METHODS FOR ESTIMATING POTENTIAL GREENHOUSE GAS EMISSIONS REDUCTIONS FROM ACHIEVING GLOBAL BIODIVERSITY TARGETS

UN environment programme WCMC

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Cover image: Aerial view of the Everglades, Juan Carlos Munoz, United States of America, Adobe Stock

Contents

1. Purpose of this document

This document describes the methods used in an analysis of the contribution to reducing global emissions of greenhouse gases that can be made by meeting emerging global biodiversity targets (proposed 2030 action targets of the post-2020 Global Biodiversity Framework, CBD (2020)). It aims to put the methods in the public domain in advance of the publication of the results as an input to COP26-related discussions and it will serve as a technical annex to that publication. A further peer-reviewed academic publication is anticipated according to the time frame of the journal submission and peer review process - likely early to mid-2022.

2. Introduction

Growing recognition of the strong links between the global agendas on climate change and biodiversity (UNFCCC and CBD) has focused attention on approaches that can help meet the goals of both agendas efficiently and effectively. This work aims to help address the question:

> How much can achieving existing and emerging global biodiversity targets on area-based conservation and ecosystem restoration contribute to climate change mitigation?

Several recent exercises have analysed global relationships among aspects of biodiversity and carbon stocks and sequestration (e.g., Naidoo et al., 2008, Strassburg et al., 2010, Larsen et al., 2011, De Lamo et al., 2020, Soto-Navarro et al., 2020 and references therein, Strassburg et al., 2020, and Jung et al., 2021), with a view to informing policy development on conservation, climate change mitigation or both. In the most recent and innovative of these, the Nature Map consortium (core partners UNEP-WCMC, IIASA, IIS and UN SDSN) has developed new ways of analysing data on biodiversity and carbon spatially to support decision making respectively on conservation (Jung et al., 2021) and ecosystem restoration from converted lands (Strassburg et al., 2020), and related biodiversity targets. In addition, these analyses have incorporated large amounts of newly available global biodiversity data not included in previous efforts (e.g., Larsen et al., 2011 and Soto-Navarro et al., 2020). These advances enable joint consideration of current biodiversity status and carbon stocks and the synergies and trade-offs between them globally. They also make it possible to explore the effects on biodiversity loss of different area targets for protected and conserved areas and for ecosystem restoration. However, to date they have not estimated the concomitant effects on greenhouse gas emissions.

This study builds on the work described by Strassburg et al., 2020 and Jung et al., 2021 to estimate the potential impacts on greenhouse gas emissions of action to reduce global biodiversity loss in accordance with targets for area-based conservation and ecosystem restoration (Figure 1). It focuses on two of the targets included in the updated Zero Draft of the CBD's post-2020 Global Biodiversity Framework (CBD/SBSTTA/24/3) :

- "Target 2. . . . protect and conserve . . . at least 30% of the planet with the focus on areas particularly important for biodiversity"
- "Target 1 . . . allow to restore [X%] of degraded freshwater, marine and terrestrial natural ecosystems and connectivity among them",

2.1 Conceptual basis

To understand the impacts of conservation or restoration measures on greenhouse gas emissions, we need to know the current/potential carbon stocks and the expected emissions in the absence of conservation interventions. The key uncertainties that need to be addressed to do this are:

- The likelihood that any given area of natural ecosystem not conserved or sustainably managed would be converted to other land uses or degraded, resulting in carbon emissions (and the likely magnitude and time frame of those emissions)
- the carbon emissions that could result from land-use change displaced rather than eliminated by conservation action (i.e., leakage: Meyfroidt et al., 2020))

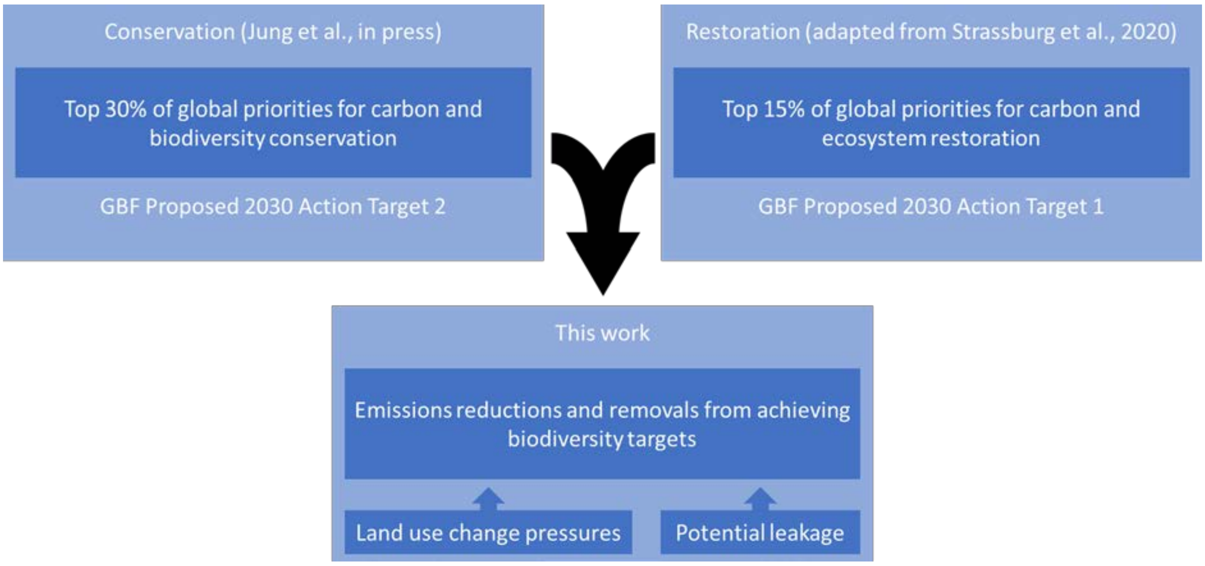

Figure 1: This work focuses on greenhouse gas emissions reductions and removals, building on the two previous studies of conservation and restoration priorities.

This document summarises the approaches used by the Nature Map consortium to optimize jointly for carbon and biodiversity outcomes when identifying global priority areas for ecosystem conservation (Jung et al., 2021) and ecosystem restoration (adapted from Strassburg et al., 2020) on land. It then describes the approach that will be used to combine these priority areas with modelled projections of land use change (from Leclère et al., 2020) and the ways that specific methodological challenges will be resolved, and uncertainties evaluated. Finally, it presents an initial review of leakage estimates that will be used to assess real-world uncertainties in the calculated emissions reductions.

Ultimately, the results of these analyses and estimations of uncertainty will be combined to provide a refined global overview of the potential emissions reductions that could result from conservation and restoration action to achieve biodiversity targets and a narrative that highlights the uncertainties associated with these estimates.

3. Identifying priority areas for conservation and restoration

The methodology adopted by the Nature Map consortium to identify the global priorities for conservation is explained in detail in Jung et al. (in press). The methodology for restoration priorities on converted lands builds on Strassburg et al. (2020), with some modifications to make it more compatible with the conservation analysis.

This section describes the common joint optimization approach to prioritization taken by both analyses, and presents a table summarising where they differ in methods or inputs from one another or from the published papers.

3.1 Nature Map prioritisation approach

The approaches used to prioritise jointly for carbon and biodiversity benefits in relation to conservation and to restoration both involve spatial conservation prioritization through linear programming to identify an optimal set of high-priority areas for biodiversity (securing species conservation status) and carbon (stocks or potential stocks). Incremental land area targets (budgets) were used for both analyses to derive nested sets of priorities covering increasing areas of land (i.e analyses were run for priority sets encompassing 10%, 20%, 30% etc of total land area).

For biodiversity, the basis of the analysis is the area of suitable habitat within species ranges that could be retained (conservation) or expanded (restoration), using IUCN habitat affiliations to identify suitable habitat. Area targets are set for each species such that sufficient suitable habitat is managed for conservation to avoid threatened status resulting from habitat loss, or restored to improve conservation status[1]. The prioritisation aims to come as close as possible to meeting these targets for all species, within a given area budget. Carbon was given equal weight in the prioritisation to outcomes for all species combined. The planning units used in both analyses are 10x10km. Details on the input data are provided in Table 1; for discussion of their limitations and associated uncertainty see Annex A and the published papers.

The methods from the published papers have been modified for the current analysis to allow the two maps to be combined; notably (i) the conservation analysis used here does not include water, and "locks in" existing protected areas before identifying further priorities (ii) neither analysis includes opportunity or implementation costs, whereas the published restoration paper does. The inputs have also been aligned to the extent possible (see Table 1 and Annex A for further details).

[1] targets set so that the species would not be threatened according to IUCN Red List criteria A on population decline (translated into 80% of a species suitable habitat) and B2 on area of occupancy (translated into 2,200km^2 of suitable habitat)

Table 1: Comparison of the methodologies for conservation and restoration prioritization (for further details, see Jung et al. (in press) and Strassburg et al. (2020) and Annex A)

			Conservation (IIASA)	**Restoration (IIS)**
Based on			Jung et al., (in press)	Strassburg et al., 2020
Input	Biodiversity	Taxa	282,152 species of birds, mammals, amphibians, plants and reptiles.	107,000 species of birds, mammals, amphibians, and plants (the subset of these species for which restorable area was available).
		Species occurrence (data from IUCN)	Species' occurrence was refined by elevation, seasonality (for relevant species), and species suitable habitat - AOH (all data from IUCN).	Species' occurrence was refined by elevation and species suitable habitat - AOH (all data from IUCN). IUCN habitats were reclassified to match five ecosystem types (forests, wetlands, arid ecosystems, natural grasslands and shrublands).
	Carbon	Actual or potential stocks	The carbon prioritization aimed at conserving as much carbon as possible, using: (i) Spatial estimates of the density of above-ground and below-ground biomass carbon, which were derived by combining multiple sources, using the Copernicus Land Cover (GLC-100) map for 2015 to select the layer used to assign above-ground biomass for each grid cell in the analysis (Garcia Rangel in prep., building on Soto-Navarro et al., 2020). IPCC (2006) root-to-shoot ratios were used to derive below-ground biomass. (ii) Vulnerable soil carbon (defined as "carbon stocks that could potentially be lost during the coming 30 years as a result of land use"), which was mapped using data from Hengl & Wheeler, 2018 and Hengl & Nauman, 2019, estimated separately for organic and mineral soils using IPCC stock change and emissions factor values.	The carbon benefit was measured by the amount of carbon dioxide sequestered following restoration to a reference ecosystem in each geographical zone, considering above and below-ground biomass and soil carbon. Built a global map of carbon stock change in the above- and belowground biomass and in the soils of restorable areas. Maps of current carbon stocks were sampled to obtain mean carbon stock values from remaining native vegetation. These values were extrapolated to restorable areas within the same geographical zone based on the 'Terrestrial Ecoregions of the World' (Dinerstein et al., 2017).
	Land cover	Current land cover	Habitat data were obtained from Jung et al. (2020) which follows the IUCN habitat classification system.	Copernicus Global Land Cover map for 2019 was reclassified from the original 37 classes into ten: 5 classes of natural vegetation (forests, wetlands, grasslands, shrublands, and deserts), 2 classes of areas potentially available for restoration (croplands and cultivated grasslands), 2 classes of non-restorable areas (ice and urban areas) and 1 class for water bodies.
		Original/ past land cover	Not relevant	Copernicus Global Land Cover map for 2015 where natural cover exists in a cell; otherwise based on Dinerstein ecoregions
		Pasture layer	Pastureland defined as grid cells with non-tree covered vegetation from Copernicus land cover data (Buchhorn et al., 2020), which is climatically suitable for tree growth in the absence of grazing, and which has at least 1 head per km^2 of a grazing livestock-unit (LSU) based on region-specific conversion of gridded livestock of the world data (Chilonda and Otte, 2006; Gilbert et al., 2018)	Used the Global Ruminant production system map (Robinson et al., 2014), filtered to exclude categories with areas deemed to excessively overlap with expert-identified areas of natural vegetation.

	Conservation (IIASA)	Restoration (IIS)
Based on	Jung et al., (in press)	Strassburg et al., 2020
Output	10x10km global conservation priorities. The top 30% of terrestrial land area with the highest global conservation value for carbon and biodiversity from the outputs of Jung et al., (in press) was used for this work, inclusive of existing protected areas. This layer represents the proportion of each cell that would need to be managed for conservation. This amounts to 30% of land.	10x10km global restoration priorities for transformed land. A subset representing the top 15% of the ranked restoration raster was used to mask the restoration proportion raster. The resulting raster was used in the joint prioritization method. This layer represents the proportion of each cell that would need to be restored to a natural state to achieve the climate and conservation objectives. This amounts to 15% of global agricultural lands and 2.33% of all lands.

The outputs of this analysis (last section of Table 1) are the result of the joint prioritization for biodiversity and carbon. The biodiversity component addresses securing species conservation status in relation to habitat loss (relates to the proposed 2030 milestone A.2 of the 2050 goal). The carbon component addresses conserving or increasing carbon stocks. Respectively, these scenarios represent achieving the protection of 30% of terrestrial land area (proposed 2030 Action Target 2) and the restoration of 15% of converted terrestrial ecosystems (relates to the proposed 2030 Action Target 1). Finally, both scenarios contribute to the understanding on the potential of Nature-based Solutions and Ecosystem-based approaches to climate change mitigation (proposed 2030 Action Target 7). Targets and goals are based on the update of the zero draft of the post-2020 Global Biodiversity Framework CBD/POST2020/PREP/2/1 (CBD, 2020).

4. Estimating potential emissions reductions and CO_2 removals

The conservation and restoration analyses adopt similar approaches to identify global priority areas. To fulfil the objective of this project of estimating potential emission reductions and removals resulting from achieving emerging global biodiversity targets we need to estimate the proportion of natural habitat that, in the absence of the implementation of biodiversity policy on area-based conservation and restoration, would be converted to anthropogenic land-uses or would not be restored at a given time in the future.

To estimate potential carbon dioxide emissions reductions and removals from the priority areas jointly, we need to:

- Agree a reference scenario, to identify emissions without these biodiversity conservation-focused interventions. We selected the “BASE” scenario of land-use change from the Bending-the-Curve (BtC) study (Leclère et al., 2020), hereafter referred to as the “BASE”.
- Identify and resolve any conflicts between the BASE scenario, conservation and restoration priority analyses. We aim to ensure that restoration only occurs in areas that the BASE scenario identifies as converted, in line with the objectives of the restoration analysis.
- Ensure that existing protected areas are handled consistently. Our priority areas include ~ 15% of the terrestrial land as protected areas. The BASE scenario assumes that there will be no land-use change in these places, which is largely but not entirely accurate given that protected areas are not always effective in preventing land use change (e.g. Herrera et al., 2019). We will therefore omit these protected areas from the priority areas for conservation in our emissions reduction analysis.
- Estimate emission reductions from conservation (avoided emissions) and removals from restoration (annual removals), aiming to include the same carbon pools in both estimates.

The results will then be used as a basis to estimate the emissions avoided (below and above-ground biomass carbon) by protecting the conservation areas from land-use change, and the potential for recovery of carbon stocks by 2050 through ecosystem restoration on converted land. We recognize that this approach does not strictly jointly prioritize areas for both conservation and restoration in a single analysis. However, we have taken steps to ensure that the same areas are not selected for both conservation and restoration (see section 4.2.1)..

Our approach comprises four main steps, summarized in Figure 2.

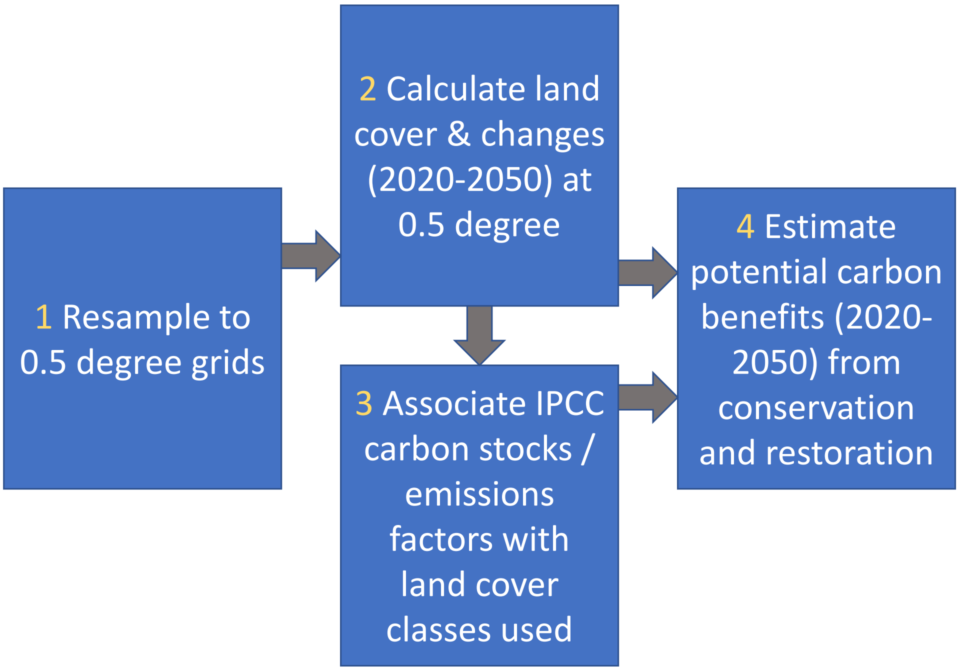

Figure 2: Steps to estimating potential emissions reductions and carbon dioxide removals. For further details, see figure in Annex B

4.1 Resample datasets to allow joint analysis

As the prioritization analyses relied on finer-resolution and differently classified land cover data (10-km grids and Copernicus classes) than the BASE scenario (0.5 degree grids and GLOBIOM land-use classes (Table 2), there are a few steps required to use these data together.

To estimate emissions reductions from the implementation of the conservation priorities, we need to compare this with the emissions under the BASE scenario. To do so, we will work at the resolution of the BASE scenario, aggregating the input layers to the 0.5 degree grid.

To estimate removals from the implementation of the restoration priorities, we will assume that all restoration is additional to the BASE scenario (which includes no restoration action). However, we do need to crosscheck the areas prioritized for restoration with the 'restorable land' in the BASE scenario. We propose to cap the area restored in any 0.5 degree cell to the area available according to the BASE scenario.

Table 2: Land-use legend for the Bending the Curve scenario (Leclère et al., 2020), including the BASE scenario used for this analysis

Land use type	Additional description
Built-up area	
Cropland dedicated to short-rotation bioenergy plantations	2nd generation biofuel perennial crops
Other cropland	
Managed grassland	Grassland managed for livestock (grazed/mowed)
Managed forest	Forest managed for both extractive and non-extractive use – e.g., carbon sequestration
Unmanaged forest	
Other natural land-cover	Vegetated non-forest (e.g. Savannah, steppe, shrubland, taiga) and non-vegetated areas, e.g. bare land
Restored land	Land that was used as managed grassland, managed forest_ or cropland and (a) abandoned and not reused for 30 years or (b) directly set aside for restoration
Abandoned other cropland	Former cropland, still heavily disturbed
Abandoned bioenergy plantations,	Former bioenergy plantation, still heavily disturbed
Abandoned managed grassland	Former managed (grazed/mowed) grassland, still heavily disturbed
Abandoned managed forest	Former managed forest, still heavily disturbed

4.2 Calculate land cover and land cover changes

4.2.1 Resolving overlap between conservation and restoration priority maps

The conservation and restoration priorities have some small overlap, as (a) the pasture layers used were different and (b) on some rare occasions agricultural area was included in the conservation analyses (where species tolerate agriculture and those areas are biogeographically placed in areas of high endemicity, which makes their conservation efficient in contributing to global biodiversity targets with the minimum amount of land conserved) (see Annex A for details). Preliminary analysis shows that 2.1 million km² (4.5% of all pixels in the combined map, and 1.4% of the earth's land area) have fractions summing to more than 1 in a 10-km combined map, and a large proportion of this area only slightly exceeds 1 (1.4 million km² have fractions between 1 and 1.1).

Within each 0.5 degree cell, we will identify the total area prioritized for restoration as indicated above. As there is some small amount of overlap between the conservation and restoration analyses, we will then cap the priority area for conservation as needed, such that restoration and conservation priorities together do not exceed the cell area.

4.2.2 Contrasting land cover change in conservation and BASE scenario

The BASE scenario produces, at 0.5 degree resolution, maps of land-cover and land-use at decadal intervals starting at 2010 up to the end of the 21st century based on the Shared Socio-economic Pathway 2 (for this analysis we are using projections from 2020 to 2050). Analysing multiple scenarios and comparing outputs can be demanding, and the interest of this work is in the potential climate benefit of area-based conservation and restoration, rather than socio-economic and technological transformative changes. In addition to this, Popp et al. (2017), found that the Integrated Assessment

Model (IAM) chosen can affect quantity, quality and distribution of projected land-use changes equally or more than the scenario, depending on the type of land-use change of interest. For this reason, and to limit the number of sensitivity analyses, we will sensitivity test the emission reductions resulting from different choices of IAM, rather than choice of scenario. That is, we will explore the results from more than one of the land-use models applied in the BTC study.

In each case, we will identify the area of change in each of the land cover classes from 2020 to 2050 in the BASE scenario. As the conservation priorities were allocated at a finer resolution than this, where part of a 0.5 degree cell that contains conservation priorities changes under BtC from a natural to an anthropogenic land use, we cannot tell whether it is the same part selected for conservation. We propose to identify a range of outcomes by calculating the results at two extremes:

(i) that conservation has a high impact on land use change, i.e. there is maximum overlap between the BASE scenario's changed area and the conservation area within any given 0.5 degree cell. This assumes that land-use change is more likely to happen in areas valuable for conservation.

(ii) that conservation has a lesser impact on land use change, i.e. that there is minimum overlap within any given 0.5 degree cell. This assumes that land-use change is less likely to happen in areas valuable for conservation.

4.3 Assign carbon stocks/emissions factors

Through a combination of spatial analysis and cross walking of land cover classifications with the IPCC default categories, we will assign IPCC Tier 1-based emission factors to the natural land cover classes used in the restoration analysis (forests, wetlands, grasslands, shrublands, and deserts), transitioning from either cropland or managed pasture. The BASE classes (Table 2) will each be assigned IPCC Tier 1-based biomass carbon stocks. In each case, global GIS layers for continents, ecological and climate zones will be used to subset the Nature Map land cover classes.

4.4 Estimate potential carbon benefits

For restoration, we will assume that all carbon benefit from achieving our restoration priorities is additional to that achieved under the BASE scenario. We will estimate, using the 10 km grid, the annual uptake of carbon dioxide resulting from transitions from cropland or pasture to each of the five natural habitats. The fixed emission factor values assume a linear increase of carbon stocks with time, across restoration interventions, which we recognise is a simplification. We then need to estimate how many years of restorative activities would be achieved between 2020 and 2050, over the global area prioritized. We will assume that *on average*, restoration action is initiated by 2030 (as specified in the Global Biodiversity Framework target). Rather than modelling different speed of action in different parts of the world or in different ecosystems, we will multiply annual uptake by 20 to give total estimated removals over the period.

For conservation, we will derive the total carbon emissions for each 0.5 degree grid cell under the BASE scenario and the minimum and maximum assumptions for conservation impact. We will calculate this in terms of the % loss of the original carbon in the BASE 2020 cell. We will then apply that % loss to the

Nature Map biomass carbon grid, to harmonise the projected emissions with the carbon stocks used in the prioritization analysis. The resulting emissions will be converted to CO_2.

As a result of this analysis, we can estimate CO_2 emissions by 2050 if no further conservation action or restoration of converted ecosystems takes place. We can contrast this with a range of estimates of the difference that would be made by protecting or restoring in accordance with our prioritization analyses. The difference between these two gives us an estimate of net emissions reduction.

4.5 Limitations and caveats: Degradation and permanence are not addressed

For restoration, the methodology developed in Strassburg et al., (2020) focused on converted ecosystems (cropland and pastures). The restoration of degraded habitats in areas with natural land-cover was not considered, due to the absence of a biodiversity model that could estimate the contribution of reducing that level of degradation to reductions in extinction risk. Similarly, habitat degradation was not considered explicitly in Jung et al., (in press) as degraded habitats are not covered separately by the IUCN habitat classification scheme. The carbon map used will have captured reduced carbon stocks in many, but not all, places where these have been degraded. This means that degraded natural habitats could have their present biodiversity value and sometimes carbon stock over-estimated in the conservation analysis. In addition, our analysis does not estimate the removal function of areas identified as priorities for conservation, and so we have not estimated the carbon value of reversing degradation of these natural habitats. Overall, the inclusion of degraded habitats in our priority areas for conservation will affect potential carbon emissions reductions and removals, but we have not estimated the direction or size of this effect. This gap will feature in discussions of the uncertainties in our estimates and future methodological development will aim to address it.

We also do not tackle the permanence of the impacts of the conservation interventions modelled here. Our analyses provide an estimate of the carbon stocks at risk that are presently associated with areas of global conservation significance and the maximum potential carbon stocks that could be sequestered if areas of global importance for habitat restoration were actively restored. It is likely that this potential will not be fully realized, due to ineffective management resulting in further conversion and greenhouse gases emissions, or increased natural disturbance such as drought, fire, pests (Baldocchi and Penuelas 2019; Anderegg et al., 2020). Our analyses also ignore the effect of future climate change on plant physiology, specifically CO2 fertilization, and changes in photosynthetic activities due to water availability, temperature, and humidity.

However, the intention of this study is to provide preliminary estimates of the maximum potential for climate mitigation from conserving or restoring areas of importance for biodiversity, not to provide precise simulations of the carbon cycles as a function of land-use practices. Follow-up studies may wish to test specific actions and complex feedbacks between elements of the earth’s systems, for instance using earth systems or dynamic vegetation models.

5. Estimating uncertainty due to leakage: a review of the evidence

Leakage refers to a situation that may occur when carbon emissions are reduced as a result of an intervention but are replaced by emissions from another location or activity rather than eliminated (Meyfroidt et al., 2020). It was first defined in 2000 by *IPCC* as “changes in emissions and removals of greenhouse gases outside the accounting system that result from activities that cause changes within the boundary of the accounting system” (IPCC, 2000). It typically involves a shift in emissions from one place that has adopted emissions regulation policies to another where policy has not been implemented or is less effective (Murray, 2009).

Agriculture, forestry and other land uses (AFOLU) constituted around 23% of total net anthropogenic greenhouse gas (GHG) emissions between 2007-2016 (IPCC, 2019). In the land-use change and forestry (LULUCF) sector, leakage generally implies the displacement of land conversion, within or across national boundaries. Leakage can potentially be significant compared to the scale of planned GHG emission reductions in mitigation projects. Thus, it constitutes a key challenge to sound climate change policy formulation and needs to be considered when assessing the potential efficacy of climate mitigation measures, including nature-based solutions such as net-zero aligned carbon offsetting measures.

In the land-use context, leakage therefore refers to emissions from LUC displaced outside of an area of jurisdiction; that is, outside an area in which climate change mitigation policies are successfully enacted (Henders and Ostwald, 2012). This leakage can be an unintended consequence of environmental policy that regulates land use but does not tackle land demand (Meyfroidt et al., 2013). Leakage can occur through the direct or indirect displacement of land use (see Box 1 below).

We have conducted a literature review to estimate the potential uncertainties in emissions reductions due to land-use leakage that could be associated with achieving the global biodiversity targets.

We set out to:

- Review existing accounting methods in different contexts and scales
- Review factors that influence leakage in different contexts
- Review existing leakage estimates from the literature
- Develop a robust narrative for leakage estimates relevant to the global analysis of emissions reductions potential from achieving biodiversity targets.

5.1 Approach to literature review

Multiple complex modelling approaches have been used to estimate the extent of leakage from conservation and restoration activities. For the purposes of our current global analysis, it was decided to estimate leakage based on existing estimates, rather than implementing our own model. Therefore, the aim of this literature review was to identify leakage quantification methods and estimates from both peer-reviewed and grey literature, including practical applications in use by voluntary carbon accounting standards. More information on the search methods used can be found in Annex C. The findings will be used to estimate the range of possible leakage -related uncertainty associated with the estimates of emissions reductions that would be achieved from meeting global post-2020 biodiversity targets on area-based conservation and ecosystem restoration.

5.2 Results of literature review

5.2.1 What types of leakage need to be considered?

When quantifying leakage, it is necessary to define the geographic scale on which leakage is expected to operate and the types of leakage being considered (Box 1): for example, direct (primary) and/or indirect (secondary) (Aukland, 2003). All these forms of leakage are relevant to our question. It is not possible to capture all leakage by direct measurement and models have been widely used to estimate the extent of different kinds of leakage.

Box 1: Types of land use change-related leakage described in the literature

- **Primary (direct) leakage:** occurs when the same agents (e.g. companies) carry out the same GHG-emitting activity, but this activity has shifted to another location (Aukland, 2003). E.g. an agricultural concession is revoked and the same company takes up a new concession elsewhere.

- **Secondary (indirect) leakage:** the result of indirect land-use change that is not usually an activity shift and is not carried out by the same actors (Aukland, 2003). This is often related to changes in supply and demand, and thus market prices, of goods and services. For example, increased commodity prices may result from the restoration of agricultural land to a more natural habitat, if there is no accompanying intervention to balance the supply and demand of agricultural products, leading to conversion of other land to production. This is often referred to as a "market effect via trade" (Hertel, 2018). This may occur at the national and international scale as well as locally.

- **Strong Leakage:** occurs when displaced emissions can be directly attributed to an emissions reduction measure. Difficulty in attribution often makes it difficult to assess the degree of strong leakage.

- **Weak leakage:** occurs when displaced emissions cannot be directly attributed to a particular measure. Often includes leakage associated with trade between countries (Blanco et al.,2014).

- **Positive leakage**: occurs when an intervention has a positive impact on reducing carbon emissions in surrounding areas, for example because co-benefits of the change in land-use management are valued locally (e.g. from reduced impact logging, agroforestry) (e.g. Heilmayr *et al*., 2020). Sometimes referred to as 'positive spillovers'.

- **Ecological leakage:** Schwarze *et al.,* (2002) describe a third type of leakage, caused by ecosystem-level processes that affect carbon stocks in surrounding areas (e.g. as a result water table changes during peatland restoration, or of reducing forest fragmentation and its effects on tree mortality). May be positive or negative.

5.2.2 What factors affect the degree of leakage?

In general, policy interventions that effectively influence larger areas will experience less primary leakage. Although there are exceptions, primary leakage is typically a more local process, and secondary leakage is more commonly on a national to international scale (Atmadja and Verchot, 2012). Different methodologies are therefore needed to assess leakage at different scales.

Table 3 summarises findings from the literature on factors that affect the degree of different types of leakage. The types and degree of expected leakage are directly linked to the drivers of ecosystem conversion/ degradation that are being tackled by a conservation intervention, including the sector involved.

Table 3: Factors that affect land-use leakage rate at the international, jurisdictional and sub-national scale.

Factor affecting leakage	**Description**	**Example references**
International leakage		
Level of cooperation and coverage of measures between countries	The more that countries cooperate on conservation/ climate mitigation measures, the less leakage will occur	▪ González-Eguino et al., 2017 ▪ Gan and Mcarl, 2007 ▪ Meyfroidt and Lambin, 2009
International trade: connection to global markets	Countries that are more connected to the global market than others, are more prone to leakage (responding to international demand for agricultural commodities). On the other hand, integrated assessment models find that global trade in agricultural commodities can lead to efficient use of land for production and overall decreased land demand - especially in the context of other interventions to reduce global demand, such as reducing food waste and shifts to more plant-based diets.	▪ Villoria and Hertel, 2011 ▪ Leclère et al., 2020
Rigidity of trade	Trade ties, preferences for products from a particular place of origin. This is associated with price elasticity.	▪ Villoria and Hertel, 2011 ▪ Meyfroidt et al., 2013
Supply chain commitments	Commodity supply chain commitments such as zero-deforestation pledges by retailers or producers will in principle reduce the likelihood of leakage, by disincentivising conversion. However, effectiveness is so far limited by coverage (of regions, commodities and actors), by limited enabling environments and by design issues (traceability, timebound commitments).	▪ Alix-Garcia and Gibbs, 2017 ▪ Lambin et al., 2018 ▪ Garrett et al., 2019
Jurisdictional and sub-national leakage		
Type of intervention	E.g. Afforestation projects have larger leakage than projects reducing deforestation	▪ Acosta and Sohngen, 2009 ▪ Murray et al., 2003
Measures introduced to mitigate leakage	If action has been taken to mitigate leakage (e.g. increase agricultural yield on croplands alongside forest protection), then leakage will be lower	▪ VCS, 2014
Extent of area covered by measure	If the intervention covers an entire jurisdiction, then it is unlikely for domestic leakage to occur. In ART-TREES, if over 90% of forest area is covered by the forest emissions assessment then it is assumed that no leakage occurs.	▪ ART, 2020
National circumstances: Socio-economic factors such as GDP and population growth	Population growth and total per-hectare values of country's forest product removed annually are positively correlated with leakage; whereas leakage is negatively correlated with national population density, and GDP annual growth rate	▪ Fuller et al., 2019
Extent to which an area is impacted by the pressure being mitigated by measure (e.g. deforestation rate) and livelihoods dependency	Leakage will not occur in an area where drivers of land use change are absent.	▪ Ford et al., 2020 ▪ Guidice et al., 2019 ▪ Lasco et al., 2007 ▪ Robalino et al., 2017
Accuracy of estimates of carbon density	There is often a lack of data to assess carbon stocks which can have a large impact on leakage estimates	▪ Boer et al., 2007

Factor affecting leakage	Description	Example references
Productivity of land that has been conserved or restored	E.g. Reducing deforestation/ LUC in low value agricultural regions has lower leakage; grazing land generally lower value than cropland	▪ Acosta and Sohngen, 2009 ▪ Andam et al., 2008
Size and speed of implementation	Quickly implemented large projects have more leakage than small slower implemented projects	▪ Acosta and Sohngen , 2009

The evidence found (Table 3) covers international, jurisdictional and local leakage, based on four broad categories of study/ source:

- Studies of local leakage as in assessments of protected area effectiveness (e.g. Ford et al., 2020)
- Voluntary carbon market standards - e.g. ART-TREES, VERRA JNR (jurisdictional scale)
- Large-scale scenario modelling – e.g. Leclère et al., 2020 (global scale)
- Observed displacement from regional/national policy and market changes – e.g. EU non-food bioeconomy (Bruckner et al., 2019)

Estimates across all spatial scales were found to vary widely. At the local scale, leakage was mostly direct (i.e. activity shifting) and related to the type and extent of GHG emitting-activity present (e.g. for subsistence and domestic commodities or linked to global commodities) (Guidice et al., 2019, Lasco et al., 2007), as well as types of mitigation measure (e.g. Murry et al., 2003), including whether mechanisms were in place to prevent leakage (ART, 2020). As the scale increases to regional and sub-national levels, the complexity of leakage effects increases to include both direct and indirect leakage (Henders and Ostwald, 2012). Jurisdictional estimates of leakage used in national carbon accounting include both activity and market leakages within their accounting system (e.g. VERRA and ART-TREES) (VCS Association, 2014; ART, 2020). Within a given jurisdiction, leakage rates will also be affected by the effectiveness of land-use policy implementation – with factors such as governance, conflict and stability playing a role.

Leakage rates vary amongst geographical regions, both because different regions face different land-use change pressures, and because different land-use transitions are associated with varying levels of emissions. For example, palm oil production has often involved the drainage of peatland and clearing of tropical forest (e.g. Indonesia and Malaysia), which are associated with high levels of GHG emissions (Valin et al., 2015). Land-use changes associated with the highest emissions for forests are conversion to shifting cultivation, which is most prevalent in Latin America and tropical Asia; and conversion to cropland, which is most relevant to tropical Africa and Latin America (Houghton, 2012). However, the long-term trajectories of these two land uses are very different. Natural regeneration means that shifting cultivation approaches neutral emissions from land conversion over longer time periods - unless the area of cultivation is increasing, or unless other subsequent land uses prevent regeneration. There is therefore a wide range of leakage rate estimates depending on the context (Blanco et al., 2014).

International leakage is more difficult to estimate, since leakage effects are indirect and causal mechanisms are not easy to determine (Henders and Ostwald 2014). Therefore, estimates often use a “weak leakage” definition (Box 1) which does not require the identification of causal links. Uncertainties in international estimates are affected by the type of input data as well as uncertainties in land use change projections and carbon stock estimates (Boer et al., 2007), and assumptions on the socio-economic behaviour associated with global commodity markets (Hertel et al., 2019).

Different policy measures exert different influences on leakage: in particular, some supply side measures enacted in isolation (e.g. limiting the supply of land for forest commodities) are likely to involve more leakage. As most natural habitat loss results from agricultural expansion, twinning these policies with measures to improve agricultural yield on existing land (sustainable intensification) can help to avoid leakage in these cases. Demand-side measures that affect the total demand for commodities (e.g. reductions in food waste or promotion of low-carbon diets) should reduce international land demand, and thus leakage, but will have only indirect influence on land use in specific locations of value to conservation. Demand-side measures that encourage sustainable sourcing (e.g. zero deforestation purchasing policies, certification schemes) may be more prone to leakage, unless adopted by an entire sector. Combined supply and demand side measures may stand the best chance of mutually achieving climate change mitigation and biodiversity conservation goals.

5.3 Identifying the most appropriate leakage rates to apply to our estimates of emissions reductions from protection and restoration interventions

The review indicates that demand-side interventions would likely result in a relatively high degree of leakage, while a combination of demand and supply side interventions would reduce leakage substantially. As our global biodiversity prioritisation analyses are not fully-fledged scenarios that model a particular set of policy interventions to facilitate the allocation of the land to conservation and restoration compatible land-uses, we should consider a range of leakage estimates.

To understand the impacts of these large-scale global changes in land-use policy are, we plan to estimate this range based on two major sources:

(i) Estimates of leakage from large-scale interventions from the scientific literature. The leakage estimates from global scale integrated assessment models can help us to understand the likely scale of leakage of global-scale changes in land use allocation, and indeed deliver a wide range of estimates from around 10 to 90% leakage. This range is unsurprising due to the different policy scenarios involved, inherent uncertainties surrounding future land use change projections, reference carbon stocks and land demand resulting from the future behaviour of the global commodity market, and therefore a range of leakage estimates is appropriate. In an analysis of real-world trends, Pendrill et al., (2019) estimated that **a third of the forest gains of the countries** with increasing forest cover were displaced to other regions between 2005-2013; **we propose that this serves as an upper bound** for our estimates.

(ii) Adapt an 'off-the-shelf' model for potential leakage related to jurisdictional scale interventions, as policy implementation at this scale would be needed to meet the global biodiversity targets. ART-TREES and VERRA JNR standards are designed for estimating leakage from forest interventions (REDD+), so we would be extrapolating to other habitat types. Where 25-60% of forests are encompassed by forest monitoring, ART-TREES requires a deduction of 10% leakage from TREES credits assigned under the standard. Whilst the objectives of the standard are focused on monitoring of emissions within the area, rather than total protection of the area, this seems like a reasonable equivalence. The highest leakage category for VERRA JNR is 15%, applied to leakage from displacement of domestic commodities and/or subsistence activities when there are no mitigation actions in place. Based on these two approaches, **we propose a 10% lower bound for our leakage estimate**.

A narrative on this range of potential leakage and mitigating policy actions will be developed, drawing also from our wider literature review.

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ANNEX A

Global conservation priorities: summary of Nature Map methodology

For this work we used recently developed globally ranked maps of conservation priority, following joint optimisation approaches (Jung et al., in press). These maps represent a comprehensive terrestrial estimate of the maximum potential value in the present state, to be managed for conserving biodiversity and carbon identified using a spatial conservation prioritisation (SCP) approach. As underlying biodiversity data we used the best available data on global species distributions (See Annex for overview in SI Table 1 of Jung et al., in press), including all extant terrestrial vertebrates and (for the first time) a representative proportion (41% or 193,954 species - representativeness explained in Jung et al., in press) of all accepted plant species names according to Plants of the World Online (WCVP, 2020). Mammal (5,685 species) and amphibian (6,660) distribution data were obtained from the International Union for Conservation of Nature Red List database (IUCN, 2019), while bird (10,953) range maps were obtained from BirdLife International. Data on the distribution of reptiles were obtained from the IUCN database where available (6,830 species), otherwise from the Global Assessment of Reptile Distributions (GARD) database (3,755 species; Roll et al 2017). We obtained native plant range maps (193,954 species) from a variety of sources, including IUCN, Botanic Gardens Conservation International (BGCI) and the Botanical Information and Ecology Network (BIEN). Where data on species habitat and elevational preferences were available, we refined each animal species' range to the area of habitat (AOH) in which the species could potentially persist (Rondinini et al., 2005; Brooks et al., 2019). We developed a map of IUCN habitat classes (Jung et al., 2020) to facilitate this analysis.

For carbon we used remotely sensed spatial estimates of the density of above-ground and below-ground biomass carbon (Garcia Rangel et al., in prep building on Soto-Navarro et al., 2020) and vulnerable soil carbon (defined by Jung et al., in press as "carbon stocks that could potentially be lost during the coming 30 years as a result of land use"). Root-to-shoot ratio correction factors (Shepaschenko *et al.*, 2018, IPCC) were applied to map the below-ground carbon (Eggleston et al., 2006; Jung et al., in press). To maximize consistency, the Global Copernicus Land cover dataset (https://lcviewer.vito.be/) was used as the underlying land cover product for both biodiversity and carbon estimates (Buchhorn et al., 2020, Jung et al., 2020). For the SCP analysis we set prioritization targets for both biodiversity conservation and carbon storage relative to the amount of land needed to improve a given species to a non-threatened species conservation status (the total area of suitable habitat for the species; Fastre et al., 2019) as well as conserving as much carbon as possible. We then solved - using a SCP approach - a series of global optimization problems that aim to jointly optimize both biodiversity and carbon in incremental area constraints, i.e. from 10% up to 100% of land area. The resulting solutions to these problems are then ranked globally, identifying the areas with the greatest potential value for conservation management of both biodiversity and carbon. Detailed information on the methods can be found in Jung *et al.,* (in press) included in Annex D.

Global restoration priorities: summary of methodology

As for the conservation analysis just described, we use a multicriteria optimization approach to identify priority areas for restoration of converted lands across all biomes and estimate their benefits. Due to poor existing definition and quantification of degraded natural ecosystems (IPBES 2018), this analysis focuses only on restoration of land converted from natural ecosystems (Strassburg et al., 2020). The optimization algorithm selects the top-priority currently anthropic areas (croplands and pastureland) in a hierarchical manner (see Annex C: Strassburg et al 2020 for further detail) by setting targets ranging from 5% to 100% of the overall anthropic area, using the land-cover maps of the Copernicus Global Land Service for 2019. Restoration in each 10 sq.km analysis unit aims to restore different types of natural vegetation depending on their original distribution. This is computed using the Copernicus map of 2015, the earliest in the Copernicus series. For analysis units that do not have any natural land cover in the 2015 maps, we use the ecoregions definitions and extent (Dinerstein et al., 2017). The natural vegetation types considered are forests, wetlands, grasslands, shrublands, and deserts, and are based on Copernicus reclassification of its land-cover maps from the original 37 classes into ten. These ten land-cover classes are: the previously mentioned 5 classes of natural vegetation (of which the first three match IPCC classes), plus 2 classes of areas potentially available for restoration (croplands and cultivated grasslands), 2 classes of non-restorable areas (ice and urban areas) and 1 class for water bodies (Strassburg et al., 2020). Therefore, the proportion of each natural land cover that will be restored in each analysis unit is based on this simple estimate of the natural vegetation original distribution.

The objective function guiding the prioritization is based on reducing species' extinction risk and maximising carbon sequestration. For the first variable, we use data on around 107,000 species of birds, mammals, amphibians, and plants and compute their extinction risk based on the amount of natural vegetation types remaining within the species habitat range, given their suitability as habitats for each species, and the altitude range of each species versus the average altitude in the analysis unit. The reduction in extinction risk is then calculated based on the restoration of areas available within each species' range given the same constraints. Potential carbon sequestration is computed in three different pools: above-ground biomass, below-ground biomass, and the soil component, as a function of the difference between the computed values of each component for each natural vegetation type restored in each planning unit, and the reference values of the same components in the current land-use being restored. The restoration method uses linear programming to optimize the spatial allocation of restoration for our 2 criteria (Strassburg et al., 2020). The objective function is the basis of the linear programming algorithm. It is determined as the sum of the benefits (carbon sequester and biodiversity layers for the present case) in each planning unit multiplied by the proportion of restored area (to be obtained by a solver) in each planning unit. We have used the Gurobi software as the linear programming solver to calculate the proportion of restored area. This proportion of restored area per planning unit is assessed by maximizing the joint benefits objective function given the constraints of each planning unit (individual anthropic area of unit) and a global maximum target (given in percentages of global anthropic area; 5% for each iteration, repeated for twenty times).

The species data used in the analysis consisted of the same fine-scale distribution maps of around 107,000 terrestrial vertebrate and plant species globally that were used in the conservation analysis. These data were then refined by removing unsuitable areas using information on species' habitat preferences and species' known altitudinal limits or, where unknown, by removing anthropogenically modified land. Given existing biases in taxonomic coverage for plant species, we calculated for the analysis in total 10 representative sets of species, containing approximately 10% of species of each taxonomic group. For carbon we used the combined amount of above-ground and below-ground biomass carbon density and vulnerable soil organic carbon density.

The carbon benefit was measured by the amount of carbon dioxide sequestered following restoration to a reference ecosystem in each geographical zone, considering above and below-ground biomass and soil carbon. This information was used to build the objective function of an optimization algorithm, selecting areas with greater benefits (climate change mitigation and/or biodiversity). Biodiversity data used were as detailed above for the conservation analysis. For carbon, we used the combined amount of above-ground and below-ground biomass carbon density and vulnerable soil organic carbon density. See Annex C: Strassburg et al., 2020 for further details.

The restoration analysis in this study focuses on the potential benefits acquired after full regeneration to the original vegetation. However, it does not account for the timescale needed for each ecosystem to be fully recovered - or the time for implementation of large-scale restoration action. The analysis assesses the long-term benefits of restoration actions, rather than focusing on restoring ecosystems that would have a greater impact in the short-term but would not have so many gains for future generations. It would be a useful addition to the analysis to identify the restoration benefits that could be achieved by e.g. 2030, 2050 and 2100.

Some areas were selected for both conservation and restoration

For Nature Map, IIS has updated the analyses published in Strassburg et al., (2020), this time using the IUCN habitat classes to derive potential habitat gains from restoration of cropland and pastureland. IIS has considered a distribution of five broad natural vegetation types when describing the conversion of the anthropogenic portion of each pixel back into the proportions of its original natural vegetation. To differentiate between natural grassland and pastureland in this restoration analysis, IIS used a slightly different global pasture layer to that used by IIASA in the conservation-focused analysis, which causes some spatial mismatch between the approaches. IIS used the Global Ruminant production system map (Robinson et al., 2018), filtered to exclude categories with areas deemed to excessively overlap with expert-identified areas of natural vegetation. In contrast, IIASA’s layer (Jung et al., 2020) defined pastureland as grid cells with non-tree covered vegetation from Copernicus land cover data (Buchhorn et al., 2020), which is climatically suitable for tree growth in the absence of grazing, and which has at least 1 head per km^2 of a grazing livestock-unit (LSU) based on region-specific conversion of gridded livestock of the world data (Chilonda and Otte, 2006; Gilbert et al., 2018). Areas which were not climatically suitable for forest cover, but with ≥1 LSU were considered rangelands, not pasture, in IIASA’s analysis, meaning that the IIASA pasture layer had a smaller spatial extent than the IIS layer. It is therefore possible that the sum of the fractions assigned to restoration and protection can exceed 1.

ANNEX B

Detailed workflow for emissions reduction and removals analysis

1 Resample to 0.5 degree grids

- 1A Priority areas for restoration (area and % of cell)
- 1B Priority areas for conservation (area and % of cell) minus existing protected areas
- 1C Biomass carbon stocks
- 1D Ecological zone - for IPCC forest classes
- 1E Climate zone - for IPCC land classes

2 Calculate land cover & changes at 0.5 degree

- 2A Cap restoration % (1A) to % transformed land in BASE 2020
- 2B Cap conservation %: where 1B + 2A > 100%, prioritise restoration
- 2C BASE 2020 → 2050 for BASE scenario (change in area of classes)
- 2D Conservation max: **maximum** overlap per cell with BASE areas converted (2B first occupies converted land from 2C) (change in area of BASE classes)
- 2E Conservation min: **minimum** overlap per cell with BASE areas converted (2B first occupies natural land from 2C) (change in area of BASE classes)

3 Associate IPCC carbon stocks / emissions factors with land cover classes used

- 3A Restoration: Assign IPCC annual emissions factors to 5 natural land cover classes from 2A x zones (1D, 1E) (transitioning from pasture/cropland)
- 3B Conservation: Overlay to identify all relevant BASE classes (2C) x ecological (1D)/ climate zones (1E)
- 3C Conservation: assign IPCC stocks to all relevant classes (3B)

4 Estimate potential carbon benefits at 0.5 degree

- 4A Restoration - C uptake / year: At original resolution: annual IPCC EFs (3A) for adjusted restored area (2A)
- 4B Restoration benefits = 20 years x 4A (assumes average initiation by 2030)
- 4C BASE emissions: Change in area of BASE classes (2C) x IPCC stocks changes (3C) → emissions. Calculate as % C loss 2020-50
- 4D Apply % loss (4C) to Nature Map biomass carbon stocks (1C) to find BASE emissions without conservation
- Conservation max (min) benefit: 4E Change in area of land cover classes (2D (2E)) x IPCC stocks changes (3C)– emissions under max (min) conservation. Calculate as % loss of C
- 4F Apply % (4E) to Nature Map biomass carbon stocks (1C) to find emissions with max (min) conservation
- 4G) Conservation benefit range = BAU emissions (4D) – conservation emissions (4F, min to max)
- 4G) Total carbon benefit = 4B + 4G

ANNEX C

Leakage Literature Review: Details of Method

The Web of Science platform was used for an initial search for relevant materials. The same search was repeated in Google and Google scholar, to capture relevant non-peer-reviewed materials such as IPCC reports and methodologies used in carbon market standards. Search terms were intentionally broad (Table 1), to effectively capture the relevant materials, and focused on the literature around leakage of emissions rather than of land-use change in general (hence the crossed-out ‘not’ terms in Table 1). However, some relevant literature on displaced land-use change (e.g. displaced deforestation), was eventually included in the review.

Materials were selected for the review based first on the relevance of their title and abstract, and then on review of the full text. Relevant studies cited by these articles were also considered for inclusion. Only English-language studies were screened for relevance. The literature identified was organised according to geographic scale, geographic region, leakage type, and time period. Quantitative methodologies and leakage estimates were extracted.

Table 1:Search terms that were used in the review. The Boolean operator 'OR' was used to link terms within categories and 'AND' was used to link terms between categories.

Concept 1	Concept 2	Concept 3
Land use	**Leakage**	**Carbon**
Terrestrial	**OR**	**OR**
	Spillover	**Not (Deforestation)**
	Displac*	**Emissions**
		Not (Conservation)