Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways

Interactions and trade-offs between nature-based and engineered climate change solutions

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Executive Summary and policy relevant messages

In this deliverable, we first provide an in-depth review of the relative merits of geological versus nature-based negative emission techniques and practices, from the perspective of the private-sector-oriented voluntary carbon "offset" market. The extremely rapid growth of this market during the two years since NEGEM was funded calls for engagement by NEGEM researchers, and we aim to develop the main body of this deliverable into a resource for participants in voluntary carbon markets, in collaboration with other NEGEM partners, with a view to submitting it as a peer-reviewed publication.

In parallel with this work, we have developed our first specific proposal for "jointly incentivising the development of high-potential high-reliability negative emissions technologies (typically engineered solutions) as well as limited-potential low-cost measures (such as many typical nature-based climate solutions)", in the words of the deliverable. This proposal, termed a "Proset" (for Progressive Offset) is detailed in a publication in second-round review with the journal *Climatic Change* and included as an Appendix. This is a specific approach to joint incentivisation through the creation of a composite financial instrument, targeted at the voluntary carbon market. Alternative approaches will also be needed, particularly in compliance markets, that we aim to continue to develop with partners through the NEGEM project. An emerging policy recommendation is to highlight the benefits of a separate quantitative targets for high-reliability carbon dioxide storage, complementing the need for separate targets for both reductions and removals already acknowledged in European climate policy.

Key policy-relevant messages include:

- The widely-held view that "a tonne of CO_2 is a tonne of CO_2", and that the primary distinguishing features of different carbon removal options are costs and co-benefits, is incorrect. Not all carbon removals are equal from a climate perspective, and they are primarily distinguished by the characteristics of the CO_2 storage solution employed, not the removal technology.
- Despite their low cost and, if well designed, substantial co-benefits, there are a number of concerns with the widespread use of biological, ("nature-based") carbon removal to offset continued fossil fuel use, including:
    - Accounting challenges associate with the time trees take to grow.
    - Limited global capacity and above-ground footprint.
    - Limited potential for supporting the most ambitious climate goals: optimistic estimates of nature-based climate solution potential suggest they could shave 0.1°C off global temperatures by 2050 (more in the longer term), which is only a few years of fossil-fuel-driven warming at the current rate.
    - Feedbacks from global warming itself (increasing microbial respiration in warming soils; increasing wildfire risk, etc.) threaten the biosphere's role as a net sink.
    - High risk of physical and indirect carbon leakage.
    - Non-carbon impacts on climate.
    - Implications for international and intergenerational equity

  Hence despite their low cost, these considerations introduce a substantial reputational and financial risk for any company relying on biological carbon storage to offset continued use of fossil fuels.
- There is a clear need to design policy instruments that allow us to take advantage of the significant opportunities for nature-based climate solutions without undermining the case for investment in more permanent carbon storage solutions. The Proset is one such instrument, tailored to the voluntary carbon market and detailed in the Appendix, but further research and policy innovation in this space is needed.

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1 *Introduction and context: Balancing sources and sinks*

With the near-universal adoption of the Paris Agreement and the accelerated announcements of net zero emissions targets by institutions of all sizes, there is unprecedented clarity on the path forward to stop dangerous anthropogenic climate change. First, we now understand that "reaching and sustaining net-zero global anthropogenic CO_2 emissions would halt anthropogenic global warming on multi-decadal time scales"[1]. The Paris Agreement enshrines this goal of net zero global emissions, calling on the world to "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases"[2]. Second, we have clear evidence that our *cumulative* carbon emissions, regardless of the specific emission pathway up until net zero global emissions, are the single biggest determinant on peak warming[3], leading to the concept of a finite carbon budget compatible with stabilizing warming at a given level (1.5 or 2.0°C). Third and finally, we have four clear representative emissions pathways from the IPCC that are deemed compatible with holding peak warming below 1.5°C. While all four of these pathways achieve net zero global emissions by mid-century, three of these pathways rely heavily on the "net" in "net zero". That is, they forecast large volumes of emissions continuing beyond 2050 that are cancelled out with commensurate volumes of negative emissions[4].

In terms of "**sources**", a supermajority of anthropogenic emissions come from fossil fuels[5]. These products have been so critical to human society and development, so ubiquitous as a means of powering transport and energy production, that stopping climate change requires a concerted effort from everyone involved in their use, from producers and suppliers, to the consumers, investors, and governments whose decisions will drive cumulative emissions before net zero. This effort requires a combination of both reducing fossil fuel use, and eliminating the warming impacts of fossil fuels that continue to be used. Producing fossil fuels is, in essence, the act of moving carbon from safely stable state in the geosphere and into the linked atmosphere-ocean-terrestrial system. This is inherently unsustainable, as non-geosphere sinks have relatively limited capacity to absorb and store excess carbon. Any future and ongoing use of fossil fuels as energy vectors will require linking their production with the act of putting back an equivalent mass of carbon into stable sinks.

Available "**sinks**" include the oceans (warming is reducing the rate of CO_2 uptake and threatens to disrupt the circulation which facilitates continued absorption), terrestrial and aquatic ecosystems (under increasing pressure from development, pollution, and climate change), soils, as well as various geological sinks including underground formations, enhanced weathering pathways, and (re)mineralization. All sinks are finite, but geological reservoirs are vast and underdeveloped relative to other sink enhancements, likely constituting thousands of gigatons of theoretically exploitable storage reservoirs[6,7] which could accommodate decades to centuries worth of anthropogenic emissions if necessary.

A growing number of companies have announced ambitions to achieve net zero emissions across their activities and supply chains and, in many cases, some or all of the emissions associated with the use of their products. These latter emissions, generally referred to as **scope 3 emissions**, per the Greenhouse Gas Protocol[8], are often the most challenging to address, so firms are turning to active enhancement of carbon sinks or active carbon dioxide removal and storage to compensate for those emissions they cannot eliminate. This report addresses some of the challenges to be considered in relying on emissions-compensation, focusing on the physical perspective. There are many administrative issues in any such "offsetting" process, such as the potential for double-counting of carbon dioxide removals in national and corporate accounts, which will become particularly prevalent as more and more countries and companies adopt net zero goals, effectively competing for the same limited resource of greenhouse gas removals, but our focus here is on the physical differences between different carbon dioxide removal and storage options.

This deliverable reviews the need for joint incentivisation and proposes one specific mechanism, tailored to the needs of the rapidly-evolving voluntary carbon market.

2 Biological and geological storage in delivering Net Zero

2.1 What must carbon storage provide to credibly deliver progress towards Net Zero?

A firm can only defensibly claim to have achieved net zero emissions if the mass of carbon dioxide stored to balance carbon dioxide generated by the firm's activities, purchases and products remains stored and out of the atmosphere in perpetuity. Carbon stored might be intentionally or unintentionally re-released to the atmosphere either due to physical leakage (e.g. forest fire, well failure), or an increase in emissions elsewhere caused by the reduction or removal (e.g. an avoided deforestation project increases development pressure on neighboring unprotected forests, leading to their conversion into cropland). Both of these events constitute "leaks", but the latter is typically referred to as "carbon leakage". To avoid confusion, we will use the terms "**physical leakage**" and "**indirect carbon leakage**" to refer to these two phenomena, and "**leakage**" to refer to their combined effect. Note also that there are numerous types of indirect carbon leakage[15], but two main forms we are concerned with: "**spatial**", as in the previous example, and "**intertemporal**", which occurs when a reduction or removal in the present (e.g. reduced land use conversion in one decade) is undone in the future (e.g. by faster conversion of forests in a subsequent decade as a result of the original protection, for example following a change in political regime or economic conditions as witnessed recently in Brazil). While the usual litany of carbon credit quality criteria (additionality, proper carbon accounting, strength of monitoring and verification, avoidance of negative impacts, etc.) must all be upheld for any carbon storage undertaken to support a Net Zero claim, we are chiefly concerned with the question of permanence of storage. Permanence is a requirement due to CO_2's role as a long-lived greenhouse gas which persists in the ocean-atmosphere system for millennia. It reflects the degree of certainty that the stored carbon will not be re-released to the atmosphere at some point in the future through leakage.

2.2 Which CO_2 storage pathways are available?

Many storage options are available including geological storage (e.g. injecting CO_2 into saline aquifers or depleted oil and gas fields, converting CO_2 into stable, mineralised forms, etc.), storage in unmanaged or managed ecosystems including vegetation and soils, and ocean storage. New pathways are likely to arise over the coming decades. However, the two most readily-available families of carbon storage technologies are forestation and geological storage. These are each eminently deployable over the 30 years.

Forestation includes both afforestation (planting trees on previously unforested land) and reforestation (regenerating a forest that had earlier been converted to a non-forested land use). Other promising forms of biological storage, including so-called "blue carbon" sequestration in mangroves and salt marshes (see NEGEM Deliverable 1.3), are under development but require further work to determine accurate measurement of stored CO_2 before they can be confidently deployed at scale. Soil carbon sequestration sequestration (see NEGEM deliverable 1.2), likewise, has significant potential, but needs better quantification before the pathway can be safely or credibly deployed at scale. Issues include highly uncertain measurement and verification, the difficulty of ensuring carbon remains sequestered when triennial ploughing threatens to re-release whatever residual carbon was absorbed due to no-till practices, nitrogen limitations on microbial conversion of carbon into more stable forms, powerful indirect carbon leakage potential, and limited overall global potential[16]. We therefore focus this section of the report on forestation, which is a more developed, de-risked, and accepted storage pathway.

Emission reductions that involve no storage of CO_2 (often called avoided emissions), or high-risk storage of uncertain volumes (e.g. avoided damage to ecosystems), are widely used in commercial offsetting markets, but their utility in supporting Net Zero claims is dubious, given the speculative and often inflated "business-as-usual" baselines required to measure the alleged emissions reduction (the exception being abatement of emissions from industrial point sources where a historical emissions baseline is easy to construct and defend), and the significant difficulty of demonstrating additionality. Over 80% of carbon credits issued by projects initiated under the Clean Development Mechanism, of which the vast majority are avoided emissions without storage, have been shown to offer no further additionality and therefore no impact on atmospheric CO_2[17], and not considered further here.

Having laid out the capture-storage pathway options, we will now assess the two primary storage options—biological and geological.

2.3 *Accounting for temporary carbon storage*

While leakage from geological sites is well-constrained and easy to monitor and remediate, reversal risk and leakage rates of carbon stored in ecosystems vary widely and are difficult to constrain. A coherent system for comparing the value of shorter-term to longer-term storage is necessary. Early discussion of permanence proposed the use of "ton-year accounting" to get around unknown leakage rates and allow such a comparison[18]. For ton-year accounting, a time horizon must be assumed beyond which carbon storage is said to be permanent (typically 100 years is chosen for convenience and convention, not based on a scientific precept), which has the effect of overvaluing very short-term storage if the time horizon is short, and undervaluing storage that persists well beyond the artificially truncated period. In attempting to value the act of keeping CO_2 out of the atmosphere for a finite time, the ton-year accounting framework essentially discounts the marginal damages from that CO_2 at a 0% discount rate over the time horizon, and at an infinite discount rate thereafter. One way of operationalizing this approach is to generate and sell credits each year in which the stored carbon persists in a sink, as was the intent with the rarely-used "temporary certified emission reduction" mechanism under the Kyoto Protocol[19]. This is akin to "renting" carbon storage for a period of time.

A stricter interpretation of permanence, and the one we recommend any firm should employ when accounting for progress towards Net Zero, is to focus on the average residence time of CO_2 in a particular sink. The reciprocal of the residence time is the smoothed annual leakage rate that would result in that residence time (e.g. a reservoir that leaks 2% each year will be depleted by two-thirds after 50 years, around 90% after a further 50 years and so on). Reversal risk is best applied as a project-specific attribute, since it is impossible to predict precisely when and to what degree carbon stored in a particular forest will be released (e.g. by fire, pests, illegal logging, etc.), but it possible to conservatively assume some annual risk that such a disturbance occurs. Term of storage (residence time in sink) is best conceived of as a portfolio-wide attribute. For example, over an entire region, it may be possible to constrain the expected annual rate of forest biomass loss due to fire. Risk of reversal and residence time are complementary, but for a given carbon storage method it may be easier or more useful to describe its reversal risk than its residence time or vice versa.

Any carbon storage option can be modelled as a leaky reservoir that re-releases over time some portion of the CO_2 it was said to have eliminated from the atmosphere (although that leakage will generally not be a simple exponential decline). For geological storage, such as in saline aquifers, leakage rates are likely to be vanishingly low. Physical leakage due to well failure is likely to be rare, detectible, localized, and possible to remediate relatively quickly[20]. This is therefore unlikely to contribute much to cumulative leakage. An alternative mechanism for CO_2 leakage from geological reservoirs is through continuous fractures that bridge the storage reservoir to the surface. Over time, some portion (as much as 50%) of the geologically stored CO_2 is immobilised by dissolution into formation water or chemical reactions with the reservoir rock[21].

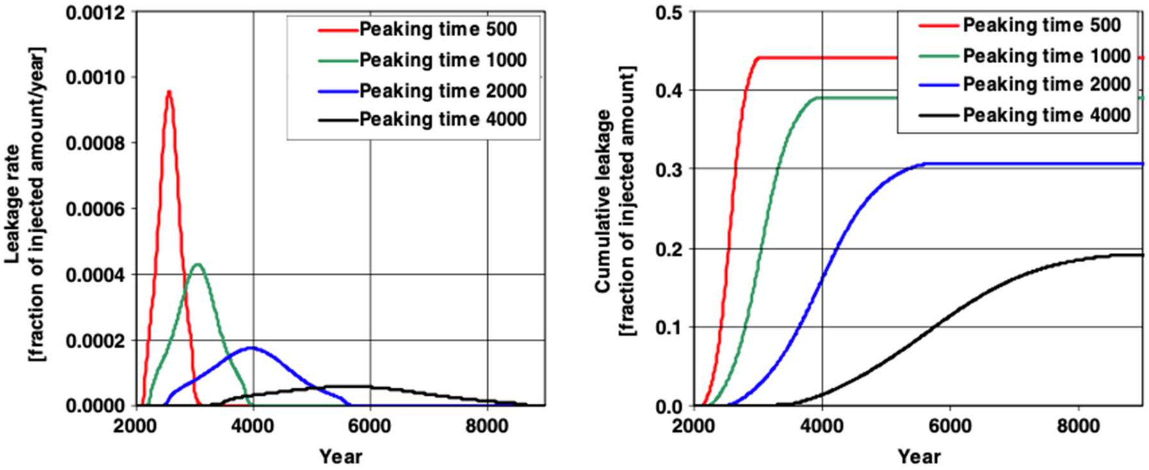

Figure 1 – Reproduced from Torvanger et al. 2012, showing modeled annual leakage rates for geological storage and the corresponding cumulative leakage as a fraction of the initially injected mass. Note that annual leakage rates are modeled as 0% for the initial period, and only rarely exceed 0.02%/year.

2.4 Assessing the merits of biological carbon storage

Achieving net zero by mid or even late-century will require contributions from multiple carbon capture-storage pathways, including biological carbon removal and storage. Biological carbon storage is a form of Natural Climate Solutions (NCS)[22], which are a subset of a broader group of Nature-based Climate Solutions (NbCS) that use protection, restoration, and management of natural and semi-natural ecosystems to advance environmental and social goals[23]. Irrespective of whatever carbon sequestration they may provide, NCS can promote progress across numerous Sustainable Development Goals by contributing to ecosystem restoration, biodiversity preservation, and sustainable economic activity (e.g. agroforestry).

These laudable impacts (often referred to as “co-benefits” when packaged with carbon credits) are not considered in this report, which seeks to narrowly address the question of whether storing carbon in ecosystems is a defensible means of delivering progress toward Net Zero over the three decades from 2020 to 2050. To answer this question, we need to understand the challenges that have been raised vis-à-vis storing CO_2 in ecosystems. Such challenges may limit the desirability of relying on biological storage as a pathway for delivering Net Zero. Ten such issues are described below (see as well summary table below):

1. **Slow rate of sequestration introduces accounting difficulties** – Trees take time to grow. Carbon absorption and sequestration begin from the moment seedlings are planted, and continue until the stand of trees reaches its “attainable maximum” or “equilibrium stock” of stored carbon provided growth is not interrupted[24]. Many forest types require decades or even centuries to achieve their attainable maxima. In some voluntary carbon market regimes, all of this theoretically possible sequestration is sold upfront in a lump sum of carbon credits. This is despite the fact that the carbon emissions the carbon removal credits are meant to offset have already been released and are causing warming throughout the forest’s growth stage, and that there is no guarantee that the attainable maximum of carbon storage will be achieved. These carbon removal credits would therefore most logically be vested into over the lifetime of the forest as carbon is confirmed to have been sequestered. Forestation carbon projects implemented in the 2020s may only be ~50% of the way through their intended sequestration by 2050, the latest date on which many firms are setting their goals for achieving Net Zero. In other words, although the maximum potential for NCS is large (on the order of 3-18 $GtCO_2$/yr for reforestation, with high uncertainty due to variation in estimates of available acreage[22]), the carbon removal they provide cannot be realized instantaneously and is

constrained by the speed of biological processes. Feedstocks with very high growth rates (eucalyptus, switchgrass) are available, but they still require decades to near maximum attainable growth, and provide limited conservation and biodiversity value. Sequestration rate is also an issue for some forms of geological storage, for example enhanced weathering, where the rates of full dissolution of weathered minerals are not yet well-constrained. In one pathway under consideration, crushed olivine is spread in shallow water on beaches to take advantage of high turbation from wave action, but the rate and completeness of olivine particle dissolution is as-yet unknown. Regardless of the storage pathway, we recommend companies only use carbon storage to claim progress towards net zero when such storage is ***ex post***, that is the storage has already been performed and confirmed, rather than ***ex ante***, in which the promise of future storage is credited upfront. However, the use of ex post accounting must not be construed as an abdication of responsibility for demonstrating additionality, which is typically easiest when the funds from carbon credit sales are used to plant new trees rather than reimburse a carbon project operator for previously planted trees. In other words, firms must ensure that carbon removal credits representing biological storage are generated primarily by newly-funded projects, but that those credits are earned only as sequestration is confirmed. The implications of following this approach are explored below in Section 3.5.2.

2. **Limited capacity and above-ground footprint** – Large scale conversion of fossil carbon into biologically-stored carbon is inherently unsustainable because the global biosphere's capacity to store carbon may be quite limited[22] relative to the likely availability of geological sinks[7]. This is primarily due to the fact that terrestrial carbon projects have a significant above-ground footprint. Storing carbon in perpetuity in trees or soils is a significant commitment to carbon preservation as a land use in the face of constantly changing economic, political, and social pressures on land for food, fiber, and development. Aside from competition for a finite land resource, there are also ecological and public acceptability challenges of forestation's aboveground footprint. Reforestation's above-ground footprint is often deemed acceptable because the land was forested in the past and this represents a return to its "natural", unmanaged sate. However, this raises a perverse incentive and the specter of carbon leakage—palm oil developers, for example, may factor in the ability to reforest plantations to earn generate carbon removal credits once productivity declines, before moving on to a new virgin plot for the next plantation. This risk of indirect carbon leakage is discussed below; see in particular the concept of the **Carbon Opportunity Cost**. In addition to concerns over indirect effects on other land use, afforestation (planting trees on previously unforested land) can also prove controversial when it would displace naturally occurring, non-forested biomes, as when WRI was shown to have misidentified 9 million km^2 of grassy biomes as "opportunities" for forestation[25].

3. **Limited ability to fight climate change** – Related to points 1 and 2, recent work has shown that the contribution NCS (including forestation, soil carbon sequestration, avoided ecosystem destruction, etc.) can make toward limiting global warming is limited by how much time these solutions have to act before net zero must be achieved (itself a function of their total availability, and feasible rate of scale-up). Even large-scale deployment of NCS (halting all global deforestation, restoring over 600 million hectares of ecosystems, etc.) was shown to reduce peak warming by only 0.1°C in 1.5°C-consistent scenarios and 0.3°C in 2.0°C consistent scenarios[26]. While NCS remain of particular importance for immediately addressing biodiversity loss, and for the substantial cooling they can provide in the second half of the century, these findings bring into question the utility of NCS to contribute the rapid carbon removal required for achieving net zero by mid-Century compatible with a 1.5°C outcome.

4. **Feedbacks threaten the biosphere's role as a net sink** – Projections of the increased rate of release of carbon from the biosphere by mid-century due to climate change (positive feedbacks), for example through thawing tundra, increased wildfires, and increased methane emissions from wetlands, are similar to optimistic estimates of the potential global rate of carbon uptake by NCS[22,27]. For example, estimates of ultra-ambitious maximum attainable NCS sequestration rates are on the

order of 10-20 $GtCO_2$/yr by mid-Century (2 $GtCO_2$/yr by 2030 if scale-up is rapid)[22], while estimates of the cumulative additional emissions from typically underrepresented earth system processes vary from 100 to 500 $GtCO_2$ over the several decades remaining until net zero must be achieved, depending on the choice of temperature target. It is therefore possible that all available NCS options will be required simply to prevent the global biosphere from further exacerbating global warming, leaving no additional biological storage capacity available to use to compensate for ongoing fossil fuel extraction and emissions. Users of NCS to convert fossil hydrocarbon into live biomass to balance fossil carbon emissions need to recognize that they are tapping into a rapidly depleting global resource that threatens to flip from being a net sink to a net source.

5. **High risk of physical carbon leakage** – Both during growth and once an attainable maximum level of carbon storage is achieved, the forests and other ecosystems used to generate carbon credits remain vulnerable to partial or complete destruction and reversal of captured carbon back into the atmosphere. Stand establishment is a common failure point, with a disturbing record of largescale reforestation and afforestation projects failing in the first years following establishment (see Turkey's recent 11 million tree project where upwards of 90% of saplings were shown to have not survived[28]). But throughout a stand's life, disturbances that release carbon could include hurricanes, fires, pests, disease, failure to protect from human harvest, and stress from longer-term shifts in climate conditions. Reversal risk from such disturbances remains a constant threat that must be monitored and responded to in the event of a reversal. The annual risk of catastrophic disturbance varies widely based on many factors including forest type, climate, geography, strength of rule of law in the host country, and other factors, all of which can also change over time. For fire risk specifically, there are maps of fire risk around the world showing wide variablity[29]. Annual risk of disturbance seems to be frequently modeled at >2%/year (see table below). These quantitative measures are likely biased toward data on industrial forestry in the US, where disturbance rates may be different than in less well-developed timber and forestry markets due to active preventative management. Loss in carbon is a function of both the frequency and severity of disturbance. Carbon credits from forest carbon sequestration should in theory reduce pressure to deforest, or increase the stand rotation time in the case of commercial forestry, but in practice the higher threat of disturbance has been shown to have the opposite effect: higher risk leads to more frequent harvests[30]. These disturbance risks are not quantitatively incorporated into forest carbon crediting regimes, but when such risk is taken into account it can eliminate or reduce credit value significantly (see Figure 2)[31]. In California a largely qualitative risk analysis was used to set a 10-20% buffer pool, but fire frequency and severity is increasing due to a combination of climate change and a legacy of fire suppression management, raising questions as to whether this buffer pool will be enough to secure the integrity of already-issued credits[32].

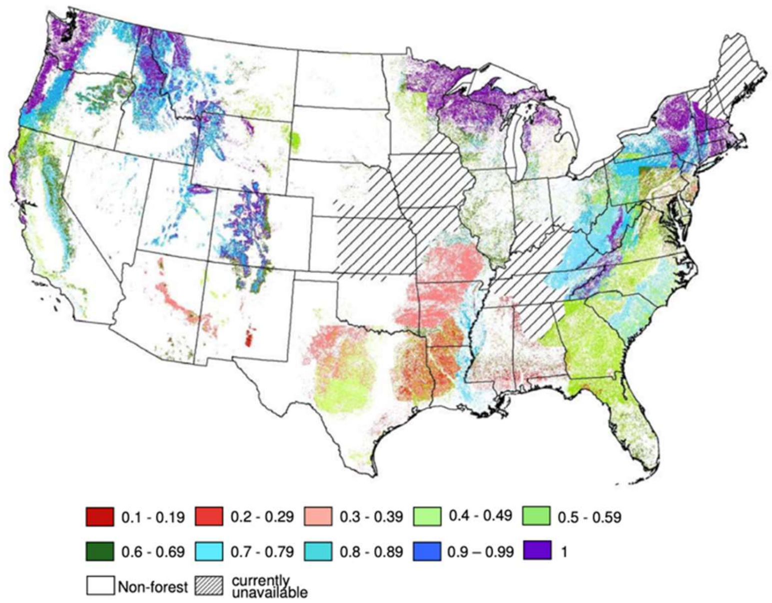

Figure 2 - Fire risk across the US, expressed as discount factors that should be applied to the value of carbon credits relying on storage at that site. For example, swathes of interior California have values in the 0.4-0.8 range, suggesting that only 40-80% of the carbon in credits from those sites is safe, and values are likely inflated. Excerpted from Hurteau et al. 2009.

Table 1. Estimates of physical leakage rates

Annual leakage rate (% of carbon lost/yr)	**Notes**	**Source**
3%	Model found a global sequestration potential from forests (assumed to be working forests on 30-year rotation) of ~7 $GtCO_2$ over a 20-year period, but this was reduced by ~60% when country risk was considered (this could be construed as a ~3% annual leakage rate). This reflected the fact that the most cost-effective locations for forestry were concentrated in developing areas whose risk was proxied using indices of risk-adjusted discount rates by country.	Benitez et al 2007[33]
0.4 - 2.4%	Cites 0.5-2% as a typical range in the literature of annual catastrophic disturbance risk rate (fires and pests), and uses a 3% rate for their model of Southern US plantation forests with a range of 0-80% mortality in each event, hence 2.4% (3% * k=0.8) as an upper bound for severity (proxy for carbon loss).	Susaeta et al 2009[34]
5.7%	Cites 1.2% rate of burn from fire and 7% loss from hurricanes in Florida, USA. This combined risk plus their top-end severity assumption (a proxy for carbon loss) yields 8.2% * k=0.7.	Stainback & Lavalapati 2008[30]

There is evidence that disturbance rates, whether from fire, hurricanes, or pests, are increasing. For example, over 40% of US forests are now at risk of invasion by pests that are already present, and in some cases the annual biomass loss from pests causing tree mortality (not to mention the changes to carbon dynamics caused by additional standing dead timber) rivals the biomass lost to fires[35].

Aside from the physical leakage rate itself, the portion of stored carbon that is at risk is also a key consideration. For carbon stored in ecosystems, most or all of the stored carbon remains at risk in perpetuity. Land conversion could extract close to 100% of stored carbon. Fires can consume in the realm of 25-50% of stored biomass (estimate based on California forests[36]) and cause long-term damage to the attainable carbon stock even decades after the fire[37]. Forest ecosystems are resilient, but on the timescale relevant for delivering Net Zero commitments and for meeting the Paris Agreement (three decades), physical leakage events from forests and other ecosystems are a major threat to desired climate outcomes. Long-term conservation is possible using government power or legal tools like conservation easements, but uncertainty rises over the multi-century timescales required for safe storage. Coarser mechanisms for de-risking physical leakage are used in most regulated carbon markets, for example an insurance buffer pool can compensate for the risk that some individual projects fall victim to fires and other reversal events. This is an *ex ante* discounting of the carbon that is expected to be sequestered. Alternatively, either the purchaser or producer of the credits could be held liable for future carbon and required to buy replacement credits *ex post* following a loss event. With geological storage, a high percentage of the stored carbon is also under threat of physical leakage in the initial period following injection, but this portion declines with time as CO_2 is immobilised in the reservoir, and early leaks are fairly straightforward to monitor and prevent. The above-ground footprint is minimal, so monitoring is a localized rather than a landscape-scale challenge.

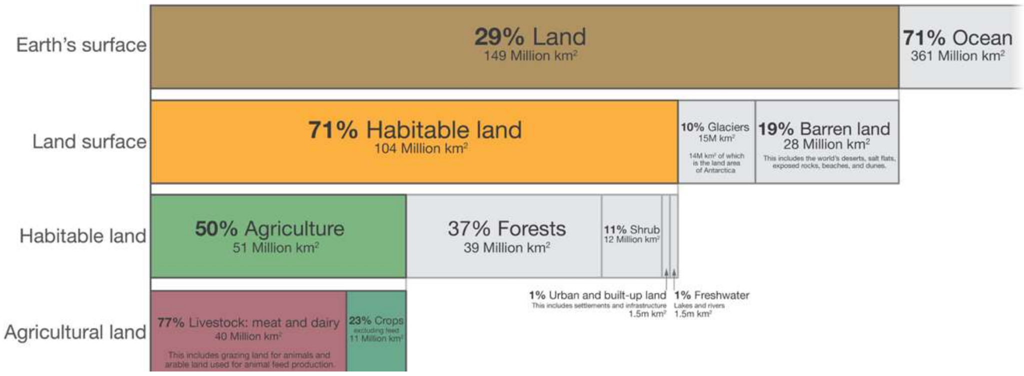

Figure 3 - Global land use from Our World in Data[38].

6. **High risk of indirect carbon leakage** – Carbon storage using ecosystems is only effective if indirect effects do not erase the carbon sequestered by causing it to be emitted elsewhere. Carbon projects rarely systematically account for these indirect effects. Productive land is in high demand for agricultural production in particular, with 50% of Earth's habitable land already under agricultural management (of which over 75% is for livestock)[38]. The majority of remaining habitable land is forests, shrub and grasslands, so almost any expansion of agricultural land comes at the expense of carbon-storing land uses, and almost any increase in forested land comes at the expense of agricultural land. The total available land is fixed, therefore only increased efficiency of production can enable food, forest fiber, and carbon goals to be met simultaneously. Growth in population and food demand currently outpaces improvements in yield, so land under management is increasing and expected to continue growing. Therefore, any forestation on land that could be put into agricultural production is in theory fully displaced by forest conversion elsewhere, causing emissions from land use conversion. If the displaced agriculture is *more* efficient in the new location, more carbon will be sequestered in the reforestation site than is lost in the conversion of forest in the new location (since less land needs to be cleared to produce the same calories), providing a carbon ***benefit***. However, this carbon benefit is only fully realised after the decades or centuries required to grow the forest, so should be discounted to the present. Conversely, if the displaced activity is *less* efficient in the new location, more carbon will be released in land clearing than can ever by sequestered in the forestation site, creating a carbon ***cost***. The determination of whether a net carbon benefit or cost is achieved is a function of the net productivity of the native vegetation and the emissions intensities of possible agricultural activities at the two sites. In other words, the starting assumption or baseline should be that forestation provides no carbon benefit or cost—only

by comparing it to displaced activities can we establish whether carbon stocks are being increased on net. Since it is difficult to attribute a specific instance of forestation to a specific instance of land use elsewhere, the World Resources Institute (WRI) proposes assuming that the replacement land use occurs at world average values for the different land use options that are foregone on the afforested land. A **Carbon Opportunity Cost** (COC) can therefore be calculated for the different potential uses of a given plot of land according to carbon efficiencies. The COC defines a more 'carbon efficient' use of land as "one that increases the capacity of global land to store carbon and reduce GHGs overall, while meeting the same global food demand"[39].

The implication is that there is no "free" land from a carbon accounting perspective, and every carbon project that sequesters carbon in terrestrial ecosystems needs to start from the premise that some emissions occur elsewhere, counteracting what seems at first to be an unequivocal carbon benefit from sequestration. Unfortunately, no carbon credit verification systems systematically calculate COCs to determine leakage. Some land that is very marginal for agricultural production and has very little or no alternative use is, in theory, available for forestation without significant threat of indirect carbon leakage. In this case the burden would be on the user to evaluate the COCs for forestation and show that it is higher than for other uses. The same conditions that limit its net primary productivity (e.g. poor soils, high rate of disturbance, unfavorable climate) likely also limit how much carbon can be sequestered in a forest. In practice, COCs are usually currently higher for agricultural applications than for forestation in many scenarios.

More conventional studies of indirect carbon leakage offer a wide range of estimates:

Table 2. Cumulative leakage rates

Cumulative leakage rate (% of carbon lost/carbon sequestered)	**Notes**	**Source**
10 - 90% overall (inclusive of avoided deforestation and afforestation) 20 - 40% for afforestation United States	The authors acknowledge that their model ignores international and inter-sectoral leakage, focusing narrowly on how forestation affects deforestation elsewhere within the bounds of the US. Given global interconnected timber markets, it is likely that additional leakage occurs as international markets increase or decrease their forested land in response to market dynamics, or due to energy or material switching.	Murray et al 2004[40]
43% over 10 years United States	Analysed the effects of US reducing forest harvest volumes by 85% over a 10-year period, finding that 43% of the reduction leaked away via increased harvests on private lands.	Wear & Murray 2004[41]
23 - 39% over 30 years (slightly more over 50 years) Bolivia	Estimates indirect carbon leakage for Bolivia, a small open market that is a price taker for timber. Model observes how removal of some timber concessions (protecting standing forests from logging) affects harvest rates elsewhere in the country. Cumulative leakage is lowered when carbon is discounted to present at a 3% discount rate (12-36% over 50 years).	Sohngen & Brown 2004[42]

Over 100% over 5 years ~4,000 km^2 decrease in pastureland converted to soy would have reduced deforestation by ~13,700 km^2 Brazil	Study statistically linked the displacement of Brazilian pastureland by mechanized agriculture (e.g. for soy) with deforestation on a distant frontier to replace that pastureland. A 10% reduction (4k km^2) of this pasture>soy conversion was modeled, yielding a reduction in deforested land three times larger (13.7k km^2 is average of results from three models). This suggests that if pastureland were instead replaced with *forest* (or any land use), this would similarly displace forest conversion to the Amazonian frontier, sapping 100% of the carbon benefit.	Arima et al 2011[43]

These estimates are region or country-specific and do not consider international effects. A survey of 34 leakage estimation methodologies found that only two addressed international leakage[44].

Forestation is appealing because additionality is usually resolvable—absent intervention, the land would continue in an unforested sate—and techniques for estimating sequestered carbon are fairly well-developed. However, from the standpoint of Carbon Opportunity Costs and indirect leakage, there may be little value to forestation in a world of rising agricultural demand where leakage approaches 100%. This is akin to the waterbed effect in cap-and-trade systems: the global rate of change in forest cover is currently still negative, and until deforestation is halted it remains difficult to determine whether growing forests in one location is simply eroded by forest conversion in another. Protecting the world's remaining extant standing forests from conversion for agriculture or timber is therefore arguably the most pressing challenge. The quandary is that carbon projects that purport to avoid destruction of ecosystems are riddled with problems of measurement and verification of carbon stock, baseline selection, additionality, and permanence.

7. **Non-carbon effects on climate** – Largescale forestation can have additional effects on warming that must be properly accounted for and converted into CO_2e terms. The three most impactful pathways with significant remaining uncertainty are:

    a. **Volatile organic compounds** – A variety of VOCs are emitted naturally by trees, some of which can create both warming (due to its interactions with CH_4 and N_2O) and cooling (as a reflective aerosol) effects. Which effect dominates is an area of active research.
    b. **Albedo** – Forested land is typically darker than unforested land, so increasing forest cover decreases the Earth's albedo (reflectivity) and causes more heat to be absorbed.
    c. **N_2O and CH_4 emissions** – Trees, particularly in tropical forests, may be emitting more CH_4 and N_2O than previously believed, which may partially undermine the net cooling effect they provide from absorbing carbon[45,46].

The first study to attempt to correct for the first two effects concluded that the massive conversion of forests into agricultural land in the 20th century, despite constituting a massive emission of CO_2, may have had a negligible warming impact due to the cooling from VOCs and the change in albedo by shifting to farmland[47]. Subsequent studies have both challenged and supported these findings[45], suggesting ongoing uncertainty that should instill caution in forest carbon credit purchasers. The third effect is only very recently being explored (see references above). As these effects come to be better understood, both future and past forest carbon project credit volumes will need to be revised upward or downward accordingly. This suggests that without further study and modifications to emissions measurement methodologies, forestation credits generated in the 2020s could be later shown to overestimate sequestration, requiring more storage to make up for the reduced impact.

8. **International and intertemporal equity** – NCS are often considered the cheapest, “low-hanging fruit” mitigation opportunities, particularly in developing countries where damage to ecosystems and biodiversity loss is accelerating and capital for more expensive abatement (e.g. lower-carbon cement production) is not available. Using carbon credits as a tool to enable wealthier countries and companies to purchase this cheap mitigation can bring significant benefits, funding much-needed ecosystem restoration and preservation that might otherwise be ignored. However, this exchange could leave developing countries bereft of the mitigation options they can most easily afford, and saddled with the harder, more expensive options; conversely, investment in some NCS opportunities today could actually increase NCS opportunities in future by building ecosystem resilience. Emitters with the most historical responsibility for climate change should arguably fund such ecosystem restoration projects in their own right and on a philanthropic or concessionary basis, without requiring carbon credits in exchange. This would ensure that these much-needed activities take place, but allow the host countries to get credit for the removals and subsequent stewarding of the carbon that has been captured and stored in biomass. Entities with more resources and higher cumulative historical emissions could be allocated a smaller share of the total available sequestration potential from these least-expensive options. This will become increasingly important with the transition from the Kyoto era of separate but differentiated responsibilities, in which developing countries (without an obligation to report emissions) could easily sell off cheap mitigation to developed countries, to the Paris era where every country contributes to emission reductions. Countries that host forestation projects will be tempted to seek accounting treatments that allow them to take some credit for biological sequestration that is also being used to generate carbon credits sold abroad, raising the threat of double-counting.

   Carbon credit purchases are typically treated as one-off transactions that do not carry enforceable future liability for the integrity of carbon storage, treating the reduction or removal as a one-time flux of carbon rather than an ongoing responsibility to preserve the stored carbon in perpetuity. Placing clear responsibility for stewardship of the storage is key, and carbon credit purchasers need to evaluate the risks of a particular steward.

   The intertemporal equity of storing carbon in ecosystems is also challenging, since forestry projects effectively become “carbon reserves” that cannot be cultivated, or harvested at a rate higher than the replacement growth rate, in perpetuity. This places significant constraints on the decisionmakers in future decades who may have make different determination of the highest and best use for a given land area. Storing carbon in ecosystems today relies on trusting future actors to put the integrity of storage above more proximate economic considerations.

9. **Reputational risk** – Relying heavily on biological storage to balance fossil CO_2 extraction is reputationally dangerous for any firm. Criticism on any or all of the above grounds is likely. Anything from ex ante versus ex post accounting decisions to claims of indirect carbon leakage undoing the benefits provided by sequestration could invite accusations of greenwashing[48]. Paradoxically, some of the same members of the environmental movement who criticize (particularly energy and extractive fossil fuel) companies’ involvement in NCS offsetting defend NCS offsets in other contexts, likely because they perceive them to be well-aligned with their other, non-climate environmental and social goals. It must be noted that this reputational risk is not limited to the current political landscape, in which mass tree planting is back in vogue as an option touted by many governments and companies. To the degree that companies understand the risks of nature-based carbon storage better than the public, they can mitigate future reputational risk by laying the groundwork to rapidly shift toward carbon storage methods that do not carry the same risks.

10. **Financial risk** – If NCS offsets fail, Companies may come under pressure to remediate any leaked CO_2 with new storage. If the economic or political costs of conducting biological storage increase due to declining availability of land or public resistance to further reliance on conversion of fossil carbon

into biological carbon, re-storing CO_2 at a later date could be more expensive. While existing legal regimes are unlikely to hold companies liable for replacing any leaked CO_2 that was paid for on a voluntary basis using specific permanence criteria (e.g. replacing failed forest projects with geologically injected CO_2), there may be significant public pressure to do so regardless.

While some of these issues (summarized in the below Table) can be overcome with improved methodologies and careful carbon credit screening, they paint an overall picture of carbon storage in ecosystems as an important but problematic asset class. In particularly, heavy reliance on NCS to balance fossil fuel extraction and use is risky and difficult to defend scientifically, given troublingly high or uncertain indirect carbon leakage, increasing risks of physical reversal, limited speed of sequestration, limited total availability, and foreseen climate feedbacks. This is not in any way to suggest that ecosystem preservation and restoration is not urgently needed, or that such activities should not be supported at scale by companies irrespective of carbon benefits, on the sole basis of stopping biodiversity loss and restoring critical ecosystems. However, all of these effects must be considered in assessing the likely risk-adjusted carbon benefits of biological storage, and may justify a stronger, earlier focus on de-risked and more permanent storage pathways.

Table 3 – Summary of known issues with storing carbon in ecosystems

	Issue	Description	Performance relative to geological carbon storage (GCS)	Recommendation vis-à-vis corporate Net Zero claims
1	Slow rate of sequestration introduces accounting difficulties	Forestation projects take significant time to sequester their cumulative carbon (e.g. IPCC uses an average of 138 years). A "1 tCO_2" credit actually provides a ~1/X tCO_2/yr sequestration rate, where X is the number of years till the attainable maximum of carbon stored is reached. Despite the inherent uncertainty of future sequestration, many carbon credits are issued in full upfront, ignoring the time delay.	GCS projects take time to deploy, but once operating the sequestration they provide is essentially instantaneous. Immobilization of stored CO_2 is a slow process, but leakage in advance of maximum immobilization is manageable relative to protecting landscape-scale, aboveground carbon sinks.	All storage (geological and biological) conducted to support a Net Zero claim should use *ex post* (storage already performed) accounting to ensure that sequestration takes place. However, preserving additionality requires funding primarily new projects. If a corporation were to rely heavily on biological storage to support a Net Zero claim, this would require funding more cumulative sequestration than the volume of carbon in products that is being balanced, since only sequestration before the date of the Net Zero claim (e.g. the first 20 years of growth if this date is 2040) can be applied to support progress.
2	Limited capacity and above-ground footprint	Large scale conversion of fossil carbon into biologically-stored carbon is inherently unsustainable because the global biosphere's capacity to store carbon may be quite limited. Aboveground footprint of forestation projects is large and likely to remain in heavy competition with other land uses over the next three decades and beyond.	Global geological storage capacity is estimated to be orders of magnitude larger than the ecosystem restoration carbon sink, and capable of storing many years of anthropogenic emissions even at multi-$GtCO_2$/yr rates. *Feasible* and *bankable* GCS will likely need to be revised down as experience with CCS scales up. Aboveground footprint is limited or non-existent for GCS.	Any use of biological storage to deliver Net Zero must consider the estimated total land area required to balance expected future production both for a corporation, and across the industry. If biological storage is not a feasible strategy for decarbonizing fossil fuel use overall, a corporation's unilateral use implies competition for a scarce resource. In determining the mix of GCS and biological storage, consider the value of the very limited above-ground footprint of GCS.
3	Limited ability to fight climate change	Due to Issues 1 & 2, recent work has shown that the total contribution of NCS (including forestation) toward cooling before net zero is achieved is only 0.1°C or 0.3°C in 1.5°C and 2.0°C-consistent scenarios, respectively (before Net Zero is fully delivered).	The fast injection rates of GCS and large overall storage capacity mean its ability to contribute to pre-2050 climate goals is less physically constrained than biological options. However, capital constraints and slow project development timelines may limit its maximum contribution.	The scale of a corporation's use of biological storage to balance ongoing fossil fuel extraction and use in partial fulfillment of Net Zero should acknowledge the limited window for this biological carbon sink to contribute to medium-term climate outcomes. A corporation should plan the evolution of the mix of GCS and biological storage for Net Zero accordingly.

4	Feedbacks threaten the biosphere's role as a net sink	Projections suggest the biosphere may transition from a net CO_2 sink to source by mid-century due to positive climate feedbacks. These emissions may exceed optimistic estimates of the potential global rate of carbon uptake by NCS, suggesting that all available NCS options may be required simply to prevent the global biosphere from further exacerbating global warming.	Geological sinks are stable to climate perturbation and not expected to spontaneously become sources.	A corporation should acknowledge and plan for the likelihood that climate feedbacks flip the biosphere from sink to source, and select the balance of GCS and biological storage accordingly. Biological sinks may need to be kept available to dedicate toward balance future biogenic emissions (see also Issue 9).
5	High risk of physical carbon leakage	Catastrophic disturbances (e.g. fire, hurricanes, pests, disease, unexpected logging) can release stored carbon. Carbon credit certification pathways do not rigorously or quantitatively incorporate these leakage rates into estimates of safely stored carbon volumes.	GCS's physical leakage risk is low relative to biological storage, and leaks are likely to be detectable and possible to remediate. However, monitoring must persist until CO_2 is immobilised.	Set a clear policy for how physical leaks (reversals) of carbon stored to support Net Zero claims (whether biological or geological) will be remediated, most likely with commensurate storage of new CO_2. Consider the risk of remedial storage in determining the mix of GCS and biological storage for Net Zero delivery.
6	High risk of indirect carbon leakage	Carbon stored in forests in one location can indirectly cause emissions elsewhere through land conversion or market effects in markets for food, fiber, and development. Carbon credits do not rigorously or quantitatively incorporate indirect carbon leakage, despite the fact that such leakage has the potential to erase all or nearly all of the alleged carbon benefit.	GCS is unlikely to cause significant indirect carbon leakage, since it has little to no aboveground footprint and does not compete with other uses for a finite land area. Some indirect effects may be caused by high expenditure on GCS in lieu of funding other, cheaper abatement.	• Implement a methodology to assess indirect carbon leakage using the Carbon Opportunity Cost (or similar) framework for all forms of carbon storage used for Net Zero. • Limit reliance on biological storage until such leakage is well-constrained, and back-modify stored volumes as methods for assessing leakage improve
7	Non-carbon effects on climate	Emissions of VOCs, methane, and nitrous oxide from forests may reduce or eliminate the cooling effects of sequestering carbon. Largescale forestation also affects the Earth's heat absorption, undermining some of the cooling from carbon sequestration. Carbon credit certification pathways do not currently account for these factors.	GCS is not known to exert significant non-carbon effects that could warm or cool the global. Albedo changes are not material given limited aboveground footprint.	• Ensure that internal policies for measuring carbon benefits of biological storage include the most recent estimates of albedo effects and non-CO_2 emissions from forests. • Ensure that such methodologies are continually reviewed, and that previously stored volumes are back-corrected as new information becomes available. • Consider limiting reliance on biological storage for delivering Net Zero until these effects are better constrained.

8	International and intertemporal equity	Biological storage often involves the sale of low-cost carbon credits generated in developing countries to wealthier countries and companies with a greater historical contribution to climate change. This exchange may deprive developing countries of their cheapest mitigation options (international equity). Similarly, using up cheap or limited storage options now reduces optionality for future decisionmakers (intertemporal equity).	Geological storage capacity is unevenly distributed, raising similar equity issues for how this limited resource should be equitably allocated among countries and companies with varying capacities to pay for storage and varying historical responsibilities for climate change.	Establish and communicate a coherent stance on how a corporation's chosen mix of biological and geological storage to deliver Net Zero will consider these issues of equity. For example, the reputational benefits and value of funding ecosystem restoration projects can be retained by supporting them in their own right on a philanthropic or concessionary basis, without requiring carbon credits in exchange (perhaps motivated by a separate "zero biodiversity loss" aim).
9	Reputational risk	Relying heavily on biological storage to balance fossil CO_2 extraction is reputationally dangerous, inviting criticisms of "greenwashing" on any or all of the above grounds. Furthermore, a corporation's methodologies for delivering its Aims will be intensely scrutinised, likely requiring a level of rigor and conservatism that exceeds that of existing certifications used in voluntary and compliance carbon markets.	GCS faces entirely different forms of public resistance, but most of these are based on antipathy toward the oil and gas sector and heavy-emitting industries. Since resistance to GCS is already rooted in its proximity to these industries, education, exposure, and outreach that improve the public acceptability of GCS simultaneously improve public perception of the positive role of oil and gas companies in advancing a net zero society.	• Reinforce existing commitments to eschew greenwashing of all forms, including as it relates to using NCS to balance fossil fuel extraction. • Establish new commitments that make clear the rigor with which a corporation will evaluate the above considerations in both risk-adjusted accounting of stored carbon, and in setting the mix of biological and geological storage to deliver Net Zero. • Publicly advocate for incorporation of issues 1-8 in existing carbon credit certification, recognizing the enhanced ambition required to credibly deliver carbon benefits from biological storage
10	Financial risk	If biological storage sites fail, purchasers of associated carbon credits will come under pressure to remediate any leaked CO_2 with new storage at prevailing costs. These storage costs may be higher due to declining land availability and improved accounting (see Issues 5, 6, and 7), or storage in more permanent reservoirs may be demanded.	GCS's low leakage rates limit risk of necessitating future remediation. But the high capital costs of GCS projects and policy uncertainty introduce other forms of financial risk.	Future financial liability can be de-risked by: • Improving techniques to properly account for risk-adjusted volumes of stored carbon, and incorporate these insights into pricing • Reduced reliance on higher-risk storage pathways • Setting aside funds for future remediation of leaked carbon

3 Conclusions

The widely-held view that "a tonne of CO_2 is a tonne of CO_2", and that the primary distinguishing features of different carbon removal options are costs and co-benefits, is incorrect. Not all carbon removals are equal from a climate perspective, and they are primarily distinguished by the characteristics of the CO_2 storage solution employed, not the removal technology.

Despite their low cost and, if well designed, substantial co-benefits, there are a number of concerns with the widespread use of biological, ("nature-based") carbon removal to offset continued fossil fuel use, including:

- Accounting challenges associate with the time trees take to grow.
- Limited global capacity and above-ground footprint.
- Limited potential for supporting the most ambitious climate goals: optimistic estimates of nature-based climate solution potential suggest they could shave 0.1°C off global temperatures by 2050 (more in the longer term), which is only a few years of fossil-fuel-driven warming at the current rate.
- Feedbacks from global warming itself (increasing microbial respiration in warming soils; increasing wildfire risk, etc.) threaten the biosphere's role as a net sink.
- High risk of physical and indirect carbon leakage.
- Non-carbon impacts on climate.
- Implications for international and intergenerational equity

Hence despite their low cost, these considerations introduce a substantial reputational and financial risk for any company relying on biological carbon storage to offset continued use of fossil fuels. Ultimately, durable net zero solutions require "like-for-like" balance of sources and sinks of carbon dioxide, with high-durability sources (including fossil fuel use, the oxidation of fossil fuels and release of CO_2 into the atmosphere being an essentially irreversible action from the climate perspective) balanced by equally high-durability storage (such as high-quality, verified geological sequestration).

There is a clear need to design policy instruments that allow us to take advantage of the significant opportunities for nature-based climate solutions without undermining the case for investment in more permanent carbon storage solutions. The Proset is one such instrument, tailored to the voluntary carbon market and detailed in the Appendix, but further research and policy innovation in this space is needed.

To prepare this report, the following deliverable has been taken into consideration:

D#	Deliverable title	Lead Beneficiary	Type	Dissemination level	Due date (in MM)
D1.2	Comprehensive sustainability assessment of terrestrial biodiversity NETPs	ETH	Report	PU	12
D1.3	Comprehensive sustainability assessment of marine NETPs	ETH	Report	PU	16

References

1. Allen, M., Dube, O. P. & Solecki, W. Chapter 1: Framing and Context. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. (2018).
2. UNFCCC. Adoption of the Paris Agreement, 21st Conference of the Parties, Paris: United Nations. (2015).
3. Allen, M. R. et al. Warming caused by cumulative carbon emissions towards the trillionth tonne. Nature **458**, 1163–1166 (2009).
4. Masson-Delmotte, V. et al. Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. https://www.ipcc.ch/sr15/chapter/summary-for-policy-makers/ (2018).
5. Myhre, G. et al. IPCC AR5, Chapter 8 - Anthropogenic and Natural Radiative Forcing. 82 (2013).
6. Ajayi, T., Gomes, J. S. & Bera, A. A review of CO2 storage in geological formations emphasizing modeling, monitoring and capacity estimation approaches. Pet. Sci. **16**, 1028–1063 (2019).
7. Consoli, C. P. & Wildgust, N. Current Status of Global Storage Resources. Energy Procedia **114**, 4623–4628 (2017).
8. WRI. Greenhouse Gas Protocol. https://ghgprotocol.org/ (2020).
15. Schwarze, R., Niles, J. O. & Olander, J. Understanding and managing leakage in forest–based greenhouse–gas–mitigation projects. Philos. Trans. R. Soc. Lond. Ser. Math. Phys. Eng. Sci. **360**, 1685–1703 (2002).
16. Ranganathan, J., Waite, R., Searchinger, T. & Zionts, J. Regenerative Agriculture: Good for Soil Health, but Limited Potential to Mitigate Climate Change. World Resources Institute https://www.wri.org/blog/2020/05/regenerative-agriculture-climate-change (2020).

17. Warnecke, C., Schneider, L., Day, T., La Hoz Theuer, S. & Fearnehough, H. Robust eligibility criteria essential for new global scheme to offset aviation emissions. Nat. Clim. Change **9**, 218–221 (2019).
18. Noble, I. et al. 2.3.6.3. Equivalence Time and Ton-Years. https://www.grida.no/climate/ipcc/land_use/074.htm (2000).
19. Galinato, G. I., Olanie, A., Uchida, S. & Yoder, J. K. Long-term versus temporary certified emission reductions in forest carbon sequestration programs*: Long-term certified emission reductions. Aust. J. Agric. Resour. Econ. **55**, 537–559 (2011).
20. Torvanger, A. et al. Quality of geological CO2 storage to avoid jeopardizing climate targets. Clim. Change **114**, 245–260 (2012).
21. Akervoll, I., Lindeberg, E. & Lackner, A. Feasibility of Reproduction of Stored CO2 from the Utsira Formation at the Sleipner Gas Field. Energy Procedia **1**, 2557–2564 (2009).
22. Griscom, B. W. et al. Natural climate solutions. Proc. Natl. Acad. Sci. **114**, 11645–11650 (2017).
23. Seddon, N. et al. Understanding the value and limits of nature-based solutions to climate change and other global challenges. Philos. Trans. R. Soc. B Biol. Sci. **375**, 20190120 (2020).
24. Ingram, J. & Fernandes, E. Managing carbon sequestration in soils: Concepts and terminology. Agric. Ecosyst. Environ. **87**, 111–117 (2001).
25. Veldman, J. W. et al. Where Tree Planting and Forest Expansion are Bad for Biodiversity and Ecosystem Services. BioScience **65**, 1011–1018 (2015).
26. Girardin, C. A. J. et al. Nature-based Solutions for climate change mitigation: contribution to peak warming and long-term global cooling. Rev. (2020).
27. Lowe, J. A. & Bernie, D. The impact of Earth system feedbacks on carbon budgets and climate response. Philos. Trans. R. Soc. Math. Phys. Eng. Sci. **376**, 20170263 (2018).
28. Kent, S. Most of 11m trees planted in Turkish project ‘may be dead’. The Guardian (2020).
29. Meng, Y., Deng, Y. & Shi, P. Mapping Forest Wildfire Risk of the World. in World Atlas of Natural Disaster Risk (eds. Shi, P. & Kasperson, R.) 261–275 (Springer Berlin Heidelberg, 2015). doi:10.1007/978-3-662-45430-5_14.

30. Stainback, G. A. & Lavalapati, J. R. R. A. MODELING CATASTROPHIC RISK IN ECONOMIC ANALYSIS OF FOREST CARBON SEQUESTRATION. Nat. Resour. Model. **17**, 299–317 (2008).
31. Hurteau, M. D., Hungate, B. A. & Koch, G. W. Accounting for risk in valuing forest carbon offsets. Carbon Balance Manag. **4**, (2009).
32. Borunda, A. The science connecting wildfires to climate change. National Geographic https://www.nationalgeographic.com/science/2020/09/climate-change-increases-risk-fires-western-us/ (2020).
33. Benítez, P. C., McCallum, I., Obersteiner, M. & Yamagata, Y. Global potential for carbon sequestration: Geographical distribution, country risk and policy implications. Ecol. Econ. **60**, 572–583 (2007).
34. Susaeta, A., Alavalapati, J. R. R. & Carter, D. R. MODELING IMPACTS OF BIOENERGY MARKETS ON NONINDUSTRIAL PRIVATE FOREST MANAGEMENT IN THE SOUTHEASTERN UNITED STATES. Nat. Resour. Model. **22**, 345–369 (2009).
35. Fei, S., Morin, R. S., Oswalt, C. M. & Liebhold, A. M. Biomass losses resulting from insect and disease invasions in US forests. Proc. Natl. Acad. Sci. **116**, 17371–17376 (2019).
36. De Santis, A., Asner, G. P., Vaughan, P. J. & Knapp, D. E. Mapping burn severity and burning efficiency in California using simulation models and Landsat imagery. Remote Sens. Environ. **114**, 1535–1545 (2010).
37. Sato, L. Y. et al. Post-Fire Changes in Forest Biomass Retrieved by Airborne LiDAR in Amazonia. Remote Sens. **8**, 839 (2016).
38. Ritchie, H. & Roser, M. Land Use. Our World Data (2013).
39. Searchinger, T. D., Wirsenius, S., Beringer, T. & Dumas, P. Assessing the efficiency of changes in land use for mitigating climate change. Nature **564**, 249–253 (2018).
40. Murray, B. C., McCarl, B. A. & Lee, H.-C. Estimating Leakage from Forest Carbon Sequestration Programs. Land Econ. **80**, 109–124 (2004).
41. N. Wear, D. & Murray, B. C. Federal timber restrictions, interregional spillovers, and the impact on US softwood markets. J. Environ. Econ. Manag. **47**, 307–330 (2004).

42. Sohngen, B. & Brown, S. Measuring leakage from carbon projects in open economies: a stop timber harvesting project in Bolivia as a case study. Can. J. For. Res. **34**, 829–839 (2004).
43. Arima, E. Y., Richards, P., Walker, R. & Caldas, M. M. Statistical confirmation of indirect land use change in the Brazilian Amazon. Environ. Res. Lett. **6**, 024010 (2011).
44. Henders, S. & Ostwald, M. Forest Carbon Leakage Quantification Methods and Their Suitability for Assessing Leakage in REDD. Forests **3**, 33–58 (2012).
45. Popkin, G. How much can forests fight climate change? Nature **565**, 280–282 (2019).
46. Welch, B., Gauci, V. & Sayer, E. J. Tree stem bases are sources of CH4 and N2O in a tropical forest on upland soil during the dry to wet season transition. Glob. Change Biol. **25**, 361–372 (2019).
47. Unger, N. Human land-use-driven reduction of forest volatiles cools global climate. Nat. Clim. Change **4**, 907–910 (2014).
48. Carrell, S. Scottish ministers face criticism for £5m Shell tree-planting scheme. The Guardian (2019).

Appendix: Prosets – making continued use of fossil fuels compatible with a credible transition to net zero

The following paper represents a proposal for the integration of nature-based and geological carbon storage in a single offsetting product, consistent with the transition to a sustainable net zero future, supporting the development of both nature-based and engineered carbon dioxide removal solutions, and maintaining near-term affordability. This instrument, named a "proset" (for progressive offset), is designed initially for the voluntary carbon market but analogues may have a role in compliance markets in future. It is in second-round review for the journal *Climatic Change*.

Prosets: making continued use of fossil fuels compatible with a credible transition to net zero

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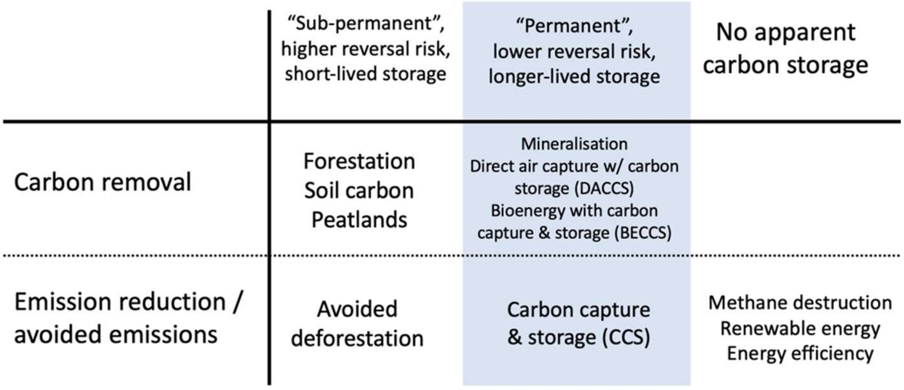
Abstract

Interest in carbon offsetting is resurging among companies and institutions, but the vast majority of existing offerings fail to make continued use of fossil fuels compatible with a credible transition to sustainable net zero emissions. A clear definition of what makes an offset net-zero-compliant is needed. We introduce the 'proset', a new form of composite offset in which the fraction of carbon allocated to geological-timescale storage options increases progressively, reaching 100% by the target net zero date, generating predictable demand for effectively permanent CO_2 storage while making the most of the near-term opportunities provided by nature-based climate solutions, all at an affordable cost to the offset purchaser.

Is carbon offsetting a credible way of compensating for emissions from fossil fuels? While firms, investors, governments, non-state actors, and academics alike have wrestled with how to approach carbon offsetting for nearly two decades, this specific question is rarely satisfactorily answered. Before the COVID-19 pandemic induced a temporary dip in global emissions, a new offset boom was underway, characterised by increasing purchase volumes[1,2] and interest in nascent carbon removal techniques[3,4]. As the pandemic gradually recedes that boom is resurging, and organisations are increasingly committing to achieve net zero emissions of carbon dioxide (CO_2) before mid-century or as early as 2030[5]. Many of these entities depend on the continued use of fossil fuels for activities such as international travel. At present, their only available options apart from ceasing these activities entirely[6] are to first reduce or substitute the activity with lower-carbon alternatives to the extent possible, and then attempt to neutralise the impact of any residual emissions with the voluntary purchase of carbon credits. The bulk of offsetting options available today are either credits that avoid emissions through investment in alternatives to fossil fuels, which as the cost of renewable energy declines face increasing challenges over non-additionality (whether the benefits "would have occurred anyway"), or nature-based climate solutions, including emission reductions through avoided damage to ecosystems, or carbon removal through forestation and other nature-based sequestration (59% of carbon offset credits originating in the 2015-2020 period come from forestry and land use projects[7]). Many of these options will no longer be available to offset fossil fuel emissions in a few decades' time. First, in the net-zero world we are moving toward, there will be no scope for large-scale compensation for emissions through the purchase of avoided emission and emission reduction carbon credits, because those reductions would have already occurred on the journey to net zero, and because, by definition, an enduring net zero state is one in which remaining emissions are balanced with exclusively *removals*. Nature-based *avoided emission* carbon credits will therefore need to be phased out as a means of neutralising ongoing fossil fuel emissions. While nature-based *removal* carbon credits will continue to play an important role throughout the net zero transition, they face several constraints including limited land area in competition for food and fiber production, and the impact of global warming itself which is likely to substantially weaken, if not reverse, many biospheric carbon sinks[8,9]. Hence for continued offsetting of fossil fuel emissions to be compatible with a sustainable transition to net zero emissions, an increasing fraction of the carbon that underpins those offsets must be allocated to carbon storage options that are likely to perist on geological-timescales with negligible risk of reversal to the atmosphere[10]. Initially that permanently-stored carbon can come from a mix of emission reductions (e.g. equipping carbon capture and storage to existing emission sources) and engineered carbon removal technologies (e.g. mineralisation, direct air capture with carbon storage), but as the net zero date approaches a full transition to exclusively removals will be necessary. See the Oxford Principles for Net Zero Aligned Offsetting[10] for a discussion of these dual transitions, and for a taxonomy of carbon credit types which we refer to in this article. We propose that this transition can be induced and packaged into a new offsetting instrument, termed a progressive offset or ‘proset’, generating demand for effectively permanent CO_2 storage at an affordable cost while not undermining the strong case for immediate investment in shorter-term storage, much of which relies on critically needed nature-based climate solutions.



	“Sub-permanent”, higher reversal risk, short-lived storage	“Permanent”, lower reversal risk, longer-lived storage	No apparent carbon storage
Carbon removal	Forestation Soil carbon Peatlands	Mineralisation Direct air capture w/ carbon storage (DACCS) Bioenergy with carbon capture & storage (BECCS)	
Emission reduction / avoided emissions	Avoided deforestation	Carbon capture & storage (CCS)	Methane destruction Renewable energy Energy efficiency

Figure 1 – This simplified taxonomy of carbon credits distinguishes between removal and emission reduction / avoided emission carbon credits on the one-hand, and by the character of the carbon storage employed on the other hand. Indicative, non-exhaustive examples of carbon project types for each category are shown. Carbon project types with the potential for geological-timescale storage—which makes up an increasing percentage of a “proset”—are shaded in blue.

Offsetting is the act of paying a third party to compensate for the impact of one’s own emissions through one of two actions: **emission reduction/avoidance** or **carbon removal**. Emission reduction or avoided emission carbon credits are generated when a third party emits less CO_2 relative to a counterfactual baseline (what they would have emitted in the absence of the offset contract). Carbon removal credits are generated when CO_2 is recovered directly from the atmosphere and stored. For all instances of carbon removal and many instances of emission reduction carbon credits, the avoided or removed CO_2 must be stored and maintained in a carbon stock, for example in wild or managed ecosystems (forests, soils, etc.), in mineral forms or subsurface formations (carbonates, saline aquifers, disused oil and gas wells, etc.), or in the oceans, long-lived products, or built environment.

There are many challenges with ensuring the atmospheric integrity of carbon credits—whether they actually deliver a climate benefit to the atmosphere—which are documented in offsetting guides[11], case studies[12], and systematic reviews[13–15]. Key concerns affecting integrity include quantification (How much CO_2 is actually avoided or removed?), constraining the risk of non-additionality (Might mitigation have taken place in the absence of demand for the credits generated by the carbon project?), indirect carbon leakage (Has deforestation in one location simply been displaced to another?), and the risk of physical reversal, sometimes referred to as durability or permanence (Will a forest remain intact in perpetuity in the face of pests, fire, logging, agricultural development, and global warming itself? Will CO_2 stored in the subsurface escape before it is chemically immobilised? Does the offset delay rather than permanently avoid emissions? What is the risk that stored CO_2 will be re-emitted to the atmosphere, and if so, how soon?). All of these criteria must be rigorously enforced to ensure integrity of the purported carbon benefit, and any carbon credit used for the purpose of transitioning to and ultimately delivering net zero emissions must represent an unequivocal, high-certainty reduction or removal of CO_2 from the atmosphere that has a low risk of non-additionality, is free from indirect carbon leakage, and is well-accounted for.

However, for the purposes of constructing a net-zero aligned “proset” we assume for the moment that these other criteria are met, and are chiefly concerned with the question of the durability of stored carbon, or the resistance of this stored carbon to being re-released to the atmosphere. CO_2 released by fossil fuel combustion represents the addition of carbon that was previously preserved safely in the lithosphere into a much more labile form, circulating freely in the atmosphere, ocean, and biosphere, and elevating global temperatures for thousands of years. Therefore to be fully effective, any carbon storage intended to compensate for fossil fuel emissions must, in effect, be equally permanent. “Physical” permanence can be delivered by employing CO_2 storage techniques with extremely low physical risks of reversal, such as the chemical immobilisation of CO_2 into mineralised forms either aboveground or in geological formations, or the incorporation of carbon into sediments. Alternatively, “virtual” or “contracted” permanence could also be delivered through financial or legal mechanisms (e.g. insurance, covenants, an accruing pool of funds) that insure that any physical reversal event must be remediated by “topping up” a comparable carbon sink. In this way, higher-risk carbon storage techniques could be made “virtually permanent”, provided trust is maintained in the institutions and legal instruments used to ensure someone is held liability for remediating reversals of CO_2 to the atmosphere. There is a premium to the climate for carbon storage that has a negligible risk of physical reversal, since it can continue to provide a climate benefit with limited human intervention even when the entities who financed the removal and storage have long since been absolved of liability or indeed have ceased to exist.

Beyond ensuring that the standard offset quality criteria are met, there are three further overarching challenges that threaten to undermine the effectiveness of voluntary carbon offsetting. The first is the risk of perpetuating the use of predominately emission reduction (and avoided emission) carbon credits in lieu of supporting a progressive transition to carbon removal credits. For clarity, we are not referring to emission reductions writ large, which remain the most important and urgent means of delivering progress toward net zero emissions for all actors. Absolute emission reductions at the firm or state level must remain the top priority in a mitigation hierarchy. Offsets should be used primarily as a means of compensating for residual, unabatable emissions, not as a replacement for cost effective direct reductions to CO_2 emissions. Rather, we refer specifically here to emission reduction and avoided emission carbon offset credits, which make up a supermajority of the credits available today on the voluntary carbon market[7]. These credits, even if perfectly administered, are not sustainable in a net zero world. Once global emissions reach net zero, there will be no scope to compensate for ongoing emissions by paying a third party to reduce their emissions. Use of avoided emission carbon offset credits must therefore be transitional, and ultimately give way to exclusive reliance on removal carbon offset credits to neutralise any residual emissions.

Proset definition: A ***proset*** is a financial instrument that allows the purchaser to compensate for the impact of CO_2 emissions from fossil fuel use by committing an equivalent quantity of CO_2 to a combination of permanent and sub-permanent storage, with the fraction stored permanently increasing progressively over time following a path that is defined by the proset itself and consistent with 100% permanent storage by a specified target date. "Permanent" denotes storage that has a negligible risk of physical reversal and is therefore expected to persist for thousands of years with minimal intervention. "Sub-permanent" denotes storage for at least 100 years, perhaps with ongoing support from buffer pools and other legal mechanisms, associated with the most secure storage options in the biosphere and oceans and with conventional storage

Second, it is not possible to compensate indefinitely for continued use of fossil fuels through carbon removal with Nature-based Climate Solutions (NbCS, meaning the management of natural or human-mediated biological systems such as forests, grasslands, wetlands, and increasingly agricultural soils to enhance carbon storage). Large scale conversion of fossil carbon into biologically-stored carbon cannot be sustained in perpetuity because the global biosphere's capacity is limited[16]. Projections of the rate of release of carbon from the biosphere by mid-century, for example through thawing tundra, changes to tropical forest carbon fluxes, or increased wildfires, are similar to optimistic estimates of the potential global rate of carbon uptake by NbCS[9]. It is therefore possible that all available NbCS options will be required simply to prevent the global biosphere from further exacerbating global warming, leaving no additional capacity to compensate for ongoing fossil fuel emissions. Users of NbCS to compensate for fossil fuel emissions need to recognise that they are tapping into a rapidly depleting global resource which is under fierce competition from other land uses, primarily agriculture and timber management to provide food and fibre.

Despite these challenges, the global market for voluntary offsetts approached 100 million metric tonnes of carbon-dioxide equivalent ($MtCO_2e$) in 2018 at an average price of around $3 per tonne[17], almost all of which represent avoided emissions and carbon storage in relatively high-risk carbon stocks[7]. This highlights a third systemic problem with the voluntary carbon market as currently constituted: offset prices are typically too low to motivate buyers to reduce their own emissions, locking in high-carbon behaviour and investment. Relatedly, 75% of carbon projects to-date operated outside of North America and Europe, predominately in poorer, "Majority World" countries[7], but sold their credits to wealthier polluting entities in "Minority World" countries. The trading of these very inexpensive permits to pollute can raise issues of equity, disenfranchisement of local communities,[18,19] and the exhaustion of "low-hanging fruit" abatement opportunties in countries that may have few other means of meeting climate goals.

Growing awareness of these problems with traditional offsetting has fuelled interest in specialised products that compensate for the impact of fossil fuel emissions by capturing and storing CO_2 for very long timescales. This interest has so far focused primarily on nascent carbon removal pathways such as direct air capture of CO_2 coupled with geological carbon storage (DACCS), remineralisation (converting CO_2 into rock), and various forms of Biomass Carbon Removal and Storage (BiCRS[20]), whose maturity, outstanding uncertainties, and theoretical potential have been reviewed elsewhere[21,22]. These are currently much more expensive than traditional carbon credits (e.g. $300-700/$tCO_2$ for DACCS[3,23], $50-500 for mineralisation[24]). In principle, conventional carbon capture and storage at industrial point sources (CCS), while an emission reduction and not carbon removal, provides the same atmospheric outcome and security of storage as the above examples, and typically at significantly lower cost due to the much higher CO_2 concentrations in industrial flue gasses as compared to the ambient atmosphere[23]. Indeed most offshore CO_2 storage infrastructure in development will likely accommodate a mix of both removed CO_2 and averted industrial emissions. However, conventional CCS faces deeper questions about its additionality when packaged into voluntary carbon credits, given overlapping incentives from other industrial and climate policies, as well as challenges to its public acceptability[25]. We therefore expect emission reductions with permanent storage (e.g. CCS) to be less readily deployable than carbon removal with permanent storage (e.g. DACCS) into the voluntary carbon market.

In summary, any entity aiming to neutralise the impact of its fossil fuel emissions in the next few years is faced with an uncomfortable choice among 1) cheap but very possibly ineffective traditional carbon credits (predominately avoided emissions), 2) moderately more expensive carbon removal credits with relatively insecure storage, or emission reduction credits with highly secure storage, and 3) carbon credits that are both removals *and* deliver highly-secure storage (e.g. DACCS), but which remain expensive and scarce for now.

Prosets: a progressive transition to permanent CO_2 storage

The solution we propose is to define a new financial instrument, named a progressive offset or "proset", which allows the purchaser to compensate for the impact of their emissions by physically storing an equivalent quantity of CO_2 in a predetermined mix of carbon stocks including the biosphere (primarily vegetation and soils) and lithosphere (the earth's crust), and potentially the ocean, long-lived products, and the built environment. The defining characteristic of a proset is that the fraction of CO_2 that is stored *permanently* increases progressively over time, following a path that is defined by the proset itself. In this context, permanent storage may be interpreted as reservoirs with an effective lifetime greater than 10,000 years, corresponding to a physical reversal rate of less than 0.01% per year, achievable in sub-surface storage where CO_2 in pore spaces is chemically immobilised over time[26]. The remaining CO_2 in a proset is stored in reservoirs with a lifetime greater than 100 years, which would likely be predominately in well-managed forests and other managed or wild ecosystems, or perhaps as elements of the built environment, biochar, or other intermediate-duration storage pathways.

The time-evolution of the permanently stored fraction is specified in the full definition of a proset, which includes the start date, the end date (which is the net zero date), and the order of the polynomial describing the increase in the permanently stored fraction. In a 2nd-order 2020-2050 proset (illustrated in Figure 1), for example, this permanent fraction increases with time from 2020, divided by the time from 2020 to 2050, and raised to the power of two (hence 2nd-order). The permanent storage fraction would therefore be $(1/30)^2$, or 0.1%, in 2021; $(10/30)^2$, or 11%, in 2030; and $(20/30)^2$, or 44%, in 2040. By 2050, the specified net zero date, it would always

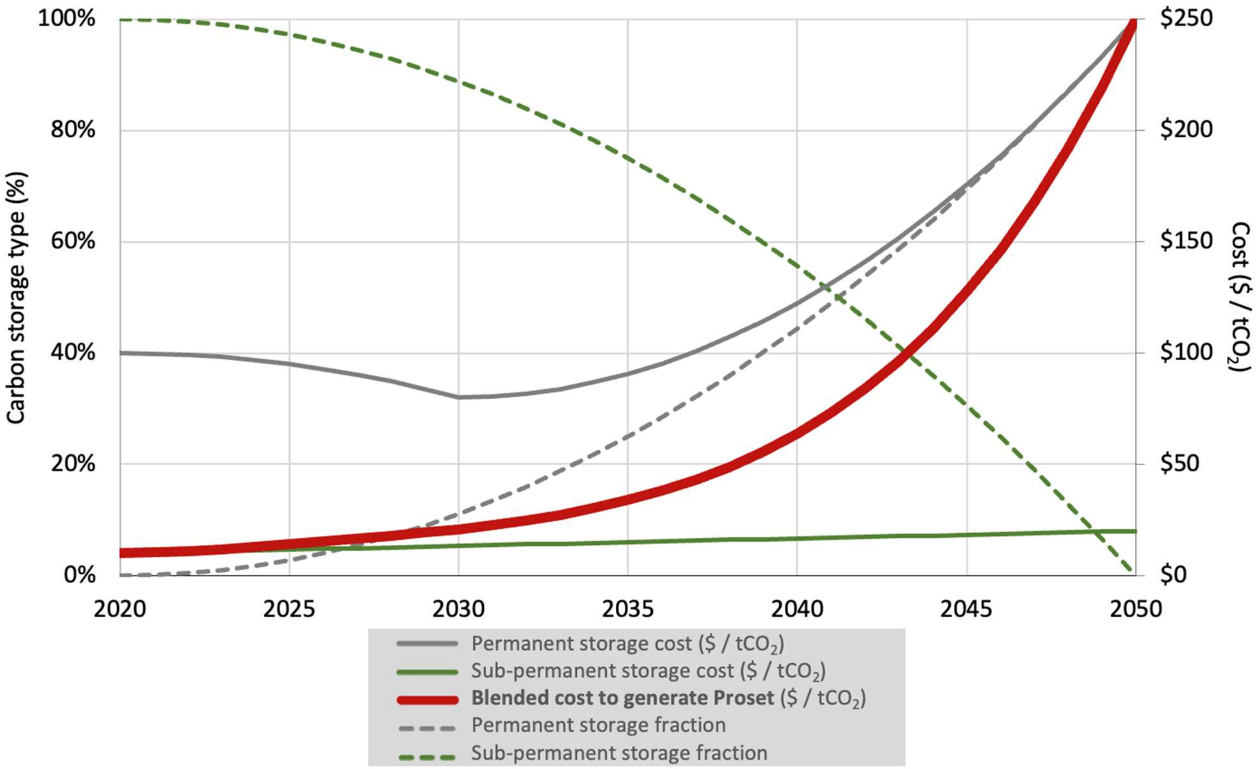


***Figure 2 – CO_2 storage method and cost for a 2020-2050 2nd-order proset**. Figure depicts an illustrative proset (2nd-order 2020-2050, see main text for full definition) with the percentages of sub-permanent (primarily biological) and permanent (primarily geological) storage as green and gray dashed lines, respectively. The costs (solid lines) of sub-permanent storage is assumed to escalate linearly from $10/t$CO_2$ in 2020 to $20/t$CO_2$ in 2050, representing an approximate cost for forestation carbon credits that increases over time as the cheapest land is exhausted. These costs are in line with recent carbon removal procurements with a high share of forest carbon storage (e.g. Microsoft). Permanent storage costs represent the assumed full-chain cost to capture or remove, transport, and store 1 ton of CO_2. This is assumed to decline from an initial cost of $100/t$CO_2$ in 2020 to $80/t$CO_2$ in 2030 due to learning-by-doing as carbon storage projects begin to scale up. From 2030 to 2050, the dominant factor is assumed to be the declining availability of cheaper, high-purity point sources of CO_2 and an ever-increasing reliance on low-purity streams of CO_2 including direct removal from the atmosphere. By 2050, we assume the steady-state cost of a blended portfolio of carbon removal with ultra-low risk of reversal (e.g. DACCS, mineralisation) approaches a backstop cost of $250/t$CO_2$. Forward-looking cost assumptions are inherently uncertain, but the general trend for a proset will hold: initial cost is low and mirrors the cost of biological carbon removal, but trends upward toward a backstop cost reflecting permanent carbon removal. Permanent storage costs are based on ref. 22.*

reach 100%. This is a general definition of a proset, but if only the end date is given, it must be assumed that the initial date is fixed to 2020, not the date on which prosets are adopted (to avoid unfairly benefiting late adopters).

A proset is a packaged product made up of a blend of constituent carbon credits with different storage attributes. The blend of credits making up a proset is determined by the year in which the proset is to be retired. As a result, prosets that are assembled, sold, and retired in 2025 would not be retirable in another year, because future years require a higher percentage of permanent storage. However, unsold 2025 prosets could be broken up into their constituent carbon credits, and repackaged into new prosets with the appropriate (and increased) percentage of permanent carbon storage for a subsequent year. Whereas unretired conventional carbon credits of a given "vintage" can persist from year-to-year until they are eventually retired, prosets must be packaged and sold within a single year. Proset providers are essentially portfolio managers responsible for purchasing requisite volumes of both shorter and longer-lived storage carbon credits to package into prosets for each year.

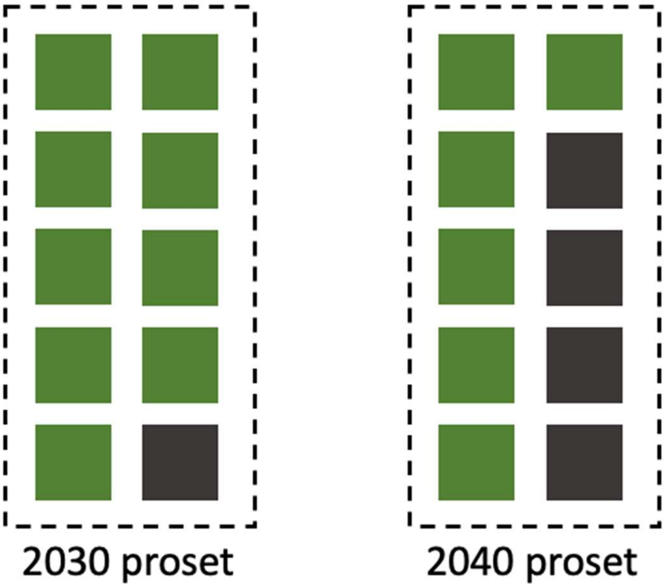


Figure 3 - Prosets packaged for given years are in practice created by aggregating a mix of shorter-lived storage (green) and longer-lived storage (gray) carbon credits. Shown here are illustrative prosets intended for retirement in the 2030 (roughly 10% long-lived storage) and 2040 (roughly 40% long-lived storage) years of a 2020-2050 2nd order proset trajectory. If this 2030 proset went unsold and unretired, its constituent carbon credits could be repackaged in another year (with the appropriately escalated permanent stored fraction).

Note that this general definition of a proset is agnostic to the source of CO_2 for both the permanent and sub-permanent storage components. Given the challenges of developing a market for permanent CO_2 storage, we believe it would make sense to allow any CO_2 that would otherwise, under normal business practice, have ended up as unabated emissions into the atmosphere, to count towards the permanently stored fraction of a proset. This would allow CO_2 capture at point sources, an emission reduction, to be utilised, provided this was not already being used to discharge some other obligation such as compliance with an emission trading system (which would compromise additionality). As point sources are brought under progressively tightening emission caps, an increasing fraction of permanently stored CO_2 would inevitably need to be sourced from carbon removal by techniques such as mineralisation, direct air capture, or some forms of biogenic CO_2 capture coupled with geological storage. Similarly, we assume that the sub-permanent storage component also transitions rapidly from emission reduction options (e.g. avoided deforestation) to carbon removal (e.g. forestation or peatland restoration) in keeping with the volumes of removals needed to meet Paris temperature goals and the ultimate destination of 100% removals balancing any residual emissions. While we assume these transitions toward removals occur organically, proset adopters might choose to further specify the breakdown in the source types of CO_2 used to generate their prosets. For example, some users might require that a progressive fraction of the permanent and/or sub-permanent storage used to create their proset come from carbon removals rather than emission reductions. For the permanently stored fraction, this would have the effect of providing targeted support for DACCS, remineralisation pathways, and perhaps enhanced weathering – all nascent carbon removal pathways which will benefit from early investment. We believe emphasis is most usefully placed on the character and security of carbon storage (permanent vs. sub-permanent), not the source of the CO_2 (removals vs. reductions). However, some proset users may have sensitivities around the inclusion of certain point source emitters (e.g. bio-diesel refineries, natural gas processing) in a voluntary prosetting scheme. The proset model can easily accommodate such exclusion criteria provided the essence of the concept—a fundamental progression toward 100% permanent storage—is maintained.

By definition, a commitment to purchase prosets to cover ongoing fossil fuel emissions provides a predictable pathway to sustainable net zero by the target date, while also neutralising the warming impact of those emissions in the meantime, consistent with both the letter of corporate commitments to achieve net zero emissions as soon as possible, and also with the spirit of these commitments to sustainably end their contributions to global warming. It does so at a cost that we estimate is, in 2020, no higher than that of many conventional, high-quality offsets, but which will increase as the net zero date approaches (see Figure 1).

In principle, as long as the permanently stored fraction rises to 100% by the proset end date, this provides a path to net zero regardless of the shape of the evolution of this stored fraction. But the higher the order of the proset, the more the effort is backloaded. A 3rd-order 2050 proset would require only $(1/3)^3$, or 3.7%, permanent storage in 2030. An observed result of least-cost ambitious mitigation scenarios from Integrated Assessment Models[27] is that the fraction of global CO_2 production that is permanently stored increases approximately quadratically, as in a 2nd-order proset, from 2020 to the date of net zero[28]. Further backloading this increase through the use of 3rd or higher-order prosets would therefore impose a disproportionate fraction of the cost onto future decades, undermining the credibility of the commitment.

The case for universally-defined prosets

Although it has been used to fund some laudable initiatives, the voluntary offsetting market has thus far failed to deliver a net zero-compliant instrument. Supply has greatly exceeded demand, resulting in very low prices and offsets of dubious quality. There are many competing standards, none of which addresses the need to transition to permanent storage. Many offset sellers already allow purchasers to specify a mix of carbon offset types, but that mix is determined by purchasers' preferences, not what a sustainable net zero pathway requires.

The fact that the fraction of CO_2 produced by the burning of fossil fuels globally that is permanently stored needs to rise to 100% by the time of global net zero emissions has long been noted[29], but the concept of a time-evolving permanent storage fraction built into the design of an offset-like product, with a pre-specified profile to achieve sustainable net zero by a specific date is, to our knowledge, novel.

While recognising the dangers of a proliferation of terms, we believe that introducing a new word to define this concept may be helpful to avoid the definitional "race-to-the-bottom" that often beset conventional offsets. The definition we propose is sufficiently general that it would apply to any monotonically increasing permanently stored fraction, and hence to any offset programme that is genuinely compatible with a sustainable transition to net zero. While we note the dangers of excessive backloading, we prefer to avoid freezing the definition of the rate of escalation of the permanently stored fraction from the outset, hoping to initiate an open discussion about the role of offsetting in the net zero transition.

A possible way forward would be for a coalition of academics, environmental NGOs, and offset providers to work toward a universally acceptable, net zero-compliant proset definition, including both the profile (or order) of the proset and the permissible characteristics of both the CO_2 storage options and the emissions sources that the proset is intended to neutralise. As discussed above, we propose focusing on the character of storage and remaining agnostic to the sources of captured CO_2, allowing point sources of CO_2 to be used to generate prosets in advance of achieving global net zero emissions, but we recognise the need for an open discussion about the implications. For example, should an oil-and-gas operator be allowed to generate prosets by voluntarily equipping gas-processing facilities with carbon capture at relatively low cost? When the alternative is venting that CO_2 into the atmosphere we think the answer is yes, at least until the regulatory framework catches up, but this should be open to debate. Such an initiative could be stewarded by an established organisation or initiative. The advantage of a centrally-defined proset is that it could potentially be used to prevent the sale of lower-quality, proset-like products that would undercut the market by adopting a looser definition of "permanent", or a late-increasing profile that backloads the transition to permanent storage. The disadvantage is that it might discourage some adopters, particularly if prosets were strongly associated with a single profit-making supplier or certifying agency. This could be addressed by making a clear distinction between supply and certification, and entrusting a non-profit entity with a detailed and binding mandate to maintain proset integrity.

In terms of the broader role of carbon offsetting in the fight against climate change, we agree with Stephen Schneider's assessment: "I don't believe offsets are a distraction. But we'll have failed if that's all we do."[30] Volunteerism has its limits, and concerted climate action eventually necessitates regulation. But voluntary carbon markets are more than just a placeholder. They can provide a testing ground for compliance markets, leading to regulation which uses voluntary action as evidence for what is possible. Prosets specifically offer a means of transitioning to permanent storage on a voluntary basis, a transition which we envision could one day be taken up by policymakers who wish to codify and enforce a balance of extracted carbon with permanent sinks[29], representing durable net zero.

Declarations

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References

1. Gross, A., Hook, L. & Powley, T. Boom times are back for carbon offsetting industry. https://www.ft.com/content/7e4665a2-1776-11ea-8d73-6303645ac406 (2019).
2. Laville, S. 'Greta Thunberg effect' driving growth in carbon offsetting. *The Guardian* (2019).
3. Izikowitz, D. Carbon Purchase Agreements, Dactories, and Supply-Chain Innovation: What Will It Take to Scale-Up Modular Direct Air Capture Technology to a Gigatonne Scale. *Front. Clim.* **3**, 636657 (2021).
4. Joppa, L. Progress on our goal to be carbon negative by 2030. *Microsoft on the Issues* https://blogs.microsoft.com/on-the-issues/2020/07/21/carbon-negative-transform-to-net-zero/ (2020).
5. B Corp. 500+ B Corps Commit to Net Zero by 2030 | Certified B Corporation. https://bcorporation.net/news/500-b-corps-commit-net-zero-2030 (2019).
6. Allwood, J. *et al. Absolute Zero*. https://www.repository.cam.ac.uk/handle/1810/299414 (2019) doi:10.17863/CAM.46075.
7. Mitchell-Larson, E. & Bushman, T. *Carbon Direct Commentary: Release of the Voluntary Registry Offsets Database*. https://carbon-direct.com/wp-content/uploads/2021/04/CD-Commentary-on-Voluntary-Registry-Offsets-Database_April-2021.pdf (2021).
8. Brienen, R. J. W. *et al.* Long-term decline of the Amazon carbon sink. *Nature* **519**, 344–348 (2015).
9. Lowe, J. A. & Bernie, D. The impact of Earth system feedbacks on carbon budgets and climate response. *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.* **376**, 20170263 (2018).
10. Allen, M. *et al. The Oxford Principles for Net Zero Aligned Carbon Offsetting*. (2020).
11. Broekhoff, D., Gillenwater, M., Colbert-Sangree, T. & Cage, P. *Securing Climate Benefit: A Guide to Using Carbon Offsets*. 59 https://www.sei.org/publications/guide-to-using-carbon-offsets/ (2019).
12. Cavanagh, C. & Benjaminsen, T. A. Virtual nature, violent accumulation: The 'spectacular failure' of carbon offsetting at a Ugandan National Park. *Geoforum* **56**, 55–65 (2014).
13. Galik, C. S. & Jackson, R. B. Risks to forest carbon offset projects in a changing climate. *For. Ecol. Manag.* **257**, 2209–2216 (2009).

14. Haya, B. *et al.* Managing uncertainty in carbon offsets: insights from California's standardized approach. *Clim. Policy* **20**, 1112–1126 (2020).
15. Cames, D. M. *et al. How additional is the Clean Development Mechanism?* 173 https://ec.europa.eu/clima/sites/clima/files/ets/docs/clean_dev_mechanism_en.pdf (2016).
16. Griscom, B. W. *et al.* Natural climate solutions. *Proc. Natl. Acad. Sci.* **114**, 11645–11650 (2017).
17. Hamrick, K. & Goldstein, A. *Raising Ambition - State of the Voluntary Carbon Markets 2016*. https://www.forest-trends.org/wp-content/uploads/imported/2016sovcm-report_10-pdf.pdf (2016).
18. Lejano, R. P., Kan, W. S. & Chau, C. C. The Hidden Disequities of Carbon Trading: Carbon Emissions, Air Toxics, and Environmental Justice. *Front. Environ. Sci.* **0**, (2020).
19. Finley-Brook, M. Justice and Equity in Carbon Offset Governance: Debates and Dilemmas. in *The Carbon Fix: Forest Carbon, Social Justice and Environmental Governance* 74–88 (Routledge, 2016).
20. Sandalow, D., Aines, R., Friedmann, J., McCormick, C. & Sanchez, D. *Biomass Carbon Removal and Storage (BiCRS) Roadmap*. https://www.icef-forum.org/roadmap/ (2020).
21. Smith, P. *et al.* Biophysical and economic limits to negative CO2 emissions. *Nat. Clim. Change* **6**, 42–50 (2016).
22. Fuss, S. *et al.* Negative emissions—Part 2: Costs, potentials and side effects. *Environ. Res. Lett.* **13**, 063002 (2018).
23. Bui, M. *et al.* Carbon capture and storage (CCS): the way forward. *Energy Environ. Sci.* **11**, 1062–1176 (2018).
24. Kelemen, P., Benson, S. M., Pilorgé, H., Psarras, P. & Wilcox, J. An Overview of the Status and Challenges of CO2 Storage in Minerals and Geological Formations. *Front. Clim.* **1**, 9 (2019).
25. Cox, E., Spence, E. & Pidgeon, N. Public perceptions of carbon dioxide removal in the United States and the United Kingdom. *Nat. Clim. Change* **10**, 744–749 (2020).
26. García, J. H. & Torvanger, A. Carbon leakage from geological storage sites: Implications for carbon trading. *Energy Policy* **127**, 320–329 (2019).

27. Huppmann, D. *et al.* IAMC 1.5°C Scenario Explorer and Data hosted by IIASA. (2019) doi:10.5281/zenodo.3363345.
28. Jenkins, S., Mitchell-Larson, E., Haszeldine, S. & Allen, M. Sustainable financing of permanent CO2 disposal through a Carbon Takeback Obligation. *Nat. Clim. Change* 10 (2021).
29. Allen, M. R., Frame, D. J. & Mason, C. F. The case for mandatory sequestration. *Nat. Geosci.* **2**, 813–814 (2009).
30. Ellison, K. Shopping for carbon credits. *Salon* https://www.salon.com/2007/07/02/carbon_credits/ (2007).