sensitivity tests in the Supplementary Information 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 some well-known 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 real concerns about credit reversals into assessments of NBS (and indeed those of technology-based offsets at risk of reversal[29]). This facilitates project comparability and, by increasing accountability, 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 those buyers who are satisfied with low-integrity offsets. If demand for robust credits does grow, this should help lift the price paid for them, thereby encouraging 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 incentivize project providers to adopt actions likely to increase permanence—such as improving land tenure and reducing opportunity costs borne by local communities, for instance by boosting farm yields on already cleared land. If successful, these actions could generate additional benefits by enhancing project additionality, reducing risks of leakage of forgone production and hence emissions elsewhere[27], and improving local livelihoods. Moreover, by being explicitly geared towards frequent low-cost analysis of remotely derived data, the PACT framework offers the twin prospects of greater accountability for offset buyers and reduced transaction costs of project proponents, as well as aligning directly with calls for digital monitoring, reporting and verification in carbon markets[30]. 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, such monitoring—if linked, as we propose, with ex post repayment for lower-than-anticipated releases—incentivizes 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, socioeconomic 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[31]. Methods for estimating permanence will need updating as our ability to forecast release schedules improves and as threats to emissions drawdowns change[15]. 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[26,27]. 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 new generalizable 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.

Data availability

All data are available in the main text or the supplementary materials. For more information on PACT see www.cambridgepact.org.

Code availability

The code for producing carbon release schedules and calculating EP is available on request.

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Author contributions
All the authors conceived the initial idea. A.B., S.K., F.V., B.G. and T.S. developed the method. T.S. created the figures. A.B., S.K. and T.S. wrote the manuscript and all co-authors revised it.

Competing interests
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Additional information
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