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Dynamic modelling shows substantial contribution of ecosystem restoration to climate change mitigation

Emma W. Littleton[1,2], Kate Dooley[3,4], Gordon Webb[3], Anna B. Harper[1,2], Tom Powell[2], Zebedee Nicholls[3,4], Malte Meinshausen[3,4], Timothy M. Lenton[2]

[1] College of Engineering, Mathematics and Physical Sciences, University of Exeter, EX4 4QJ, United Kingdom

[2] Global Systems Institute, University of Exeter, EX4 4QJ, United Kingdom

[3] School of Geography, Earth and Atmospheric Sciences, University of Melbourne, Parkville, 3010, Australia.

[4] Climate & Energy College, University of Melbourne, Parkville, 3010, Australia.

Correspondence to: e.w.littleton@exeter.ac.uk

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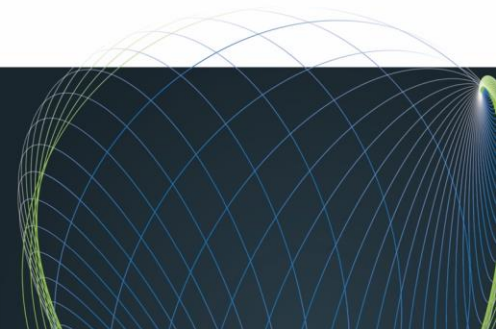
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Abstract

Limiting global warming to a 1.5°C temperature rise requires drastic emissions reductions and removal of carbon dioxide from the atmosphere. Most modelled pathways for 1.5°C assume substantial removals in the form of biomass energy with carbon capture and storage, which brings with it increasing risks to biodiversity and food security via extensive land-use change. Recently, multiple efforts to describe and quantify potential removals via ecosystem-based approaches have gained traction in the climate policy discourse. However, these options have yet to be evaluated in a systematic and scientifically robust way. We provide spatially explicit estimates of ecosystem restoration potential quantified with a Dynamic Global Vegetation Model. Simulations covering forest restoration, reforestation, reduced harvest, agroforestry and silvopasture were combined and found to sequester an additional 93 Gt C by 2100, reducing mean global temperature increase by ~0.12°C (5-95% range 0.06-0.21°C) relative to a baseline mitigation pathway. Ultimately, pathways to achieving the 1.5°C goal garner broader public support when they include land management options that can bring about multiple benefits, including ecosystem restoration, biodiversity protection, and resilient agricultural practices.

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1. Introduction

Following the adoption of the Paris Agreement, with its overall objective to 'balance sources and sinks' of greenhouse gases to limit global warming to 'well below 2°C', international attention has turned to the possibilities for removing carbon dioxide from the atmosphere. Given a rapidly dwindling carbon budget, early deployment of carbon-dioxide removal is a key part of an ambitious mitigation strategy[1]. While prominent scenarios have relied on large-scale land conversion for bioenergy with carbon capture and storage to achieve the Paris goals[2], there is potential for negative social and environmental impacts[3], and additional land conversion could result in net losses of carbon from the land[4]. Hence approaches that restore nature, with significant benefits to biodiversity, ecosystem services and local communities are gaining widespread interest[5–7], but their quantitative potential is uncertain.

The recently developed One Earth Climate Model (OECM) includes a 1.5°C compliant pathway through a global transition to 100% renewable energy and reliance on ecosystem-based land management practices[8,9]. These were developed to highlight the importance of protection and restoration of natural ecosystems in achieving the Paris climate goals, alongside sustainable forest management and agriculture. A book-keeping approach, coupled with Monte Carlo analysis, found that these practices resulted in additional cumulative removals with a median of 152 Gt C between 2020 and 2150, a significant contribution to a 1.5°C mitigation pathway[10,8]. However, the necessary scale of land-based mitigation poses significant challenges, and further analysis is required to understand the feasibility and carbon-cycle responses to widespread restoration of the biosphere.

Here we apply these previously developed land-based carbon mitigation options in a dynamic global vegetation model (DGVM). This allows for a spatial analysis of the distribution of ecosystem-based land mitigation options, and an alternative quantification of the potential contribution of land restoration to meeting the 1.5°C target. DGVMs model plant growth and ecosystem carbon balance in response to climate and land-use changes on a spatial grid. Compared to a bookkeeping approach, spatially explicit global modelling allows carbon density to vary spatially depending on environmental conditions, rather than relying on standard growth values for each region or biome; further, it does not assume that forests are mature by the end of the period studied, instead allowing forests to reach maturity at a growth speed that is supported by their local climate and soil conditions.

The ultimate potential to remove carbon from the atmosphere via terrestrial ecosystems is likely comparable to historical losses from the terrestrial biosphere caused by land clearing and degradation[11]. Thus the restoration of degraded ecosystems can be viewed as aiming to restore

previously lost carbon[12]. Historical land use emissions to date have been estimated at between 119–187 Gt C since pre-industrial times[13,14,11,15]. Processes previously not included in the land-use change flux mean the carbon debt could be towards the upper end of this range[13].

2. Carbon-dioxide removal in pathways for 1.5°C

In recent years, policy and scientific debate has focused on the potential for 'nature-based solutions' to remove carbon-dioxide from the atmosphere at gigatonne scale, with potentially significant co-benefits. The potential to protect and restore ecosystems and to regenerate and more sustainably manage lands exists across all climatic biomes and country classifications.

A series of high profile papers have built these expectations for large-scale sequestration and storage of carbon-dioxide in terrestrial ecosystems[16,17], although these studies rely on large reforestation areas (678 Mha and 900 Mha respectively). Critique of large scale tree planting as a climate mitigation strategy ranges from afforestation of non-forest biomes, lack of accounting for soil carbon in the baseline[18], incorrect consideration of the global carbon cycle[19], unusually large per-hectare sequestration rates[20], and overlooking environmental or socioeconomic constraints such as (re)converting land from existing uses (agriculture, forestry, etc)[21].

In response to what has been described as a narrow focus on afforestation (tree-planting) in climate policy, others seek to emphasise the importance of biodiversity and ecosystem integrity in climate responses. Ecosystems require functional resilience to sequester carbon over the long-term, and to resist, recover or adapt to changing conditions and disturbances that are becoming more rapid and severe under climate change[7]. Plantations are "much poorer at storing carbon than are natural forests, which develop with little or no disturbance from humans" and continue to sequester carbon for decades[22], meaning the regeneration of natural forests over other types of tree planting must be prioritized[23]. At the same time, the social and economic impacts of proposals for nature restoration must be considered to address social and environmental justice concerns, as well as physical feasibility[24].

Studies that focus broadly on ecosystem restoration opportunities rather than a narrow tree planting focus so far have been regionally focused[25]; not spatially explicit[5,9]; or intervention-specific[26]. An enhanced understanding is needed - both of the limitations to terrestrial carbon storage as a climate solution, and the types of land management pathways that maximise social, environmental and climate benefits. The five land management pathways elaborated here are designed to strengthen ecosystem function and resilience, enhance agricultural productivity, and to prevent risk of displacement of people and existing land uses by minimising land-use change.

The potential of ecosystem restoration remains underexplored as an option that minimizes land-use change, protects and enhances biodiversity, and delivers sustainably managed and productive landscapes. We explore the mitigation potential at a global scale of five spatially explicit ecosystem-based land management pathways: Forest Restoration; Reforestation; Reduced Harvest; Agroforestry and Silvopasture. Ongoing loss and degradation of primary forests is a pressing concern for both climate and biodiversity goals[27,28], with both conversion to agriculture and industrial logging identified leading causes of forest loss and degradation[29,30]. Hence, restoring degraded ecosystems and reforesting recently deforested areas offers

significant mitigation potential that increases over the next few decades. Restoration activities that rebuild ecological connectivity and improve the outlook for biodiversity and ecological function by buffering and linking primary ecosystem core areas can also encourage integrated climate mitigation and adaptation action to minimise pressure on land[7,27,31].

3. Methods

The methodology presented here extends the OECM[9] pathways by developing a global spatial dataset to identify suitable restoration areas and by modelling these to incorporate soil carbon flux, temperature feedbacks and bioclimatic effects in the overall carbon uptake results. The areas identified for ecosystem restoration were simulated in a community land surface model, the Joint UK Land Environment Simulator (JULES), which incorporates the dynamic global vegetation model TRIFFID to simulate vegetation and carbon cycle processes[32]. The additional CO_2 removal achieved in JULES through the targeted ecosystem restoration pathways was then combined with sectoral mitigation pathways for energy, industry, agriculture and land use from the OECM scenario and run through the simple climate model MAGICC to quantify the resulting temperature change over the century.

3.1 Spatial identification of restoration areas (targeting biodiversity and livelihood protection)

For each of the five pathways, spatial distribution was identified using global datasets. The 'Global map of forest condition'[33] was used for the forest pathways, and ESA-CCI Landcover maps[34] for the year 2000 were used to identify cropland and grazing lands for the agricultural restoration pathways. Each of these datasets was then overlaid with additional datasets reflecting precipitation values, biodiversity, and social constraints. These constraints reduced land area available for all pathways from the full potential identified in the primary datasets. Based on an N96e global grid (cell size of 1.875° longitude by 1.25° latitude), differing spatial resolutions were downsampled to 1% of this cell size. Datasets and land area for each pathway are shown in Table 1, and further explained in the SI.

Forest Restoration takes forest areas that are partially deforested or degraded[33] and uses a database identifying five critical conservation attributes as a Global Safety Net (GSN): Species Rarity, Distinct Species Assemblages, Rare Phenomena, Intactness, and Additional Climate Stabilisation Area[35] to target high priority areas for restoration (Fig SI 1.3). Reforestation was limited to biomes that would naturally support forests by identifying previously forested land in close proximity (within 5 pixels (between 70-105km) for tropical forests and within 1 pixel (between 11-18km) for temperate forests) to intact or degraded natural forests[33], resulting in 274 Mha of land in proximity to intact forests in sub-tropical and tropical forest biomes, while 70 Mha were identified in temperate biomes. Reforestation in boreal biomes was excluded, due to albedo affect accompanying changes from deforested to forested land types, specifically at high latitudes, which can potentially increase warming[37,38].

Table 1. *Primary datasets and dataset overlays (constraints based on climate, biodiversity and social considerations) used to spatially identify restoration opportunities for five ecosystem restoration pathways.*

Pathway	Primary dataset [Source]	Full area extent (Mha)	Dataset overlays	Representation in JULES	Targeted area (Mha)
Forest Restoration	Degraded forests [Potapov et al., 2011[33] (values 8 and 9)]	1,151	Coincident with Global Safety Net areas [35]	50% reduced forest cover; allowed to fully regenerate	541
Reforestation	Deforested land, formerly closed forest [Potapov et al., 2011[33] (value 6)]	889	Close proximity to intact or degraded closed forests [33]	100% reduced forest cover; allowed to fully regenerate	344
Reduced Harvest	Closed managed forests (natural or planted) [Potapov et al., 2011[33] (value 14)]	1,440	Exclude planted forests [36] Exclude low, moderate, & high shifting cultivation [31]	50% reduced forest cover; allowed to fully regenerate in tropics and subtropics; allowed to regenerate 50% in temperate and boreal	1,047
Agroforestry	Mosaic and non-mosaic cropland [ESA-CCI[34]]	2,146	With mean annual precipitation 400 to 1000 mm year^{-1}	Full cropland; trees planted on 20% of area during establishment	849
Silvopasture	Grassland and herbaceous cover [ESA-CCI[34]]	1,521	With mean annual precipitation 400 to 1000 mm year^{-1}	Full pasture land; trees planted on 20% of area during establishment	478
Total area targeted for forest restoration and agricultural regeneration:					**3,259**
Proportion of total area requiring land cover change (reforestation adjacent to existing forests):					*344*

Reduced Harvest describes a reduced harvest intensity in production forests in boreal and temperate biomes, based on evidence from different climatic regions suggesting that harvest reductions lead to significant increases in forest carbon stock compared to other forest management interventions[39–43]. In tropical and subtropical biomes, commercial timber extraction is halted given the lack of evidence that any form of reduced impact logging can lead to increased carbon stocks[44,45]. These management interventions apply only to natural managed forests and not to plantations, resulting in reduced harvest and a doubling in rotation length in 706 Mha of managed forest in the temperate and boreal biome, and 340 Mha of tropical forest removed from harvest altogether (Fig SI 3.2). Areas of shifting cultivation were excluded from consideration of reduced harvest, to avoid impacting communities dependent on subsistence agriculture[46].

To identify the spatial areas for agricultural lands, we relied on ESA-CCI Landcover data[34]. Temperate, subtropical and tropical cropland and grazing areas with mean annual precipitation in the range 400 to 1000 mm.a^{-1} were targeted for restoration via Agroforestry and Silvopasture pathways to ensure both the potential for regrowth and additionality of regeneration measures. By 2040, approximately 40% of total cropland, that was also within the defined precipitation band, was included in the Agroforestry pathway (Fig SI 4.2) and 40% of low-latitude pastures were included in the Silvopasture pathway (increased tree/shrub balance and reduced fire

management) (Fig SI 5.1),noting that we are referring here to managed pasture rather than natural rangelands[47]. The resulting global distribution of ecosystem restoration areas is shown in Figure 1.
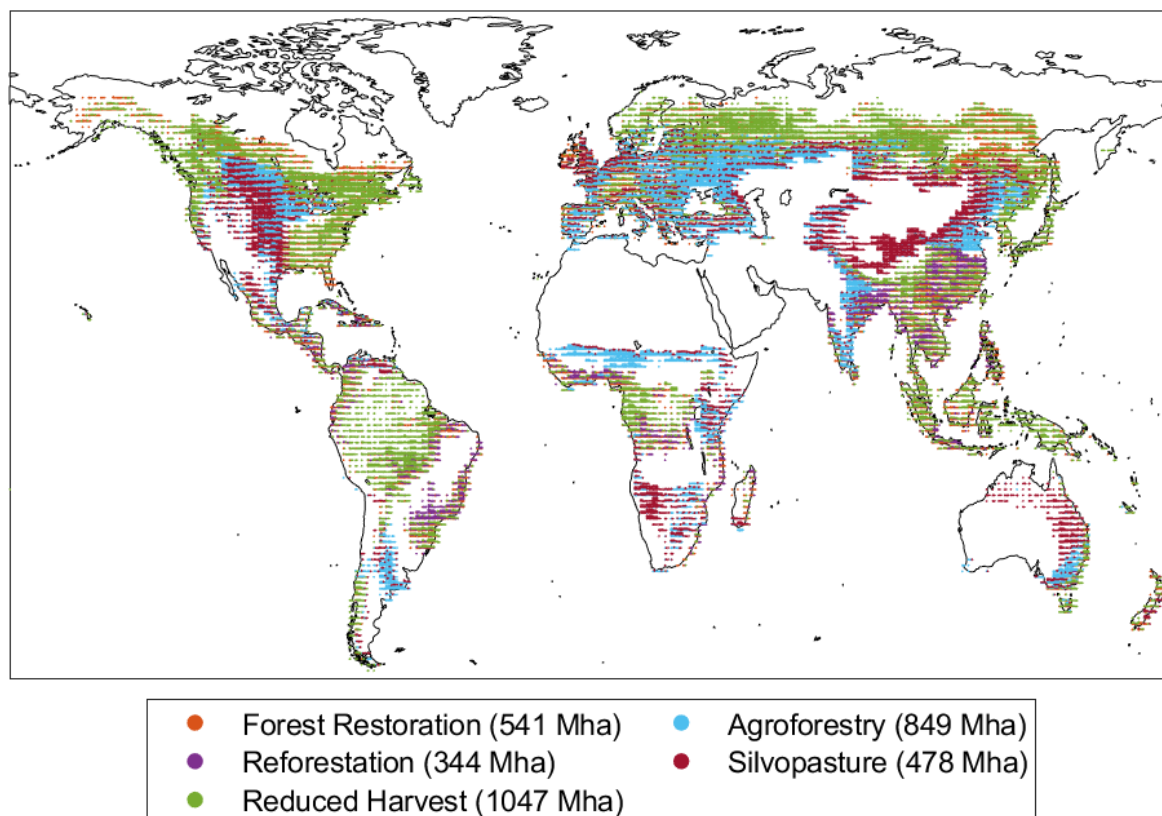

Fig 1. *Global distribution of proposed ecosystem restoration pathways (Mha).*

Limitations

A key limitation of the spatial identification of restoration areas is that the 'global map of forest condition'[33] used for forests date to 2001, and is not as robust in identifying different forest cover types as more recent datasets. This dataset provides global maps of degraded forest area, deforested areas suitable for reforestation and natural forests under management and harvest regimes. While more recent datasets are available for forest cover and loss[48,49], these do not distinguish between natural and planted forests, which was a key requirement for our land management pathways. Other recent datasets for degraded forests are focused on tropical regions[25]. The 'global map of forest condition'[33] used here presents a single contiguous dataset containing three key forest classes we needed to identify: degraded forests, natural managed forests and intact forests. ESA-CCI Landcover[34] was used for pathways involving agricultural land, and for consistency with the forest map, datasets from 2000 were used. The total land areas for different land cover derived from these datasets (primary forest, secondary natural forest, cropland, grazing land) are close to the non-spatially explicit land areas given in FAO data. Given the relatively coarse spatial resolution of the DGVM (2-3 Mha per grid cell), any uncertainties in the global land area data used are not expected to impact the results. The lack of global spatially consistent datasets that delineate natural from planted and primary from secondary forests is a key research limitation in calculating the carbon sequestration potential from changes in land management.

3.2 Dynamic global vegetation modeling

Net primary productivity (NPP) in JULES is calculated based on environmental conditions for each of a set of user-defined plant functional types (PFTs), which then compete with each other for space[50]. Soil carbon is increased by litter delivery from plants and decreased by degradation at each timestep, dependent on soil temperature and moisture. This study uses the JULES-BE branch of JULES vn5.1[51], which allows for the additional land use class used here to represent agroforestry and includes functionality to automatically plant new agricultural areas with a user-defined selection of PFTs.

A spatial dataset on the extent of forest degradation and overharvesting was unavailable; as such, this study uses a standard assumption of 50% degradation globally for the Forest Restoration and Reduced Harvest pathways. Given that Forest Restoration occurs in degraded or partially cleared forests, only 50% of the targeted area was allowed to be reforested in JULES, to represent baseline (degraded) carbon stocks in the landscape. For Reforestation, forest regrowth in JULES was allowed to occur over 100% of the targeted area. Reduced Harvest was represented with forest regrowth occurring over 50% of the land area in tropical and sub-tropical biomes to represent a recovery of degraded forests when logging activities are ceased (carbon stocks in degraded forests have been found to be between 14-65% lower than intact forests[52,53]); regrowth occurred over only 25% of land area in temperate and boreal biomes to represent only a partial recovery in forest carbon stocks as harvest is reduced but not ceased. Agroforestry and Silvopasture were both represented by planting 20% of the targeted area with a mix of broadleaf and needleleaf trees, to represent mixed use areas where trees and shrubs are integrated into cropping and grazing lands. 20% represents a progression from existing tree-cover in croplands[26].

JULES simulations were run using meteorological forcing output from HadGEM2-ES, covering the period 1880-2014 (historical) and 2015-2100 (SSP1-2.6) on a 3-hourly timestep at the N96e grid size. Baseline land use was taken from IMAGE output of crop and pasture area over the period 1880-2014 (historical; based on the HYDE land use dataset) and 2015-2020 (SSP1-2.6). During 2021-2030, the rate of conversion of natural land to crop and pastureland in each grid cell was decreased linearly until reaching a fixed level in 2030. From 2031 onwards, seven separate simulations were run: one with no further land cover transitions (control simulation); one simulation for each separate ecosystem restoration pathway described above; and one simulation incorporating all ecosystem restoration pathways at once. For each pathway, the area identified for ecosystem restoration is increased linearly over a decade, reaching its full extent (Figure 1) by 2040. These areas are then held constant for the remainder of the simulation.

An extended run representing continued growth to 2150 was conducted for each simulation using meteorological data for 2091-2100, repeated on a loop five times to cover an additional 50 years (necessary because meteorological driving data was not available beyond 2100).

3.3 Temperature pathway

MAGICC is a reduced complexity climate model, widely used for assessing the climate implications of global emissions scenarios. The configuration used here is identical to the setup used in Nicholls et al. (2021)[54] with the model's underlying equations described in Meinshausen et al (2011)[55] alongside updates described in Meinshausen et al (2020)[56]. All temperature projections are reported relative to 1750.

The OECM 1.5C scenarios used values from the OECM[9] for all greenhouse gas emissions other than CO_2 from agriculture, forestry, land use and land-use change (AFOLULUC). The (no removals) scenario represented CO_2 AFOLULUC emissions using values from the SSP1 baseline scenario. To reduce the risk of double counting, we set CO_2 AFOLULUC emissions to zero from 2050 onwards in our baseline scenario. For the OECM 1.5C+ scenario, the same AFOLULUC emissions values were used to represent agriculture, forestry and land use, to which we added the additional land carbon system uptake from the ecosystem restoration measures, as quantified by the modelling performed with the JULES model (Section 3.2). Consistently using the SSP1 baseline (as quantified by the IMAGE IAM) for AFOLU CO_2 emissions allows the effect of the ecosystem restoration measures to be assessed independently of other changes to agricultural land use or greenhouse gas emissions. Net AFOLULUC CO_2 emissions are lower in the OECM 1.5C+ scenario than in the OECM 1.5C (no removals) scenario. Accordingly, global mean temperatures are also lower in the OECM 1.5C+ scenario than in the (no removals) scenario.

4. Results and Discussion

By spatially identifying target areas for ecosystem restoration, we quantified additional carbon uptake over the century of 93 Gt C. When combined with an ambitious renewable energy scenario, this additional carbon uptake reduced 2100 temperature by a further 0.12°C (compared to the no removals scenario).

4.1 Enhanced terrestrial carbon stocks

Figure 2 shows the change in terrestrial carbon content over the study period, relative to a simulation in which no land use transitions occur after 2030. Together, the five pathways result in a cumulative terrestrial carbon increase of 93 Gt C by 2100 (115 Gt C by 2150). Although only natural regeneration is used with no active planting of trees in the three forestry pathways (plantation of trees occurs on smaller areas in the Agroforestry and Silvopasture pathways), carbon uptake is immediate and rapid, declining in pace after the first few decades as forests reach maturity. The carbon flux into terrestrial vegetation reaches its peak in 2041 at 3.1 Gt C per year; after this the flux declines, averaging 1.1 Gt C per year over 2050-2100. The largest carbon gains resulted from the Reduced Harvest pathway (33 Gt C by 2100), followed by Reforestation (29 Gt C) and Forest Restoration (21 Gt C). Agroforestry and Silvopasture produced the smallest sequestration values at 5.2 and 1.6 Gt C respectively. Agroforestry and Silvopasture differ from the three forestry pathways in that they utilise the model feature in which the targeted areas are automatically planted with trees upon land conversion; this results in a faster increase in carbon followed by a decline as the tree fraction shrinks back to what the climate can support. This planting process is repeated in 2100 to restore the tree cover in Agroforestry and Silvopasture areas to 20%, resulting in the rapid but temporary increase in carbon stocks visible in Fig. 2.
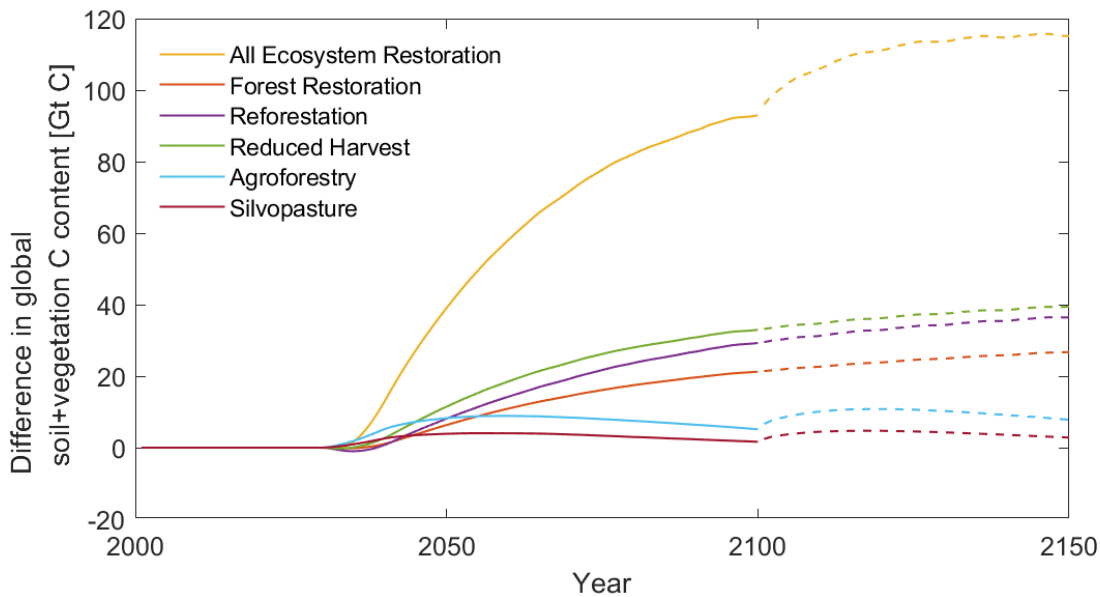
Fig 2: *Carbon accumulation in terrestrial ecosystems as a result of all ecosystem restoration pathways, relative to a scenario with no land cover change after 2030. The extended simulation from 2100-2150 is illustrative, based on 2090s climate.*

Spatial carbon accumulation for all pathways is shown in Figure 3, whereas Figure 4 shows each pathway individually. The quantity shown is tonnes C per hectare of targeted area – i.e. it is normalized for size of targeted area (Figure 1), but is still a combination of all pathways which each have different maximum densities (visible in Figure 4). While environmental conditions affect the maximum density of forests, a large part of the spatial variance in Figure 3 results from differences in distribution of the different pathway areas (discussed in Section 4.2 below).
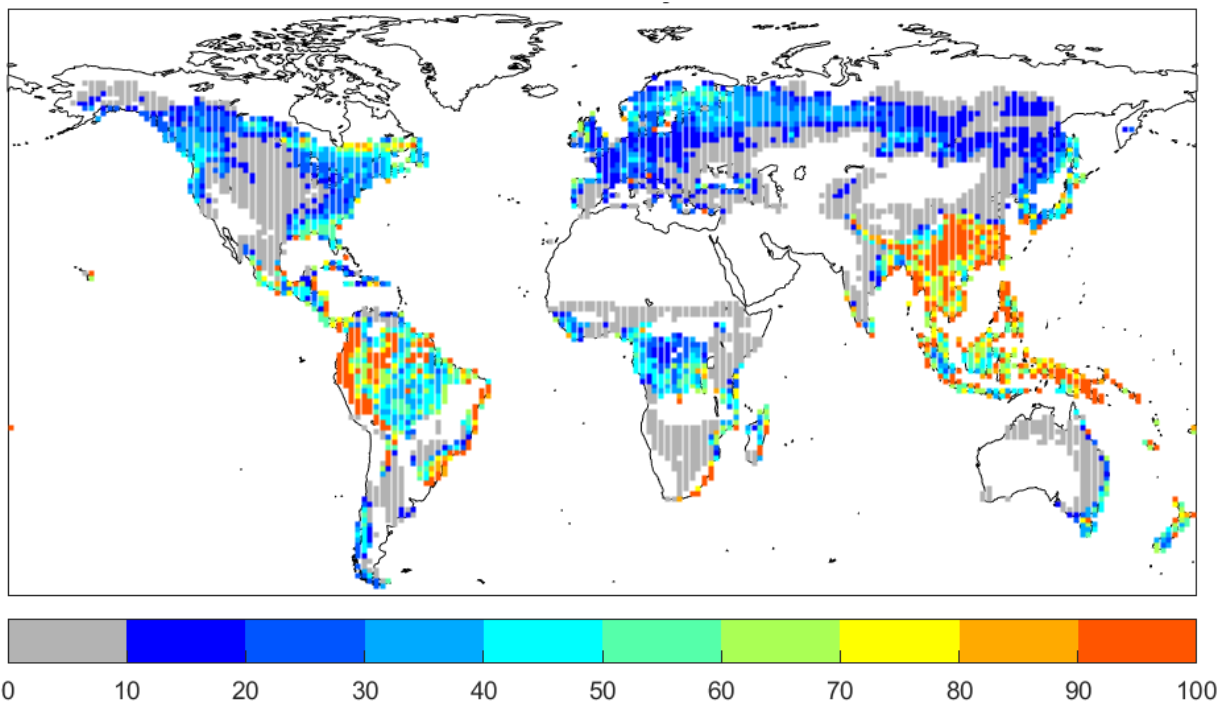

Fig 3. *Carbon storage in all ecosystem restoration pathways combined, expressed as tonnes of additional carbon per hectare of targeted area in 2100.*

While the largest concentrations of carbon storage occur where humid tropical and warm temperate forests are allowed to regenerate (South America, China, Southeast Asia), Figure 4 shows that Forest Restoration and Reduced Harvest can add significant carbon over a large area of Europe, Russia and North America; these regions are also most favourable for Agroforestry and Silvopasture compared to more mixed results in the seasonally dry tropical regions where trees frequently do not survive as well (un-irrigated, not specifically drought-tolerant tree species). This representation of agroforestry in seasonally dry tropical regions likely underestimates their true potential for carbon storage. In these systems the co-benefits of integrating trees into farming systems are deeply linked with improving farmer livelihoods and increasing their resilience[57], and as such farmers are likely to be highly invested in selecting appropriate tree species and ensuring their survival.

Total carbon sequestered for all pathways is also given in Table 2, broken down by world region and decade. The largest increases occur during the ten years to 2050, largely from Reforestation and Reduced Harvest in China, Latin America and Southeast Asia (Rest of Asia), followed by Forest Restoration and Reduced Harvest in North America and Russia (Reforming Economies). Carbon accumulation is substantially slower after 2070 as the majority of these forests reach maturity, particularly those in humid tropical biomes.

Table 2. *Gross regional carbon sequestration rates (Gt C per year, averaged over the preceding decade). The ten world regions used are as categorized for the RCP database*[58].

	2020	2030	2040	2050	2060	2070	2080	2090	2100	cumulative
Africa	0.00	-0.03	0.10	0.35	0.13	0.08	0.03	-0.01	-0.01	5.8
China +	0.00	-0.09	0.17	0.57	0.37	0.34	0.27	0.20	0.13	18.8
India +	0.00	0.00	0.04	0.13	0.08	0.06	0.05	0.04	0.03	4.0
Latin America	0.00	0.00	0.15	0.71	0.39	0.28	0.24	0.14	0.11	18.7
Middle East	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0
Northern America	0.00	0.02	0.23	0.55	0.25	0.16	0.11	0.08	0.05	12.1
Pacific OECD	0.00	0.00	0.05	0.13	0.05	0.04	0.02	0.02	0.02	2.8
Reforming economies	0.00	-0.04	0.31	0.67	0.24	0.15	0.09	0.05	0.05	12.7
Rest of Asia	0.00	0.00	0.11	0.57	0.31	0.23	0.16	0.10	0.05	14.3
Western Europe	0.00	-0.01	0.12	0.24	0.07	0.04	0.03	0.02	0.00	3.9
World Total	*0.0*	*-0.2*	*1.3*	*3.9*	*1.9*	*1.4*	*1.0*	*0.7*	*0.4*	*93.0*

4.2 Characteristics of land management pathways

The land restoration pathways presented here are distributed across natural forests and more intensively managed lands (harvested forests and agricultural lands). Figure 3 shows that each individual restoration pathway occurs across all biomes (with the exception of reforestation, which does not occur in northern latitudes). This distribution of five spatially explicit land-use management pathways is notable for prioritising forest restoration based on 'global safety net' to prevent biodiversity loss, targeting reforestation adjacent to existing intact forests to extend conservation buffer zones, and increasing agricultural productivity through Agroforestry to regenerate permanent croplands and Silvopasture throughout dryland areas.
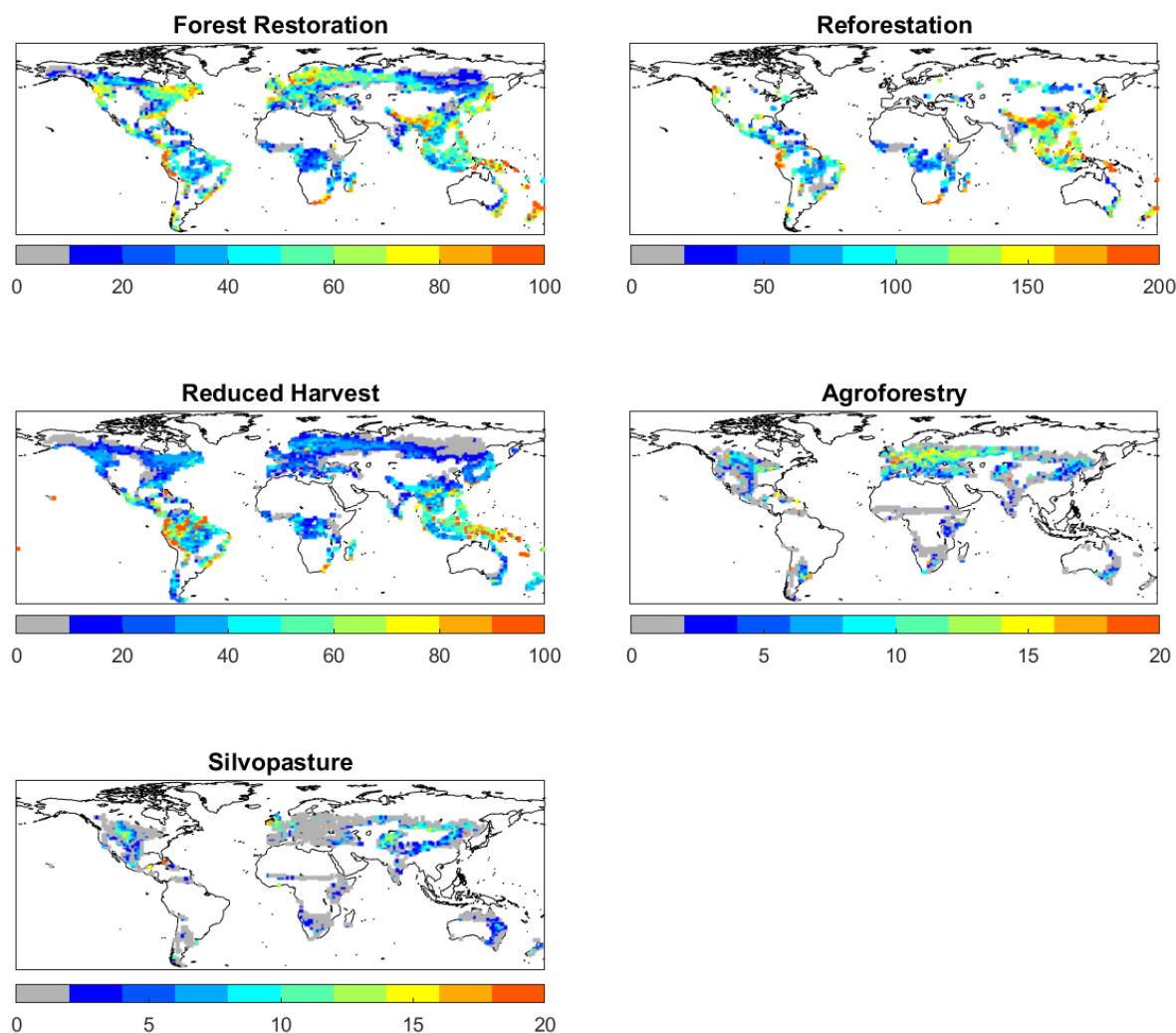
Fig 4. *Carbon storage in individual ecosystem restoration pathways, expressed as tonnes of additional carbon per hectare of targeted area in 2100.*

The Forest Restoration pathway distribution prioritises buffering and reconnection of primary forests and other carbon dense primary ecosystems, which increases resilience, stability and adaptive capacity[59,60]. Some of the highest sequestration values (80-100 t C ha^{-1}) overlap with biodiversity and carbon 'hotspots' in the Amazon Basin and Southeast Asia[61]; carbon densities of 70-90 t C ha^{-1} are also notable across China and northern Europe where a significant area of this pathway is represented (Fig. 1).

Reforestation occurs on recently deforested areas adjacent to intact forests. By prioritizing direct proximity to forested lands, reforested areas can form buffer zones and corridors between forested areas, increasing resilience and recovery in both intact forests and adjacent reforested land[62–64]. High Reforestation areas represented here in China, with carbon densities of 140-200 t C ha^{-1}, are consistent with national policies, although allowing reforestation to occur through natural succession when restoration areas are proximate to native vegetation is both more cost-effective and has a greater success rate than planting of new forests[23,65,66]. Reforestation is also the only pathway used here that involves a land cover change, with 344 Mha converted from deforested to reforested land. While this represents a low land use change area compared to comparable studies[16,17], it does not completely eliminate impacts on agricultural production. Converting land to forests and retaining those forests requires reduced pressure for agricultural

13

land. This can be achieved through dietary changes, but also through more sustainable agricultural and livestock production[67–69].

The Reduced Harvest pathway is a changed management approach to forestry that shifts harvest from natural forests to planted forests without increasing plantation area, therefore requiring decreased harvest intensity in temperate and boreal biomes and a cessation of commercial timber extraction in tropical forests (resulting in the greatest carbon gains from this pathway in tropical regions, reaching 80-100 t C ha^{-1} by 2100 in Southeast Asia and the Amazon basin). The economic impacts of reduced harvest can be offset against a shift away from timber products and increased efficiency and recycling of wood-based products, but may require compensation to land managers[70–72]. There is some debate about the role of timber in substituting more carbon intensive products, ie., in the construction industry, but research suggests only a small portion of harvested wood ends up in long-lived products, and that accumulation of carbon in standing forests provides the greatest climate benefit[73,74]. When identifying suitable areas for Reduced Harvest, roughly 280 Mha of landscapes identified as shifting cultivation use were excluded from our pathway. When traditionally managed these areas can represent a carbon sink over longer timescales and are an important contributor to ecosystem services such as soil fertility and stabilisation, food and livelihood security, and land usage and access rights[75,76].

In predominantly managed ecosystems, regeneration can occur through changed forestry practices and restoration of agricultural lands through increasing trees and shrubs in the landscape based on agroforestry and silvopasture approaches. Agroforestry provides significant water retention and productivity co-benefits along with enhanced carbon storage, and has wide geographic applicability[26,77,78]. Silvopasture requires a reduction in grazing intensity to allow regeneration of grasses and shrubs to occur, which increases carbon in above-ground biomass[79]. While carbon gains of 5-15 t C ha^{-1} by 2100 are common across Europe and North America for Agroforestry, Silvopasture results in lower uptake, owing to higher initial soil carbon content in temperate pasture lands compared to croplands.

4.3 Temperature reduction from enhanced carbon uptake

When combining these ecosystem restoration pathways with an ambitious 100% renewable energy scenario (the OECM 1.5C+ scenario[9]), median temperatures briefly reach 1.5°C in the late 2030s, before declining to 1.1 °C by the end of the century as fossil fuel emissions are reduced to zero and atmospheric removals increase (Fig SI.6.1). Achieving the 1.5°C temperature threshold relies on aggressive reductions in fossil fuel emissions, particularly between 2020 and 2030. In our scenario, fossil fuel emissions drop by approximately 8% per year between 2020 and 2055, to reach zero by 2055. This rate of decarbonisation is extremely ambitious; for comparison, the coronavirus pandemic caused a global reduction in fossil fuel emissions of about 7% in 2020[80].

The additional removals from the ecosystem restoration pathways reduce 2100 warming by a further 0.12 °C (5-95% range, 0.06 – 0.21 °C) compared with the OECM scenario without large scale removals (Fig SI.6.2). Given the linearity of the transient climate response to cumulative carbon emissions (TCRE)[81,82], we would expect 93 Gt C of carbon removal to result in similar temperature reductions, irrespective of baseline scenario (although how the linear relationship between cumulative CO_2 emissions and temperature may change under net negative scenarios including non-CO_2 forcers is less certain[83–86]).
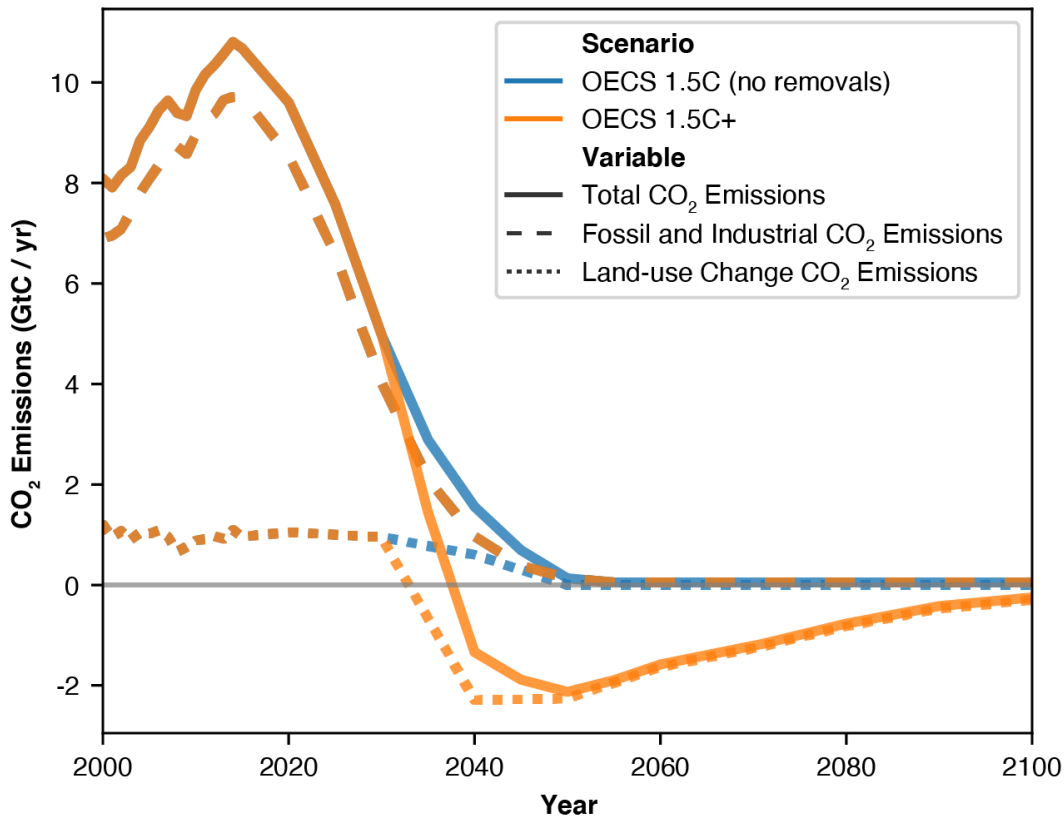
Fig 5. *OECM 1.5+ scenario (orange) shows additional sequestration compared to the OECM 1.5 (no removals) scenario (blue). Steep reductions in energy and industry emissions from 2020 are coupled with removals from forest and agricultural land restoration starting from 2030.*

5. Conclusion

Our 1.5°C-compatible mitigation pathway includes 93 Gt of carbon sequestration via ecosystem restoration over 3,259 Mha of land area, requiring only 344 Mha of land cover change (for reforestation). Restoration of degraded forests and regeneration of agricultural lands also provides multiple other ecosystem service and livelihood benefits in addition to carbon storage. However, achieving 1.5°C remains heavily dependent on an ambitious reduction in fossil fuel use – in the OECM 1.5C scenario used here, energy and industry emissions decline by 8% per annum until 2055 (when energy and industrial CO_2 emissions reach zero), with a transition to 100% renewable energy generation by 2050. Without a reduction of fossil fuel emissions to near zero by mid-century and strong action in the decade to 2030, the chance of limiting global-mean temperature rise to 1.5°C is effectively zero.

Significant CO_2 removals can be achieved through ecosystem-based approaches, with removals consistent with the lower end of the range presented in 1.5°C pathways with no or little overshoot (in the order of 100-1000 Gt CO_2 removal over the century)[87]. These pathways rely on respecting principles of ecosystem integrity to promote biodiversity and ecosystem resilience. In implementation, there is strong evidence that recognising indigenous and other forms of collective land management have demonstrated the greatest ability for land protection and stewardship.

The ecosystem restoration pathways modelled here also overcome some of the drawbacks of previous work on this subject, for example by minimizing land-use change; targeting reforestation only as buffers to existing primary forests; prioritising co-benefits for agricultural activities rather than reclamation of land; and excluding arid and high-latitude zones.

While the benefits of such approaches are receiving increasing attention from policymakers, particularly in the form of 'nature-based solutions', the removal pathways presented here are distinct in two ways. First, the design of these pathways is based on principles of ecological restoration and minimising land-use change. This is a very different approach to one that promotes large areas of tree-planting. Conserving and restoring existing forests provides more immediate and longer-lasting climate benefits than planting new trees, in addition to significant co-benefits. The second important conclusion relates to limitations to land-based mitigation – as noted elsewhere, the rates and amounts of net carbon uptake are slow and low compared to the rates and amounts of carbon dioxide we release by fossil fuel combustion[37]. Hence, removal of carbon dioxide from the atmosphere does not compensate for the release of fossil fuel emissions but is needed in addition to reducing emissions to near-zero, in order to lower atmospheric concentrations of CO_2. We stress that removing emissions is inherently riskier than avoiding emissions in the first place, and climate mitigation is not a zero-sum game - more mitigation in one sector does not reduce the need for mitigation effort in another sector - action must be as ambitious as possible across all sectors.

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exeter.ac.uk/gsi

🐦 **@GSI_Exeter Global Systems Institute**

University of Exeter, Laver Building,
North Park Road, Exeter, EX4 4QE

General enquiries:
infogsi@exeter.ac.uk
Tel +44 1392 722633