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Biodiversity implications of land-intensive carbon dioxide removal

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Pathways consistent with global climate objectives typically deploy billions of tonnes of carbon dioxide removal (CDR) from land-intensive methods such as forestation and bioenergy with carbon capture and storage. Such large-scale deployment of land-intensive CDR may have negative consequences for biodiversity. Here we assess scenarios across five integrated assessment models and show that scenarios consistent with limiting warming to 1.5 °C allocate up to 13% of global areas of high biodiversity importance for land-intensive CDR. These overlaps are distributed unevenly, with higher shares in low- and middle-income countries. Understanding the potential conflicts between climate action and biodiversity conservation is crucial. An illustrative analysis shows that if current biodiversity hotspots were protected from land-use change, over half the land allocated for forestation and bioenergy with carbon capture and storage in the assessed scenarios would be unavailable unless synergies between climate and conservation goals are leveraged. Our analysis also indicates CDR-related biodiversity benefits due to avoided warming.

As global climate action remains insufficient[1,2], and in light of the soon-exhausted remaining carbon budget for at least a 50% chance of staying below 1.5 °C of global warming[3], carbon dioxide removal (CDR) is gaining political attention. Modelled pathways that outline how global warming could be limited to less than 2 °C or 1.5 °C largely depend on CO_2 removals from afforestation and reforestation as well as from bioenergy with carbon capture and storage (BECCS)[4,5]. These CDR options are land intensive, and their gigatonne-scale deployment may come with severe sustainability risks[6–8], including risks to biodiversity, if implemented poorly[9]. Understanding the potential biodiversity implications is crucial to enable just climate action that fosters synergies between climate change mitigation and biodiversity conservation, rather than falling into the trap of environmental problem shifting[10].

Climate change mitigation pathways generated by integrated assessment models (IAMs) play a key role in informing policymakers about the effectiveness and implications of climate policy choices[11].

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However, implications for biodiversity have not been accounted for in the previous generations of pathways[12]. Previous studies have already started to assess mitigation-related biodiversity implications—some with an explicit focus on implications of afforestation, bioenergy or BECCS[8,13–19]. Existing studies, assessing changes to species richness due to afforestation, bioenergy or BECCS, mostly rely on a single model framework (for example, refs. 13–16), and consider between 5,500 and 25,000 terrestrial vertebrate and plant species. Multimodel studies assessing land use-related implications for biodiversity exist[20–23]; however, they are largely without an explicit focus on CDR, which is a key driver of future land-use change.

Three central entry points arise to explore biodiversity implications more comprehensively: (1) assessing consensus across multiple IAM frameworks concerning interregional differences in CDR-related biodiversity implications, (2) increasing the number and diversity of considered species (beyond vertebrates and plants) and (3) illustrating implications of biodiversity conservation for CDR deployment[13,20].

Here, we perform a multimodel assessment of existing, cost-effective mitigation scenarios to explore land allocation for forestation (afforestation, reforestation or forest restoration) and bioenergy crops (for BECCS) within areas of high biodiversity importance, considering around 135,000 terrestrial species (fungi, plants, invertebrates and vertebrates) and more than 170 hotspots. Specifically, we focus on CDR land allocation within climate refugia (defined as areas where at least 75% of the baseline species richness will remain for a given global warming level)[24,25] and within terrestrial biodiversity hotspots (characterized by exceptionally high species richness, including endemic and rare species)[26] to unveil location-specific overlap. We focus on CDR-related biodiversity implications owing to the key role of CDR in driving land-use change in the assessed scenarios (as shown in the Supplementary Information). We complement this main analysis with an assessment of land use-related biodiversity implications beyond CDR (Supplementary Information).

We show the magnitude of CDR land allocation within climate refugia throughout the twenty-first century for three warming scenarios: current policies, a 2 °C scenario and a 1.5 °C scenario (Table 1). We then explore the geographic distribution of CDR land allocation within climate refugia and evaluate agreement across five considered model frameworks to identify deployment areas within climate refugia and biodiversity hotspots that require particular policy attention. Ultimately, we highlight how much of the allocated land would not be available for land-intensive CDR deployment if the goal of halting the loss of areas of high biodiversity importance were to be strictly enforced[27,28]. Building on our analysis findings, we discuss circumstances under which land-intensive forestation and BECCS will be ineffective and detrimental to biodiversity conservation and how focusing on the restoration of natural ecosystems could jointly achieve carbon sequestration and biodiversity conservation. Our discussion is informed by an illustrative evaluation of potentially beneficial or likely harmful spatial overlaps between scenario-based CDR and areas of high biodiversity importance.

We base our analysis on existing mitigation scenario data from the original Shared Socioeconomic Pathways (SSP) quantifications from the Asia–Pacific Integrated Model (AIM)[29,30], the Global Biosphere Management Model (GLOBIOM)[31] and the Integrated Model to Assess the Global Environment (IMAGE)[32,33]. In addition, we consider data from the Global Change Analysis Model (GCAM)[34] (2020 SSP quantification) and the REMIND-MAgPIE integrated assessment modelling framework[35,36] (original SSP quantification), insofar as these two models meet the data requirements for specific components of our analysis. The scenarios and biodiversity metrics used in this analysis are detailed in the Methods (for an overview, see Table 1).

Table 1 | Overview of scenarios and biodiversity metrics used in the main analysis

Scenarios	Description
1.5 °C scenarios	The 1.5 °C scenarios (Fig. 1) are based on RCP1.9. This representative concentration pathway was combined with two shared socioeconomic pathways: a world shifting towards sustainability (SSP1) and a world following historical patterns (SSP2)[79,80]. RCP1.9 was considered to show CDR-related biodiversity implications of a highly ambitious mitigation scenario.
2 °C scenarios	The 2 °C scenarios (Fig. 1) are based on RCP2.6 and two socioeconomic pathways (SSP1-2)[80,81]. The analysis underlying Figs. 2–4 is based on SSP2-26, a 2 °C scenario in which socioeconomic development follows historical patterns, while global warming is limited to less than 2 °C, with median peak warming of 1.8 °C across the five considered model frameworks[4]. SSP2-26 was used as a focus scenario as it fulfils this analysis' data availability requirements for the three main model frameworks.
Current policies	Current policies are roughly in line with RCP4.5, based on the socioeconomic pathways SSP1-3. SSP3 represents a world characterized by resurgent nationalism and regional rivalry. RCP4.5 exceeds 2 °C but stays below 3 °C throughout the twenty-first century[1,4,81]. This scenario is shown in Fig. 1 to highlight CDR-related biodiversity implications of a mitigation scenario based on the current level of political ambition.
Biodiversity	**Description**
Climate refugia	This metric describes, for various global warming levels, areas within which climatic conditions would still be suitable for at least 75% of the species initially present, considering around 135,000 terrestrial species (fungi, plants, invertebrates and vertebrates)[24,25,82,83]. In Fig. 1, this metric is always matched to the scenario warming for a given time step. In Figs. 2–4, this metric is used to depict climate refugia resilient to 1.8 °C (median peak warming of the focus scenario SSP2-26 across the five considered models).
Biodiversity hotspots (current)	This metric is based on the IPCC AR6 WGII definition of biodiversity hotspots, combining WWF G200 data on ecoregions for conservation[84], inhabiting exceptional levels of biodiversity richness and endemism, and data on biodiversity hotspots for conservation priorities[85–88]. This metric is used in Fig. 4.
Biodiversity hotspots (resilient)	This metric combines current biodiversity hotspots and climate refugia areas resilient to 1.8 °C by looking at the spatial intersection of these two metrics. Resilient biodiversity hotspots are hotspot areas resilient to global warming of 1.8 °C (median peak warming of the focus scenario SSP2-26 across the five considered models). This metric is used in Figs. 3 and 4.

Global implications of CDR deployment

We observe that the share of land-intensive CDR located within remaining climate refugia (while tracking warming-related refugia loss) increases over time (Fig. 1a,b). The degree of overlap scales with the stringency of mitigation action: under current policies, the share of land-intensive CDR (forestation and BECCS combined) within climate refugia is consistently below 6%. This share increases to up to 9% in scenarios consistent with 2 °C of warming and 13% in those consistent with the 1.5 °C warming limit of the Paris Agreement. While ambitious mitigation scenarios result in a marked decrease in the warming-related climate refugia loss compared with the current policies scenario[24,25], their higher dependence on land-intensive CDR results in a relative increase in spatial overlap with climate refugia.

In the evaluated scenarios, markedly more land within climate refugia areas is allocated for forestation than for the conversion to bioenergy cropland (for BECCS). While global CDR land allocation within remaining climate refugia is negligible in 2020, it increases towards the end of the century to up to around 11% for forestation and up to around 4% for the conversion to bioenergy cropland (for BECCS) in the 1.5 °C scenarios, albeit with distinct model fingerprints (Fig. 1a).

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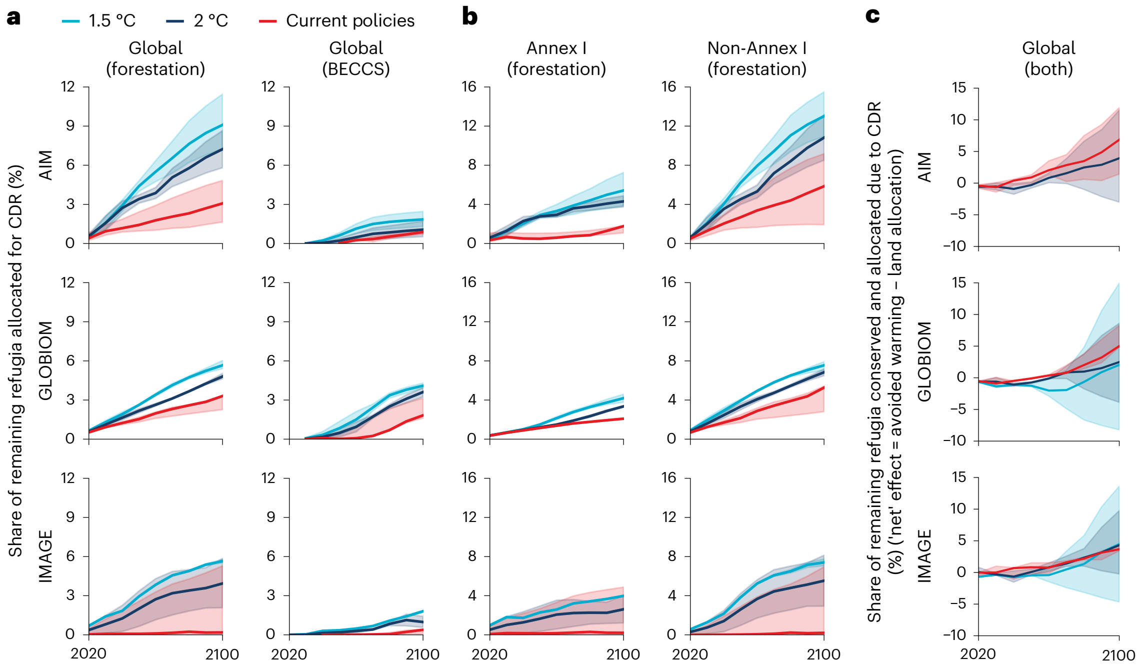

Fig. 1 | Global climate refugia implications of CDR deployment (2020–2100). **a**, The global share of remaining (remaining per warming level per time step) climate refugia allocated for forestation (afforestation, reforestation and forest restoration) and BECCS. **b**, The share of remaining climate refugia allocated for forestation across Annex I and non-Annex I countries. **c**, The 'net' effect of forestation and crop-based BECCS on climate refugia by showing the share of remaining climate refugia that would be conserved owing to CDR-related avoided warming, minus climate refugia land allocated for CDR deployment (assuming fully negative effects). Scenarios correspond to RCP1.9 (1.5 °C scenario), RCP2.6 (2 °C scenario) and RCP4.5 (current policies). The line plots show the median and the full range across the considered shared socioeconomic pathways (SSP1-3). Uncertainty ranges also span the potential outcomes from no climate refugia recovery to full recovery after peak warming in the context of overshoot. For each time step, climate refugia data are matched to the warming level of the respective scenario and model framework to dynamically track how much climate refugia is remaining. The underlying global warming information is based on median estimates of the GSAT from the reduced-complexity earth system model MAGICC v7.5.3 and the AR6 best estimate for the TCRE (for details, see Methods). In **c**, the 1.5 °C scenario for AIM is not shown owing to lacking data on CO_2 removal from forestation. GCAM and REMIND-MAgPIE were not considered for this analysis component as these two models do not report the required AR6 CO_2 removal data or partly lack SSP–RCP combinations. The results for the share of remaining climate refugia allocated for crop-based BECCS across Annex I and non-Annex I countries as well as the warming-related CDR implications are shown in the Supplementary Information.

The AIM model allocates considerably more remaining climate refugia for forestation than GLOBIOM and IMAGE. The scale of land allocation for bioenergy crops (for BECCS) within globally remaining climate refugia is relatively consistent across the three models.

To illustrate the potential 'net' biodiversity effect, we subtract the share of remaining climate refugia allocated for CDR deployment from the CDR-related avoided warming loss of climate refugia (taking a conservative approach by assuming fully negative biodiversity effects of CDR-related land allocation). The estimated 'net' biodiversity effect is highly uncertain with a tendency towards 'net' benefits (Fig. 1c). However, the degree to which CDR deployment may reduce warming-related climate refugia loss (up to around 25% avoided warming loss) strongly depends on underlying assumptions about climate refugia recovery after peak warming in the context of temperature overshoot (Methods and Supplementary Information). Assuming no climate refugia recovery after peak warming strongly reduces the potential of CDR to avoid long-term climate refugia loss, thereby reducing the potential 'net' benefit of CDR deployment or even leading to 'net' harm (Fig. 1c).

Regional patterns and hotspots

The global results mask important regional differences in the overlap between CDR on land and climate refugia. We assess these differences through the lens of the annex-based classification in the United Nations Framework Convention on Climate Change (UNFCCC) (Methods). Up to 15% of the remaining climate refugia in non-Annex I countries is allocated for forestation compared with around 7% in Annex I countries, highlighting a dual inequity. These regions, which are often least responsible for causing climate change, face a dual challenge of preserving biodiversity and contributing CO_2 removals via forestation to help reduce the impacts of climate change (Fig. 1). No such pattern was observed for the BECCS (Supplementary Information).

To diagnose regional model fingerprints more granularly, we select a focus scenario (SSP2-26) that has the necessary information across three of the five models (Methods), identify a common CO_2 removal level (6 $GtCO_2$) and set the climate refugia extent to 1.8 °C of global warming, which roughly corresponds to the median peak warming of the focus scenario across the five considered models. Holding these elements consistent across the models allows us to consistently tease out country-level and regional differences.

Generally, we observe notable regional and country-level differences across the considered models (Fig. 2). At the country level, substantial shares of national refugia are allocated for CDR deployment, even at moderate CO_2 removal levels of 6 $GtCO_2$. High relative allocation shares are especially observed in countries with very little remaining climate refugia areas, even when CDR land allocation is low in absolute terms. Countries with largely intact climate refugia areas at 1.8 °C, such as the USA, see comparatively low relative CDR land allocation within national refugia areas, despite large absolute CDR deployment.

For all five models, we identify several regions where at least two models deploy CDR within 1.8 °C-resilient climate refugia for SSP2-26 in 2100 (variations are presented in the Supplementary Information).

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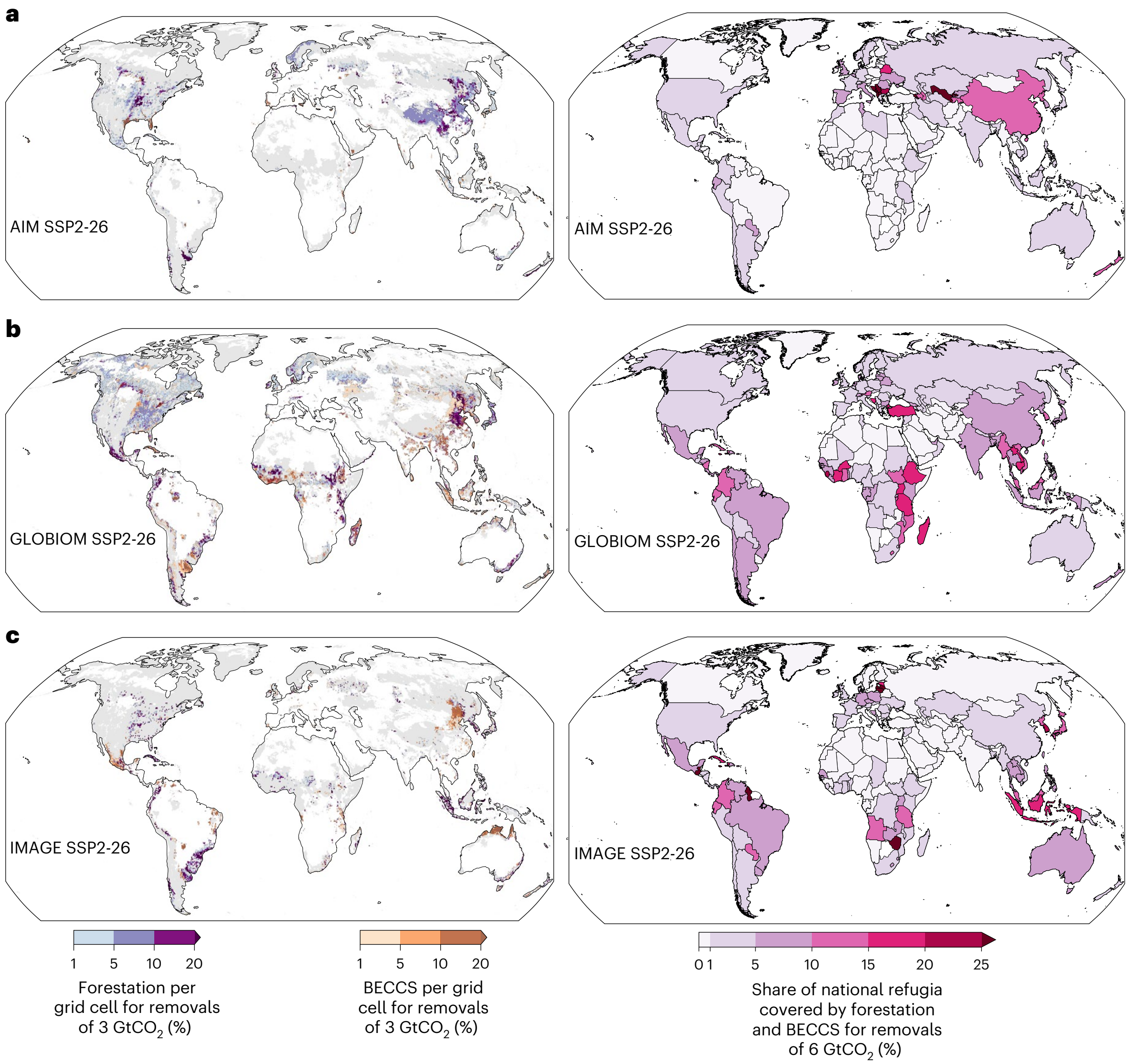

Fig. 2 | Spatial land allocation for CDR deployment within climate refugia resilient to 1.8 °C. The figures are based on the focus scenario SSP2-26 and show the results for an annual CO_2 removal of 6 $GtCO_2$. The remaining climate refugia at 1.8 °C are shown in grey in the left column. **a**–**c**, The spatially explicit (left column) and country-level (right column) allocation of climate refugia for CDR deployment is shown for the three model frameworks AIM (**a**), GLOBIOM (**b**) and IMAGE (**c**). Global warming of 1.8 °C roughly corresponds to the median peak warming of the focus scenario SSP2-26 across the five model frameworks and is therefore chosen as the warming level for climate refugia. The CDR land allocation in all maps in this figure corresponds to the CO_2 removal of 3 $GtCO_2$ via forestation (afforestation, reforestation and forest restoration) and 3 $GtCO_2$ via crop-based BECCS as this is the highest CO_2 removal level reached by both CDR options across all three model frameworks in SSP2-26, allowing for a consistent comparison across CDR options and models. GCAM and REMIND-MAgPIE were not considered for this analysis component as these two models do not report the required AR6 CO_2 removal data. The robustness of the results presented here is evaluated in the Supplementary Information. Information on CO_2 removal scaling and related land requirements is provided in the Supplementary Information. Basemaps were generated in Cartopy using Natural Earth data[89].

This model consensus exercise highlights areas of particular importance where potential CDR–biodiversity conflicts or synergies may arise (Fig. 3). The areas of model consensus primarily lie within Eastern China (for forestation), parts of the USA, West Africa (for BECCS) and Indo-Pacific Island states.

A majority of model consensus areas lie in regions that may not be suitable for land-intensive CDR deployment. For forestation, this is the case in climate refugia areas without reforestation potential[37], while for BECCS, this is the case in areas of bioenergy cropland interference with biosphere integrity[8,38]. In a few cases, we also identify model consensus areas, where CDR deployment may be beneficial to biodiversity (Fig. 3). However, CDR deployment in such potentially suitable areas can still result in negative outcomes if mode and intensity of implementation are not sensitive to the local context or if deployment negatively affects aspects such as species composition, phenology or habitat connectivity[39,40]. We stress that our evaluation of potentially beneficial or likely harmful implications is for illustrative purposes to provide a first-order indication of the effect direction and that our approach is conservative as it considers exclusion criteria beyond biodiversity (Methods). Generally, more granular analyses are required to adequately assess the location-specific suitability of CDR deployment[41]. Particular attention also needs to be paid to 1.8 °C-resilient biodiversity hotspots, in which at least two of the five models deploy CDR (Fig. 3)—many of these consensus regions are today composed of croplands, forests and shrublands[42,43]. While land-intensive CDR is a key driver of land-use change in the assessed scenarios (Supplementary Information), non-CDR drivers of land-use change, such as urban[44] or cropland expansion[45], may also affect biodiversity. Information

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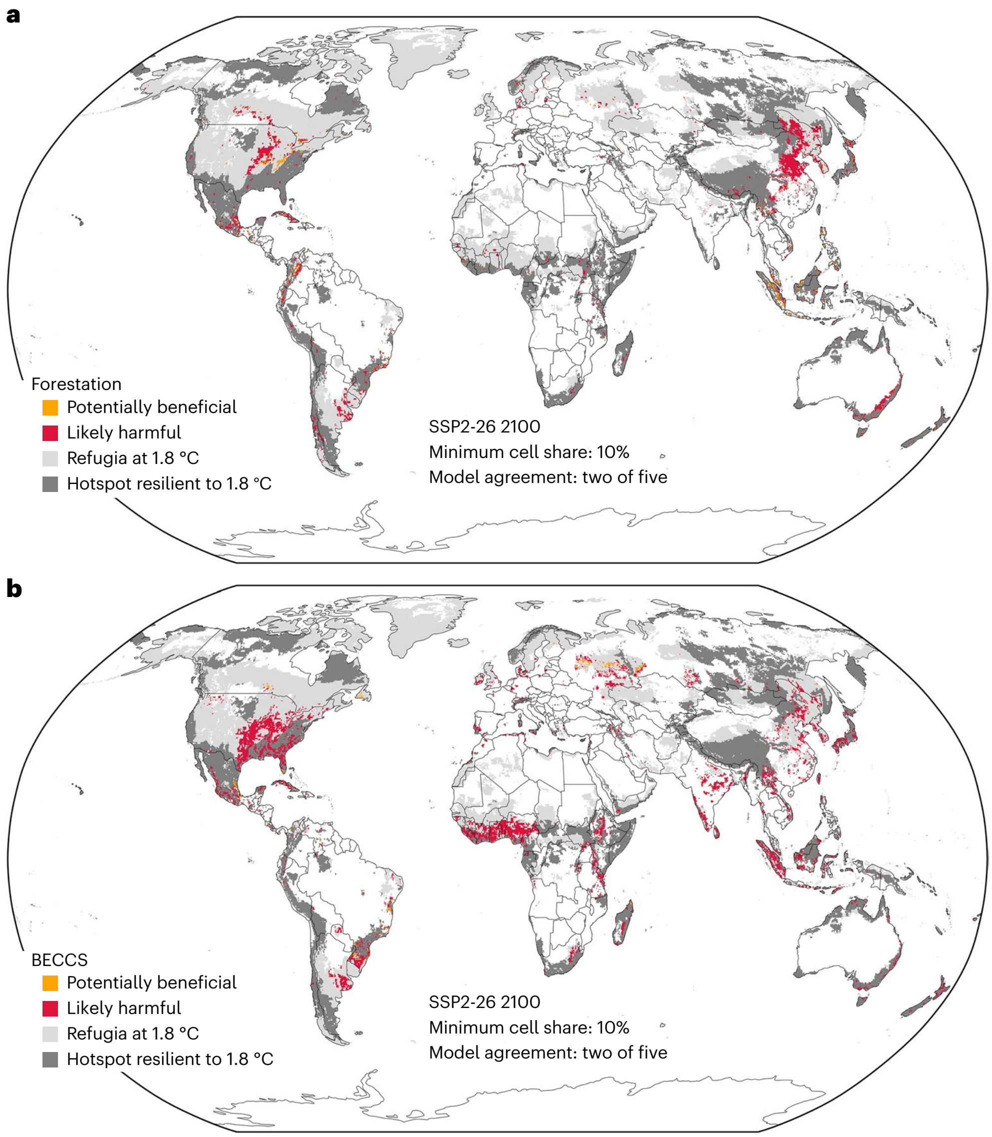

Fig. 3 | Model agreement on land allocation for CDR deployment within biodiversity areas. The figures are based on the focus scenario SSP2-26 in 2100 and the five considered model frameworks AIM, GCAM, GLOBIOM, IMAGE and REMIND-MAgPIE. The remaining refugia at 1.8 °C are shown in light grey, whereas refugia areas that are also resilient biodiversity hotspots are shown in dark grey. CDR land allocation within refugia areas that could potentially benefit from such land interventions is shown in yellow, while refugia areas that such land interventions would likely harm are shown in red. The CDR land allocation outside of refugia areas is not shown. At least two out of the five considered models need to allocate at least 10% of a grid cell surface for CDR deployment within a climate refugia area to be mapped in this figure. **a**, The results for forestation (afforestation, reforestation and forest restoration). **b**, The results for BECCS. Supplementary results, based on alternative minimum thresholds for model agreement and relative cell allocation are presented in the Supplementary Information. Basemaps were generated in Cartopy using Natural Earth data[89].

on the scenario-based biodiversity impacts of land-use types beyond forestation and BECCS is provided in the Supplementary Information.

Implications of conservation

While land-intensive CDR is not per-definition detrimental to biodiversity, large-scale allocation of areas of high biodiversity importance may conflict with internationally agreed targets for biodiversity conservation, which imply halting land-use change-related biodiversity loss. The 2030 Agenda for Sustainable Development has set the goal of halting "(…) the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species" (SDG 15.5)[27]. The more recent Kunming-Montreal Global Biodiversity Framework reiterates this target by aiming to "(…) bring the loss of areas of high biodiversity importance, including ecosystems of high ecological integrity, close to zero by 2030" (target 1)[28].

To illustrate the potential implications of these targets for CDR deployment, we omit areas of high biodiversity importance from CDR land allocation. As areas of high biodiversity importance are not clearly defined, we use three biodiversity metrics (defined in Table 1) to estimate how much less land for CDR deployment would be available if areas of high biodiversity importance were strictly excluded from allocation in the 2 °C focus scenario (SSP2-26). If current biodiversity hotspot areas were excluded from CDR deployment, more than 50% (median estimate) of the scenario-based land allocated for forestation and BECCS would not be available by 2050 (Fig. 4). The share of CDR land not available for allocation is largely stable across the three evaluated time steps, underlining that potential CDR deployment constraints owing to interference with biodiversity conservation may arise as early as 2030. However, models could still allocate land in other less cost-effective places, resort to alternative, less land-intensive

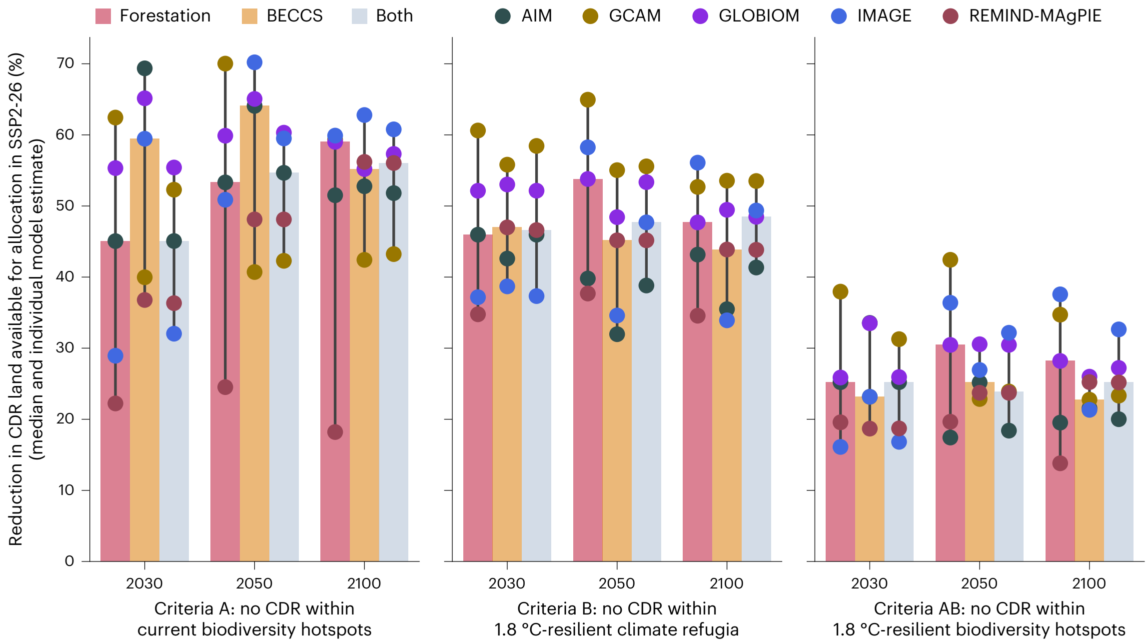

Fig. 4 | Share of allocated land not available for CDR deployment under strictly enforced biodiversity conservation. The results are shown for forestation (afforestation, reforestation and forest restoration), bioenergy cropland (for BECCS) and for both CDR options together for the years 2030, 2050 and 2100, based on three different exclusion criteria. The first criterion (A) excludes land from CDR allocation that is a biodiversity hotspot, regardless of the hotspot's resilience to 1.8 °C. The second criterion (B) excludes land from CDR allocation that is a climate refugia resilient to 1.8 °C, irrespective of whether these refugia areas are biodiversity hotspots. The third criterion (AB) excludes land from CDR allocation that is a climate refugia resilient to 1.8 °C while also being a biodiversity hotspot. The robustness of the results presented here is evaluated in the Supplementary Information.

mitigation options or pursue more biodiversity-sensitive deployment approaches, as more recent IAM-based analyses partly already do[12,46,47]. Also, more granular differentiations between afforestation, reforestation and forest restoration within areas of high biodiversity importance could further ease the illustrated land constraint, for example, by allowing CDR in areas with reforestation potential where biodiversity may benefit from deployment (Supplementary Information).

Discussion

In this study, we explore potential biodiversity implications of future land conversion for forestation and bioenergy crops (for BECCS) in deep mitigation pathways from the original SSP quantification. CO_2 removals from forestation and BECCS could reduce long-term warming-related climate refugia loss by up to around 25% in the evaluated scenarios. However, the effectiveness of such CO_2 removals for reducing warming-related refugia loss is highly uncertain and contingent on the ability of climate refugia to recover from temperature overshoot. Higher deployment of land-intensive CDR in the evaluated scenarios results in increased allocation of remaining climate refugia. We show that up to 11% of global remaining climate refugia areas may overlap with areas selected for forestation (around 4% overlap with bioenergy cropland for BECCS), in scenarios consistent with limiting warming to 1.5 °C in 2100. While this overlap does not automatically imply a loss of climate refugia, the assessed magnitude of refugia allocation is concerning given the sensitivity of species response to human disturbances. Even a species loss of 5% could be catastrophic for global ecosystems[48].

Already at a moderate annual CO_2 removal rate of 6 $GtCO_2$, substantial shares of peak warming resilient climate refugia would be allocated for forestation and BECCS in some countries, while the exact allocation shares are highly uncertain. Importantly, the share of remaining climate refugia allocated for CDR deployment differs largely between regions, with disproportionate allocation in UNFCCC non-Annex I countries, which are largely non-high-income countries[49–53]. Given the uneven distribution of responsibilities and capabilities to address both the climate crisis and the biodiversity crisis, and in the light of the biodiversity finance gap of US$700 billion per year[28], Annex I countries are obliged to substantially increase biodiversity-related financial flows to non-Annex I countries.

Strictly enforcing area-based biodiversity conservation, as agreed in international policy frameworks, could increase the challenge to allocate land for CDR deployment, as more than 50% (median estimate) of the land for scenario-based forestation and BECCS would not be available for allocation when excluding current biodiversity hotspots. While IAMs can design new scenarios that achieve similar CO_2 removal levels without interfering with biodiversity, the overall competition for land may increase, especially in light of other non-biodiversity-related CDR constraints such as fire risk[54], food security[55,56] and planetary boundaries other than biosphere integrity[8], which are not the focus of this study.

However, CDR is not per-definition detrimental to biodiversity and prioritizing biodiversity conservation helps to protect existing carbon pools and can promote additional carbon sequestration[57–59]. While misinformed tree planting harms biodiversity in many regions[60], carefully increasing forest cover can support habitat conservation[61]. In degraded ecosystems, which have historically been forest land, forest restoration and reforestation with highly diverse and locally adapted plant species can increase the extent and connectivity of habitats and therefore support biodiversity conservation while sequestering carbon[26,62]. Such approaches to carbon sequestration are not only favourable from a biodiversity but also from a mitigation standpoint as more carbon is sequestered[62] and carbon stored in natural ecosystems is more resilient to climate change than plantation forests based on fast-growing monocultures[63]. We have indicated where such reforestation and restoration potential may be realized within the identified scenario-based model consensus regions of CDR deployment, providing an entry point for location-specific climate policy planning. Still, nuanced assessments of reforestation potential in such areas are needed to protect intact grassy biomes, which have partly been misinterpreted as degraded forests in the past[60]. Natural areas that have historically not been forest land, such as savannas or grassland, are unsuitable for forest-based

CDR, as deployment would likely yield negative biodiversity effects[26,62] and increase vulnerability to disturbances such as fire[63]. Many of the consensus regions of scenario-based forestation (and more so the land allocation fingerprints of the individual models) fall into such likely unsuitable areas[8,37,38,64].

Mostly negative implications for biodiversity are expected from the use of bioenergy crops for BECCS, and irrigation-related sustainability concerns may further increase land demand for bioenergy crops, intensifying pressure on biodiversity[65,66]. Allocating abandoned cropland for BECCS may be favourable[26,67] but does not guarantee sustainable outcomes[41]. Moreover, perennial bioenergy crops on intensively farmed cropland may be more sustainable than annual bioenergy crops[68,69]. Using biogenic waste and residues as feedstock for BECCS could reduce its additional land footprint. Also, BECCS may constrain warming-related biodiversity loss[13,14]. However, the larger the dependence on forestation and BECCS, the less likely it would be that the potential land-related co-benefits can be realized, while preventing negative implications[7].

Our illustrative analysis flags areas of high biodiversity importance that may be harmed by scenario-implied land-intensive CDR deployment, calling for a careful assessment and prioritization of areas for which policy goals for climate action and biodiversity conservation can be aligned. Such an alignment is not only required to conserve biodiversity but also to protect carbon pools as biodiversity loss can trigger the release of carbon, leading to a lose–lose situation for the climate and biodiversity[57]. Our illustrative indication of potentially beneficial and likely harmful model consensus areas for CDR land allocation pose an entry point for future IAM-based analyses to produce more biodiversity-sensitive mitigation scenarios.

While forestation and BECCS feature prominently in mitigation pathways[4,5], direct air carbon capture and storage has become another dominant option, and more IAMs model larger CDR portfolios, including enhanced weathering[70] or biochar[71]. Diverse CDR portfolios help reduce negative externalities[70,72–74] by reducing the dependence on land-intensive CDR. Nevertheless, some of these newer CDR options are still nascent, costly or may also be associated with a considerable land footprint[75,76]. Ensuring that CDR use is restricted to suit critical needs[77,78] and drastically raising the ambition for near-term gross emission reductions are key steps to avoid overreliance on land-intensive CDR and to avert negative implications for biodiversity. Ultimately, prioritizing the restoration of degraded ecosystems can partly alleviate negative implications by simultaneously supporting biodiversity conservation and carbon sequestration while strengthening the climate resilience of ecosystems.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-026-02557-5.

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Methods

Analysis overview

We combined 12 existing datasets in the main analysis of this study: (1) spatial data on climate refugia areas, (2–3) spatial data on biodiversity hotspots, (4–8) spatial land-use data on forestation and bioenergy cropland (for BECCS) for various scenarios and from five different model frameworks; (9–10) two maps indicating the constrained land allocation potential for reforestation and bioenergy cropland, (11) non-spatial data on CO_2 removals from forestation and BECCS for the same scenarios and model frameworks as for the land-use data and (12) spatial data on the world administrative boundaries at the country level.

First, we estimated the scenario-based CDR land allocation within remaining climate refugia throughout the twenty-first century by overlaying climate refugia data and land-use data from the three model frameworks that satisfy the data requirements for this analysis component (AIM, GLOBIOM and IMAGE). We also estimated the avoided warming effect of CDR deployment and its implications for warming-related climate refugia loss. Second, we combined the CO_2 removal data with the land-use data to estimate spatially explicit land allocation for a given CO_2 removal via forestation and BECCS for each of these three model frameworks. Then, we spatially overlaid the CO_2 removal-based land allocation data from the three model frameworks with the data on climate refugia. Third, we evaluated the scenario-based CDR land allocation agreement in biodiversity areas across all five considered model frameworks. Ultimately, we estimated how much of the total CDR land allocation is outside of climate refugia areas and biodiversity hotspots. Data preprocessing of the world administrative boundaries and the biodiversity hotspots was done in QGIS 3.28 while all other analysis steps were implemented in Python 3.11. Details on our analysis approach are provided below. The analysis code is made available at https://doi.org/10.5281/zenodo.15210722 (ref. 90).

Climate refugia

Data on climate refugia were retrieved from previous analyses[24,25,82,83] based on the Wallace Initiative database and are available at 10 arcmin spatial resolution. This existing dataset describes the climatically suitable range of around 135,000 terrestrial species (fungi, plants, invertebrates and vertebrates) and the potential change in species' climatically suitable ranges for various levels of global warming relative to pre-industrial warming levels (1850–1900) based on the species distribution model MaxENT[24,91]. The dataset builds on the assumption that the current statistical relationship between climatic conditions and species distribution will hold in the future. Future projections of species' distribution are based on 21 regional climate change projections (CMIP5). The individual species' models were aggregated to depict remaining species richness per grid cell for various levels of global warming. Refugia areas are defined as places (grid cells) where at least 75% of the initially present species will remain for a given warming level, requiring at least 11 of the 21 regional climate model projections to agree on a refugia's future existence. The dataset and its underlying methodology are further detailed in refs. 24,25,82,83. Where necessary, we linearly interpolated between available warming steps to retrieve climate refugia maps per hundredth of a degree of warming.

Biodiversity hotspots

Data on biodiversity hotspots are based on the WWF Global 200 ecoregions (G200)[84], in combination with ref. 85 and subsequent updates[86], following the hotspots definition in IPCC AR6 WGII[26]. The G200 ecoregions are characterized by "(…) exceptional levels of species richness or endemism, or those with unusual ecological or evolutionary phenomena."[84] The complementary hotspot dataset contains 36 recognized biodiversity hotspots for conservation priorities, which implies that these areas inhabit at least 1,500 endemic vascular plant species and have already lost 70% or more of their primary native vegetation. The datasets and their underlying methodology are further detailed in refs. 84–88.

Forestation and BECCS

Data on the location and extent of forestation and bioenergy cropland (for BECCS) areas for several SSP–RCP scenario combinations (original SSP quantification)[79,80] were retrieved from AIM-SSP/RCP v2018[92] at 30 arcmin spatial resolution, from GCAM-Demeter-LU[34] at 3 arcmin spatial resolution, from GLOBIOM[31] at 5 arcmin spatial resolution, from IMAGE 3.0.1[32] at 30 arcmin resolution and from REMIND-MAgPIE 1.6-3.0[35,36] at 30 arcmin resolution. A variable for bioenergy cropland is available in the datasets from the five model frameworks, whereas forestation is approximated as the net increase in managed and unmanaged forest cover per grid cell between 2010 and a given future time step. The AIM dataset is further detailed in refs. 29,30 and the GCAM dataset is further detailed in ref. 34. Further detail on GLOBIOM is provided in ref. 93 and IMAGE 3.0.1 is described further in ref. 32. REMIND-MAgPIE 1.6-3.0 is described further in refs. 35,36.

Our estimation of the fraction of bioenergy cropland used for BECCS relies on global AR6 data on primary bioenergy with or without carbon capture and storage for each considered model and scenario. AR6 R10 level data, which would allow for higher granularity across regions, is not available. AR6 R5 level data is available[4]; however, we refrained from using R5 data instead of the global data as this would require additional assumptions about cross-regional biomass trade since the biomass is not necessarily used in the region where it is produced. Such assumptions are not straightforwards given the available data, and trade flows differ across models.

Data on CO_2 removals via forestation and BECCS were retrieved from the AR6 Scenarios Database[4] for several SSP–RCP scenario combinations[79,80] (Supplementary Information), based on the three models AIM/CGE 2.0, MESSAGE-GLOBIOM 1.0 and IMAGE 3.0.1. Information on primary bioenergy from bioenergy crops and residues from the three main model frameworks was used per considered scenario to estimate the fraction of BECCS-related CO_2 removal coming from bioenergy crops (Supplementary Table 5). CO_2 removal and CDR-related land use per scenario and year is shown in the Supplementary Information. GCAM and REMIND-MAgPIE were not considered here as these two models do not report the required AR6 CO_2 removal data. Global land cover for six land-use types across all five considered models and related scenarios is shown and discussed in the Supplementary Information. The selection of models and model assumptions are further discussed in the Supplementary Information.

We used 10-year time steps for all spatial and non-spatial scenario data related to forestation and BECCS. In this analysis, it was not possible to distinguish afforestation, reforestation and natural forest restoration owing to the limited differentiation in the evaluated land-use data. Thus, we collectively refer to these CDR options as forestation, which captures both forest expansion and natural regrowth. Consistent with the standard practice of this generation of models, the gridded scenario data on forestation and BECCS relies on net land-use transitions per grid cell. Land-use expansion and contraction are further discussed in the Supplementary Information.

Biodiversity-sensitive CDR deployment areas

To indicate where land-intensive CDR deployment could be potentially beneficial or likely harmful, we made use of a constrained reforestation potential map[37] and a constrained bioenergy cropland map[8].

The constrained reforestation potential map is based on a conservative, biodiversity-sensitive definition of forests (more than 60% tree cover) and indicates areas where forests are currently absent but naturally occur. Further, the constrained reforestation potential map excludes areas with unfavourable albedo[94], areas in peatlands or wetlands with vulnerable carbon stocks[62], croplands[95] and areas that fall within fire-adapted and fire-maintained ecosystems. If scenario-based forestation occurs in such reforestation potential areas[37], we indicated 'potentially beneficial' biodiversity implications. While forestation in such areas may in principle be beneficial to biodiversity, the implications for biodiversity still depend on the mode of implementation, for example, in terms of forestation intensity and selected forest species. If scenario-based forestation occurs in places that are not within reforestation potential areas, we indicated 'likely harmful' outcomes, as this would imply forest in places where forests do not naturally occur.

The constrained bioenergy cropland potential map[8] is based on a map showing maximum biomass plantation potential while reserving current agricultural areas and excluding areas that are not compatible with the planetary boundary constraint for biosphere integrity[8,38]. If scenario-based bioenergy cropland occurs in places that are not within the constrained BECCS potential areas, we indicated 'likely harmful' outcomes as this would interfere with biosphere integrity or agricultural production. Likewise, if scenario-based bioenergy cropland occurs in places that are within the constrained BECCS potential areas, we indicated 'potentially beneficial' implications owing to avoided interference with the planetary boundary constraint for biosphere integrity and current agricultural areas. Nevertheless, depending on the mode of implementation, for example, regarding the land-use intensity, bioenergy cropland in such areas could still be harmful for biodiversity.

The indication of potentially beneficial and likely harmful biodiversity implications of forestation and BECCS are for illustrative purposes and suit as a first-order estimate, but more granular analyses are required to better capture CDR land use-related biodiversity impacts, especially since the maps used to indicate constrained CDR deployment potential consider additional aspects beyond biodiversity. To complement the results presented in the main analysis and to indicate biodiversity implications of all scenario-based land use beyond forestation and BECCS, we used characterization factors by ref. 96 to estimate the potentially disappeared fraction of global species for 2020 and 2050 across all considered models and scenarios. The results and discussion of this supplementary analysis are provided in the Supplementary Information.

World administrative boundaries

Spatial data on global administrative boundaries are retrieved from ref. 97 and joined with non-spatial data on the UNFCCC annex country classification[98] to spatially distinguish between Annex I countries and non-Annex I countries. Annex I is composed of highly industrialized countries and countries transitioning to a market economy. The group of non-Annex I comprises all other countries, mostly not classified as high-income countries[49,52,99]. We only considered UNFCCC parties but not territories and dependencies. Areas of unsettled sovereignty status, as classified in the world administrative boundaries data, are shown as blank.

Data resampling and matching

For the analysis of CDR land allocation within climate refugia, we resampled the CDR-related data to 10 arcmin to match the spatial resolution of the climate refugia. GCAM and GLOBIOM data were downsampled, whereas AIM, IMAGE and REMIND-MAgPIE were upsampled using nearest neighbour resampling. These resampling steps allowed us to align the spatial resolutions of the datasets while preserving their numerical properties. Spatial vector data for the world administrative boundaries, the G200 ecoregions and biodiversity hotspots for conservation priorities were also rasterized to match 10 arcmin spatial resolution.

We combined the SSP–RCP CO_2 removal data from the AR6 Scenarios Database for AIM/CGE 2.0, MESSAGE-GLOBIOM 1.0 and IMAGE 3.0.1 with the SSP–RCP land-use data from AIM-SSP/RCP Ver2018, the corresponding version of GLOBIOM and IMAGE 3.0.1 to estimate land-per-removal throughout the twenty-first century. GCAM and REMIND-MAgPIE were not considered for this analysis component as these two models do not report the required AR6 CO_2 removal data or partly lack SSP–RCP combinations. For the link between CO_2 removal data and land-use data on forestation and bioenergy croplands for BECCS, we had to rely on available datasets from different model versions of AIM. While this is not a perfect match between datasets, we believe that matching CO_2 removal and land demand for the two considered CDR options based on the SSP–RCP scenarios from similar versions of the same model framework is reasonably accurate for the purpose of this analysis. The same applies to GCAM concerning the estimated share of bioenergy cropland for BECCS.

Analysis underlying Fig. 1

To estimate the magnitude of land allocation for forestation and bioenergy cropland (for BECCS) within remaining climate refugia, we overlaid the spatial CDR land allocation data with the spatial climate refugia data. We did this for the three model frameworks AIM, GLOBIOM and IMAGE for RCP1.9, RCP2.6 and RCP4.5 across SSP1-3, while matching the climate refugia data to the global warming levels of the SSP–RCP combinations for the considered time steps until 2100. GCAM and REMIND-MAgPIE were not considered for this analysis component as these two models do not report the required AR6 CO_2 removal data or partly lack SSP–RCP combinations. For each scenario and for each time step, we calculated the share of climate refugia (remaining for a given warming level) allocated for forestation or bioenergy cropland (for BECCS) at the global level, across Annex I countries, and across non-Annex I countries. Here, we only considered direct UNFCCC parties but not territories, dependencies or areas of unsettled sovereignty status (see note above).

Global warming levels per scenario are based on median estimates for the global mean surface air temperature (GSAT) based on the reduced-complexity earth system model MAGICC v7.5.3. To estimate the share of remaining climate refugia lost when excluding CO_2 removals from forestation and crop-based BECCS, we first linearly interpolated annual CO_2 removal between available time steps for 2020–2100 and estimated cumulative total CO_2 removal between 2020 and each subsequent time step. Next, we used the AR6 best estimate for the transient climate response to cumulative CO_2 emissions (TCRE) to estimate avoided warming due to CDR per time step (similar to the approach in ref. 100). Ultimately, we added the estimates for avoided warming per time step to the original scenario warming curves to estimate counterfactual warming-related climate refugia loss. Since the ability of climate refugia to recover from warming-related loss after peak warming in the context of temporary temperature overshoot is uncertain, the results (in Fig. 1) span the range of outcomes for two extreme recovery assumptions, namely no climate refugia recovery to full climate refugia recovery. To illustrate the potential 'net' biodiversity effect (Fig. 1c) we subtract the share of remaining climate refugia allocated for CDR deployment (Fig. 1a) from the avoided warming loss of remaining climate refugia (Supplementary Fig. 3a). In addition to median estimates, we also illustrate the warming-related climate refugia loss for the 83.3rd percentile range of GSAT and TCRE, which corresponds to the upper bound of the likely range (Supplementary Information). We denote 'net' biodiversity effect in quotations as this estimation is based on the conservative and illustrative assumption that CDR-related land allocation would lead to climate refugia loss. However, CDR deployment may be in part beneficial to biodiversity, as described and discussed in the main analysis.

Analysis underlying Fig. 2

To estimate the extent and location of forestation and bioenergy cropland (for BECCS) areas for a targeted CO_2 removal level (3 $GtCO_2$ per option) we determined the first year (target year) in the scenario timeseries (2020–2100), in which the targeted CO_2 removal level is achieved, based on the CO_2 removal data in the AR6 Scenarios Database. We then linearly interpolated between available years in the spatially explicit land-use data for forestation and bioenergy cropland (for BECCS) to determine the CDR land allocation in the target year. The focus scenario for this analysis is SSP2-26. The 'middle of the road' narrative for socio-economic assumptions (SSP2) was chosen as a progression of historical patterns. RCP2.6 was chosen as this is the most ambitious scenario for which all required variables are available across the three model frameworks AIM, GLOBIOM and IMAGE. GCAM and REMIND-MAgPIE were not considered for this analysis component as these two models do not report the required AR6 CO_2 removal data or partly lack SSP–RCP combinations. The target CO_2 removal level of 3 $GtCO_2$ per CDR option was chosen as this is the highest CO_2 removal level that is reached by both forestation and BECCS across all three model frameworks in SSP2-26, allowing for a consistent comparison across CDR options and models.

Next, we spatially overlaid the estimated CDR land allocation for the targeted CO_2 removal level for forestation and BECCS with the climate refugia areas resilient to 1.8 °C of global warming and calculated the share of total remaining climate refugia allocated for the deployment of forestation and BECCS. Ultimately, we intersected the spatially explicit overlays with the world administrative boundaries to compare CDR land allocation within remaining climate refugia at the country level. Climate refugia areas resilient to 1.8 °C of global warming were chosen for this analysis as this roughly corresponds to the median peak warming in SSP2-26 across the five considered model frameworks, implying that these climate refugia areas are warming resilient for the entire period for which the scenarios were initially computed. To test the robustness of our results, we also compared CDR land allocation within remaining climate refugia for the scenarios SSP1-26 and SSP2-26 for the scenario year in which the combined CO_2 removal from both CDR options equals the target annual CO_2 removal (6 or 10 $GtCO_2$) for the first time, regardless of the relative contribution of the two CDR options (Supplementary Information).

Analysis underlying Fig. 3

To evaluate model agreement, we identified areas (1) within climate refugia resilient to 1.8 °C of global warming that could potentially benefit from CDR deployment or (2) within climate refugia resilient to 1.8 °C of global warming that would likely be harmed by CDR deployment, in which at least two of the five considered model frameworks deploy forestation or BECCS. We did this for the focus scenario SSP2-26 in 2100 and imposed a minimum threshold for CDR deployment of 10% of the surface area per grid cell to be considered as notable agreement. The distinction between climate refugia that could potentially benefit or likely be harmed by forestation or BECCS is based on refs. 8,37,38, as described above. To test the robustness of our results, we also assessed model agreement based on SSP1-26 and varied the minimum thresholds for grid cell surface allocation and number of agreeing models, as described in the Supplementary Information.

Analysis underlying Fig. 4

To estimate the impact of enforcing biodiversity conservation on land allocation for CDR deployment, we used the following criteria to exclude areas for CDR deployment that are currently biodiversity hotspots (A), climate refugia resilient to 1.8 °C of global warming (B) or biodiversity hotspots that are also climate refugia resilient to 1.8 °C of global warming (AB). Next, we calculated how much less land for CDR deployment would be available when imposing the different exclusion criteria. We did this based on the focus scenario SSP2-26 for forestation, BECCS or both across the five considered model frameworks and focused on 2030, 2050 and 2100. Further results for SSP1-26 and for the reduction in CDR land if allowing land allocation in areas that could potentially benefit from CDR deployment are shown in the Supplementary Information.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Underlying data on climate refugia can be made available upon reasonable request. Underlying data on the WWF G200 ecoregions are available at https://databasin.org/datasets/a5b34649cc69417ba52ac8e2dce34c3b/. Underlying data on biodiversity hotspots for conservation priorities are available via Zenodo at https://doi.org/10.5281/zenodo.3261807 (ref. 86). Underlying data on CO_2 removals and biomass-based primary energy from the AR6 Scenarios Database are available via Zenodo at https://doi.org/10.5281/zenodo.7197970 (ref. 4). Underlying data on land use from AIM-SSP/RCP Ver2018 are available at https://doi.org/10.18959/20180403.001 (ref. 92). Underlying data on land use from GCAM-Demeter are available at https://doi.org/10.25584/data.2020-07.1357/1644253 (ref. 101). Underlying data on land use from GLOBIOM are available via Zenodo at https://doi.org/10.5281/zenodo.15964077 (ref. 102). Underlying data on land use from IMAGE 3.0.1 are available via Zenodo at https://doi.org/10.5281/zenodo.17046335 (ref. 103). Underlying data on land use from REMIND-MAgPIE 1.6-3.0 are available via Zenodo at https://doi.org/10.5281/zenodo.17047534 (ref. 104). Underlying data on the UNFCCC annex country classification are available via GitHub at https://github.com/setupelz/regioniso3c. Underlying data on the constrained reforestation potential map are available at https://www.naturebase.org. Underlying data on the constrained biomass plantation map are available via Zenodo at https://doi.org/10.5281/zenodo.14514051 (ref. 105). Underlying data on world administrative boundaries are available at https://geonode.wfp.org/layers/geonode%3Awld_bnd_adm0_wfp.

Code availability

The analysis code is available via Zenodo at https://doi.org/10.5281/zenodo.15210722 (ref. 90).

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Author contributions

R.P., S. Fuss and J.R. conceptualized the study. R.P., P.H., Y.W., A.L.D.A., F.K., S. Frank, T.H., J.C.D., V.D., F.H., A.P., S. Fuss, G.G. and J.R. worked on the integration of the land-use data. R.P., J.P., N.F. and R.W. worked on the integration of the climate refugia data. R.P. implemented the data analysis and wrote the original draft, and all authors reviewed and edited the paper.

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Competing interests

The authors declare no competing interests.

Additional information

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Policy information about availability of computer code

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