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The choice of land-based climate change mitigation measures influences future global biodiversity loss

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Climate mitigation is reported to benefit biodiversity globally. However, the impacts of mitigation measures based on large-scale land-use modifications can be concentrated in the regions where they are introduced, resulting in regional mismatches between mitigation efforts and biodiversity benefits. Here, we evaluated the impacts of large-scale deployment of bioenergy with carbon capture and storage and afforestation to attain the climate stabilization target stated by the Paris Agreement on global and regional biodiversity by using an integrated model framework. Our results highlight that climate mitigation efforts can benefit global biodiversity regardless of large-scale implementation of land-based mitigation measures. However, the negative impacts of mitigation measures on biodiversity are concentrated in regions with a higher contribution to land-use change and carbon sequestration. The results imply the need to consider the unequal regional distribution of benefits from climate mitigation, as well as mitigation options that avoid regional biodiversity loss by minimizing land-use change.

Simultaneous achievement of climate change mitigation and biodiversity conservation is a significant challenge as societies try to reach or maintain a good quality of life and achieve sustainability. The progression of climate change can negatively impact human life through many pathways, such as reduced food production and increased natural disasters[1,2]. Biodiversity loss may cause degradation of the essential flow of several ecosystem services now and in the future[2,3]. Drivers of climate change and biodiversity loss interact in complex ways, and co-beneficial measures for climate mitigation and biodiversity conservation are attracting increasing attention[4].

The Paris Agreement on climate change highlighted a very low emissions scenario, with its call to hold the global average temperature increase to well below 2 °C and to pursue efforts to limit the temperature increase to 1.5 °C[5]. To achieve these goals, future total CO_2 emissions from 2011 to 2100 would need to be kept within about 1350 $GtCO_2$ or 500 $GtCO_2$ (50% likelihood of limiting global warming to within the 1.5 °C or 2 °C), respectively. However, Intergovernmental Panel on Climate Change (IPCC) Assessment Report 6 and its mitigation scenarios make it clear that keeping cumulative CO_2 emissions within these ranges through emissions reduction alone would be quite challenging, and large-scale carbon dioxide removal (CDR) by carbon sequestration is almost a necessity to meet the above goals[6].

Most global climate change mitigation pathways to limit warming to 1.5 °C and 2 °C, modeled by Integrated Assessment Models (IAMs), rely heavily on large-scale land-related CDR, including the deployment of biomass for bioenergy with carbon capture and storage (BECCS) and afforestation. Although Direct Air Capture and CCS (DACCS) recently has experienced remarkable decreases in cost and drawn increasing attention[7–10], BECCS and afforestation are still considered to be the major CDR options[11]. However, scenarios with large-scale deployment of these measures have raised many concerns[12,13]. The introduction of large-scale bioenergy croplands would damage or reduce the size of the habitats of many organisms and thereby cause a decrease in biodiversity. Expansion of forest areas by inappropriate tree planting, such as afforestation of naturally open habitats, could have negative impacts on biodiversity because of the

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loss of habitats for non-forest organisms[3,4,14]. Although climate stabilization through land-based mitigation measures could provide benefits for biodiversity on a global scale[15], carbon sequestration by BECCS and afforestation may be incompatible with biodiversity conservation on a regional scale because the impacts of these measures may concentrate in specific regions that make a higher contribution to land-use change. Even though it is critically important to evaluate the potential co-benefits and trade-offs between current mitigation goals and biodiversity conservation on both global and regional scales, very little is known about how global scale implementation of BECCS and afforestation would interact with regional biodiversity conservation.

Here, we evaluated the impacts of large-scale deployment of BECCS and afforestation to achieve negative emissions on both global and regional biodiversity. By using an integrated model framework that consistently represents the energy-economic system, spatially explicit land use, and biodiversity, we quantitatively assessed the impact of climate change (e.g., temperature change) and of land-use changes via mitigation measures on biodiversity simultaneously. In addition, the Paris Agreement states that efforts to achieve the long-term temperature goal must be carried out on the basis of equity and in the context of sustainable development and efforts to eradicate poverty[5]. However, mitigation measures based on large-scale land-use modifications such as BECCS and afforestation may place excessive pressure on the regional biodiversity where they are introduced. Based on these results, we discuss what strategies can maximize the compatibility between climate change mitigation and biodiversity conservation.

The impacts of climate change and land-use change through mitigation measures on biodiversity were evaluated by using the Asia-Pacific Integrated Model (AIM) modeling framework[15–17]. We considered four future scenarios depending on the degree of implementation of BECCS and afforestation: baseline, BECCS (2C-BECCS), afforestation (2C-Aff), and optimal use of BECCS and afforestation (2C-Opt). The baseline scenario assumes no greenhouse gas (GHG) emission reductions. The three mitigation scenarios assume emission pathways for CDR where CO_2 emissions by 2100 will be about 1000 $GtCO_2$ (the Lower-2 °C pathway in Rogelj et al.[18]). For each scenario, grid-based (0.5 arc degrees) land-use change and regional contribution to carbon sequestration were projected (17 economic regions worldwide). We then assessed the impacts of mitigation measures on global and regional biodiversity. Future climate change is also considered by using available climate scenario information[19]. We projected temporal changes in species richness and species composition from 2030 to 2090 under each future scenario based on changes in suitable habitat for 8428 species in five taxonomic groups (vascular plants, amphibians, reptiles, birds, and mammals) and evaluated the impacts of each mitigation measure on global biodiversity. Regional and social equity of mitigation measures were examined by the relationship between mitigation efforts or economic conditions and biodiversity loss. We found that climate change mitigation efforts could reduce global biodiversity loss regardless of large-scale implementation of BECCS and afforestation. However, regions that contributed more to land-use change and carbon sequestration tended to experience more negative impacts on biodiversity. The biodiversity impacts of land-use change for CDR may be biased towards certain regions, and we need to carefully consider the regions for implementation of mitigation measures.

Results

Impacts of climate mitigation on global biodiversity

The introduction of mitigation measures through BECCS and afforestation has the potential to reduce risks of future biodiversity loss and alteration of species composition due to climate change on a global scale. Under the baseline scenario, global biodiversity was projected to decrease over time due to climate change (Fig. 1a). The reduction in species richness relative to the current value was 0.015 in 2030 and 0.069 in 2090. In contrast, the introduction of climate mitigation measures reduced the baseline declining trend of biodiversity. Future reductions in species richness under the 2C-BECCS and 2C-Aff scenarios were 0.014 and 0.020 in 2030 and 0.033 and 0.047 in 2090, respectively. The differences between the baseline and mitigation scenarios were unclear in the mid-century, but became more visible in the latter period. In both the baseline and mitigation scenarios, the range of variance increased over time, and the baseline scenario had greater variance than that of the mitigation scenarios. Of the mitigation scenarios, species richness was slightly better maintained under the 2C-BECCS scenario than under the 2C-Aff scenario, although these differences were minor compared with those between the baseline and mitigation scenarios (Fig. 1a). Climate change has also facilitated species replacement in local communities (Fig. 1b). Under the baseline scenario, the similarity index decreased steeply over time, reaching 0.692 in 2070 and 0.630 in 2090 (Fig. 1b). Under the mitigation scenarios, the similarity index also decreased over time, but to a lesser extent than under the baseline scenario. The similarity index decreased to 0.762 and 0.741 in 2070 under the 2C-BECCS and 2C-Aff scenarios, respectively, and slightly decreased after that (0.759 and 0.735 in 2090, respectively). Interestingly, the differences in the similarity index between the baseline and mitigation scenarios are clearer than those of species richness. Of the mitigation scenarios, the 2C-BECCS scenario again showed a somewhat lower decline than the 2C-Aff scenario (Fig. 1b). The intensity of land-use change, which could be a primary driver of mitigation scenario differences, also differed, with the degree of land-use change in the 2C-Aff scenario being larger than that of 2C-BECCS (Fig. 1c, d).

Specific impacts of climate change on regional biodiversity

The specific impacts of climate change on species richness had different trends in the boreal regions of the Northern Hemisphere compared to the other regions (Fig. 2a). The differences in species richness between the baseline and the mitigation scenarios projected by CC-model showed that climate change mitigation could reduce the amount of species richness decrease in a wide range of regions, including Central and South America, Africa, and Europe (Fig. 2a, red regions). In contrast, climate change under the baseline scenario had less impact on species richness in Arctic and sub-Arctic regions and the Tibetan Plateau compared to the mitigation scenarios (Fig. 2a, blue regions).

Specific impacts of land-use change on regional biodiversity

The specific impacts of land-use change through mitigation measures on species richness also varied among regions (Fig. 2b, c). In the LU-model, land-use change under the 2C-BECCS scenario caused lower species richness compared to the baseline scenario in parts of Central and South America, Sub-Saharan Africa, and Central Asia (Fig. 2b, blue regions). In contrast, land-use change under the 2C-BECCS scenario caused greater species richness in parts of Sub-Saharan Africa, East Asia, and Oceania (Fig. 2b, red regions). Land-use change under the 2C-Aff scenario caused lower species richness compared to the baseline scenario in parts of North, Central, and South America, Sub-Saharan Africa, Europe, North Asia, Eastern Asia, South East Asia, and Oceania (Fig. 2c, blue regions). In contrast, land-use change under the 2C-Aff scenario caused greater species richness compared to the baseline scenario in parts of Central Asia, East Asia, and Sub-Saharan Africa (Fig. 2c, red regions). Overall, the impacts of land-use change on biodiversity were greater under the 2C-Aff scenario than under the 2C-BECCS scenario both in intensity and extent of impacts (Fig. 2b, c).

Regional differences in the impact of mitigation measures on species richness were influenced by what the land use was prior to being converted to cropland or forests (Fig. 3). In many areas where species richness was lower under the 2C-BECCS scenario than under the baseline scenario in the LU-model, land-use conversion was mainly from other natural land and pasture to cropland, while land use in most of these areas remained unchanged under the baseline scenario (Fig. 3a). In many areas where species richness was lower under the 2C-Aff scenario than under the baseline scenario in the LU-model, land-use conversion was from other natural land and pasture to forests, while land use in most of these areas remained unchanged under the baseline scenario (Fig. 3b). On the other

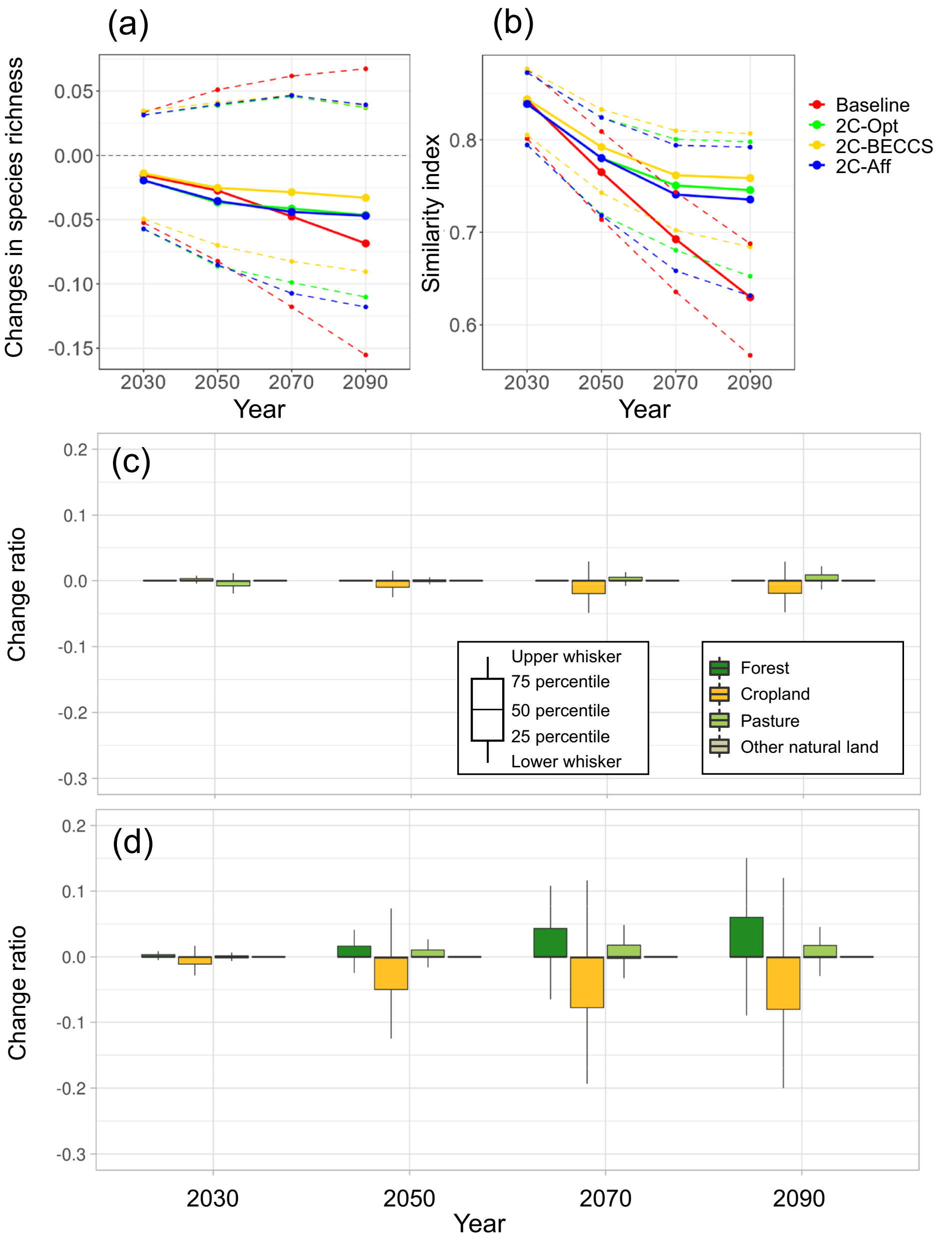


Fig. 1 | Temporal changes in biodiversity indices and land-use ratio for each grid. a Temporal changes in species richness. Changes in species richness were calculated as $[(NS_{future} - NS_{current})/NS_{current}]$, where NS_{future} and $NS_{current}$ indicate the future and current number of species, respectively. Negative values mean a decrease in species richness in the future. **b** Temporal changes in the similarity index. Lower values mean greater species replacement from the present to the future. For both **a** and **b**, solid lines indicate the median index values for all grids for each scenario. Upper and lower dashed lines indicate the 75th and 25th percentile values, respectively. **c**, **d** Temporal trends of land-use change relative to the baseline scenario under the **c** 2C-BECCS scenario and **d** 2C-Aff scenario. The land-use change ratio was calculated as the difference in the occupancy ratio of each land-use category (forest, cropland, pasture, and other natural land) between the mitigation and baseline scenarios (mitigation – baseline).

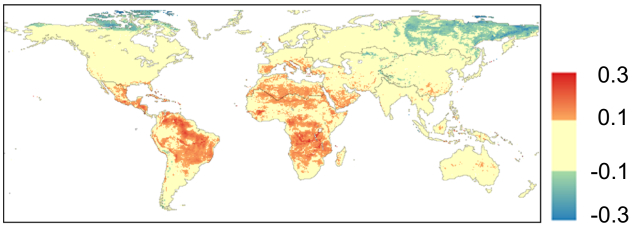
hand, in areas where species richness was higher under the 2C-BECCS scenario than under the baseline scenario in the LU-model, forests tended to be converted to cropland under the baseline scenario, while pastures tended to be converted to cropland under the 2C-BECCS scenario (Fig. 3c). In regions where species richness was higher under the 2C-Aff scenario than under the baseline scenario in the LU-model, large parts of forest were converted to cropland or pasture under the baseline scenario, whereas large parts of pasture were converted to forest under the 2C-Aff scenario (Fig. 3d).

In both the 2C-BECCS and 2C-Aff scenarios, expansion of cropland or forest through mitigation measures affected changes in species richness in various types of ecoregions including grassland, desert, and forest ecoregions (Fig. 4 and Supplementary Fig. 1). Under the 2C-BECCS scenario, species richness in tropical grassland ecoregions in South America was lower than that under the baseline scenario in the LU-model. In these regions, pasture tended to be converted to cropland. Under the 2C-Aff scenario, species richness in tropical forest ecoregions, tropical and temperate grassland ecoregions, Mediterranean ecoregions, and desert ecoregions in North America, Central America, South America, Sub-Saharan Africa, East Asia, and Oceania was lower than that under the baseline scenario in the LU-model, and other natural land and pasture tended to be converted to forest. Regions where biodiversity was positively impacted by land-use change through mitigation measures were very limited. Under the 2C-BECCS scenario, species richness was not higher than that under the baseline scenario in any regions in the LU-model. Under the 2C-Aff scenario, species richness in temperate grassland, desert, and other ecoregions in East Asia and Oceania was higher than that under the baseline scenario in the LU-model, and land-use in these regions changed from pasture to forest.

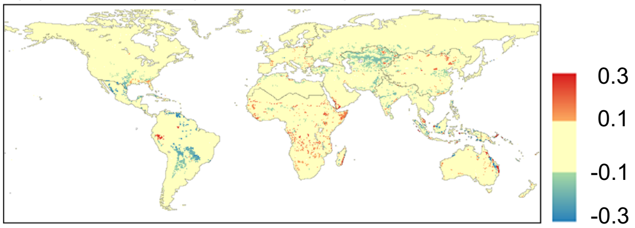
Regional mismatch between contribution to carbon sequestration and conservation of biodiversity

Economic regions that contributed to mitigation through land-use change and carbon sequestration were projected to experience greater biodiversity loss. Both for the baseline and mitigation scenarios, loss of biodiversity was greater in AIM regions that experienced larger-scale land-use change (Fig. 5a; baseline, $R^2 = 0.072$, $p = 0.298$; 2C-Aff, $R^2 = 0.364$, $p = 0.010$; 2C-BECCS, $R^2 = 0.316$, $p = 0.019$). Loss of biodiversity was also greater in AIM regions that contributed to carbon sequestration (2C-Aff, $R^2 = 0.203$, $p = 0.069$; 2C-BECCS, $R^2 = 0.194$, $p = 0.077$), and the slopes of regression

(a) CC-model (2C-BECCS and 2C-Aff)



(b) LU-model (2C-BECCS)



(c) LU-model (2C-Aff)

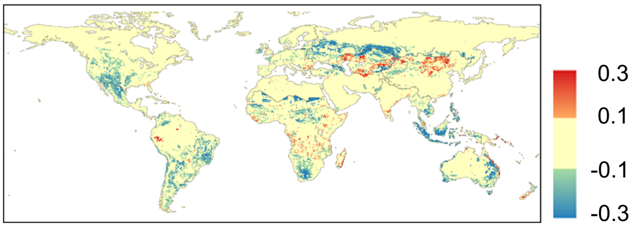


Fig. 2 | Regional variations in specific impacts of climate change and land use change on species richness in 2090. Impacts on species richness were calculated as $[(NS_{Mitigation} - NS_{Baseline})/NS_{current}]$, where $NS_{Baseline}$ and $NS_{Mitigation}$ indicate the number of species under the baseline and mitigation scenarios, respectively, and $NB_{current}$ indicates current number of species. **a** Specific impacts of climate change. Future number of species were calculated using CC-model that used future climate data as climate variables but current land-use data as land-use variables. **b**, **c** Specific impacts of land-use change. Future number of species were calculated using LU-model that used future land-use data as land-use variables but current climate data as climate variables.

line tended to be larger for the 2C-Aff scenario than for the 2C-BECCS scenario (Fig. 5b). Although there was large variation, implementation of mitigation measures tended to mitigate the adverse impacts on biodiversity in regions with lower GDP (Fig. 5c; baseline, $R^2 = 0.135$, $p = 0.147$; 2C-Aff, $R^2 = 0.022$, $p = 0.567$; 2C-BECCS, $R^2 = 0.080$, $p = 0.272$).

Discussion

Our results indicate that the introduction of mitigation measures through BECCS and afforestation has the potential to reduce risks of future biodiversity loss due to climate change and maintain the current species composition on a global scale. The regions where the climate stabilization could reduce biodiversity loss were extensive, including Central and South America, Africa, Europe, South East Asia, and Oceania (Fig. 2a). On the other hand, at high latitudes and altitudes of the Northern Hemisphere, such as Arctic and sub-Arctic regions and the Tibetan Plateau, species richness was projected to be higher under the baseline scenario than under the mitigation scenarios. These regions have been projected to experience increases in temperature and precipitation compared to other regions under the baseline scenario (Supplementary Fig. 2). The projected increase in species richness in these regions, therefore, would be caused by range shifts of species whose distribution has been restricted by low temperature and precipitation. Although such migration of species toward non-native northern and higher regions could increase species diversity at the local scale, it could also homogenize species composition across regions. The new local species community would largely differ from the original one, resulting in the loss of locally endemic compositional diversity (Fig. 1b and Supplementary Fig. 3). Climate mitigation suppressed the increasing trend of local species diversity in these regions, but it would also prevent the loss of endemic compositional diversity by suppressing such migration of non-native species, which may conserve ecosystem functions maintained by locally unique communities[20,21]. In addition, such climate change in the Arctic and sub-Arctic regions could lead to large-scale environmental changes not experienced in recent years, such as thawing and melting of permafrost and draining of ice sheets[22,23]. Current knowledge is insufficient to project how species respond to such large-scale environmental changes. We need to carefully monitor realistic future biodiversity changes in these regions. Overall, mitigation measures are expected to reduce both the loss and gain of global biodiversity due to climate change, thereby maintaining species and compositional diversity at or near their current levels.

Although land-based mitigation measures could reduce global biodiversity loss, the expansion of bioenergy cropland and forests through the introduction of BECCS and afforestation could have a negative impact on regional biodiversity. In many regions where land use change has a negative impact on biodiversity, cropland area tended to increase in the 2C-BECCS scenario, and forest area tended to increase in the 2C-Aff scenario (Fig. 3). These results suggest that the biodiversity impacts of land-use change for CDR may be biased towards certain regions, and that we need to carefully consider the regions for implementation of mitigation measures.

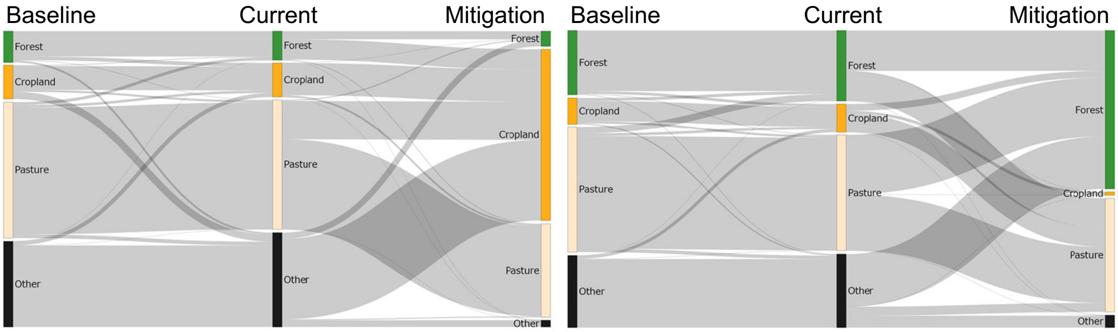
The impacts of cropland expansion on biodiversity were remarkable in the tropical grassland ecoregion of South America, where conversion of pasture to cropland had negative impacts on biodiversity. Bioenergy cropland was projected to increase particularly in South America and Sub-Saharan Africa under the 2C-BECCS scenario (Supplementary Fig. 4). The negative impacts on biodiversity may be concentrated in this region, where large parts of native savanna grassland have been converted to pasture and cropland[24,25]. The use of these already altered lands may prevent the degradation of remaining original natural biodiversity. However, concentrating impacts in this region may unduly reduce the opportunity to restore the natural biodiversity of the Neotropical savanna, which contains the world's largest savanna and is an important but threatened biodiversity hotspot[26]. Eliminating regional bias in the burden of CDR implementation would be an important issue.

The impact of forest expansion on biodiversity was remarkable in non-forest ecoregions in North and South America and Sub-Saharan Africa, where conversion of pasture and other natural land to forest had negative impacts on biodiversity. Because most of these regions were originally grassland ecosystems, such as savannas and prairies, replacing non-forested lands with forests would lead to a decline in biodiversity[14,27,28]. If we aim to balance afforestation and biodiversity conservation, we should consider zoning based on the biome characteristics of an area. For instance, reforestation should be prioritized in areas where forests have been destroyed, rather than conducting afforestation in naturally unforested regions. In addition, to promote CDR through the carbon sequestration capacity of forests, there could be alternative options to afforestation with land-use change. One option is carbon sequestration from tree biomass through the efficient use of existing planted and secondary forests that have been artificially maintained. In forests, trees eventually die, and CO_2 is released through their decomposition[29,30]. However, if the tree biomass can be used as harvested wood products (HWP) and can be sequestrated for a period of time, the residential time until emissions can be extended[31]. The forest use and management may cause biodiversity decline in some cases[32,33], and in this study, it was difficult to directly compare the impact of forest use and management on biodiversity and of land-use change. Extensive expectations to HWP as carbon sequestration may also cause deforestation of natural forests[34], which may in turn cause biodiversity decline. However, to enable CDR that takes advantage of forest functions without excessive reliance on land-use change, we need to consider appropriate zoning of forests to be used and forests to be conserved.

In this study, it was difficult to distinguish whether the afforestation is monoculture or close-to-nature forests because of the lack of comprehensive

(a) 2C-BECCS Negative

(b) 2C-Aff Negative



(c) 2C-BECCS Positive

(d) 2C-Aff Positive

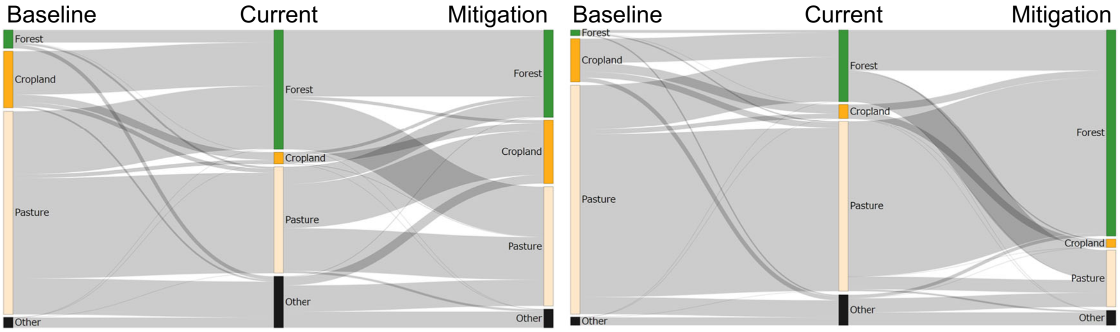


Fig. 3 | Land-use change that has negative/positive impacts on species richness. **a** Changes in the most dominant land-use category in the current, the baseline scenario, and the 2C-BECCS scenario in grids where species richness was lower under the 2C-BECCS scenario than under the baseline scenario. **b** Changes in the most dominant land-use category in the current, the baseline scenario, and the 2C-Aff scenario in grids where species richness was lower under the 2C-Aff scenario than under the baseline scenario. **c** Changes in the most dominant land-use category in the current, the baseline scenario, and the 2C-BECCS scenario in grids where species richness was higher under the 2C-BECCS scenario than under the Baseline scenario. **d** Changes in the most dominant land-use category in the current, the baseline scenario, and the 2C-Aff scenario in grids where species richness was higher under the 2C-Aff scenario than under the baseline scenario. Future species richness were calculated using LU-model that used future land-use data as land-use variables but current climate data as climate variables.

information on which parts of the world's forests are monocultural plantations at present. However, the impact of afforestation on biodiversity will vary depending on the tree species and the structure of the planted forest. The introduction of monoculture forests and plantations of non-native tree species can lead to a decline in local native biodiversity. Careful consideration must be given to the type of forest to be restored.

In both the 2C-BECCS and 2C-Aff scenarios, the replacement of other natural lands by cropland and forest caused biodiversity loss. Other natural lands are not necessarily ecosystems with high species richness (e.g., dryland and rocky ecosystems), compared to highly diverse ecosystems such as tropical forests[35]. However, endemic species communities have been formed in these ecosystems[36]. We should be cautious about land use change in these ecoregions. It may be possible to minimize the impact on biodiversity by using areas that are already intensively used, rather than natural areas.

Our results suggest there is an inequitable balance between the contribution to carbon sequestration and the conservation of regional biodiversity in some economic regions. We therefore need to consider mitigation measures that can reduce the regional inequities of impacts on biodiversity. Previous studies have pointed out that measures such as the restoration of natural ecosystems and appropriate management (i.e., nature-based solutions [NbS]) can lead to CDR in place of BECCS and afforestation, both of which alter natural ecosystems from their original state. Although there is limited knowledge about the potential of NbS to conserve biodiversity, introducing such measures would help to achieve compatibility between climate mitigation and biodiversity conservation.

Although there is a wide range of variation, both the 2C-BECCS and the 2C-Aff scenarios could decrease inequities of impacts on biodiversity among economic regions from an economic perspective by reducing diversity losses in regions with lower levels of GDP. Implementing additional policies to balance climate change mitigation and biodiversity conservation in developing low-income regions may be challenging. Therefore, we need to ensure that the burden of mitigation measures is not concentrated in those regions.

In this study, we treated bioenergy cropland for BECCS as equivalent to normal cultivated land because there are few areas where BECCS have been actually introduced on a large scale, and there is limited knowledge of the impact of BECCS on biodiversity. However, in reality, the impact on biodiversity should vary depending on the type of crop introduced to the cultivated land and the management method. The expansion of forests through afforestation may give the impression that it also contributes to the maintenance of biodiversity. However, the use of homogenous plantations with trees of the same age or species, or use of non-native species, would be less likely to maintain biodiversity as compared with secondary forests consisting of diverse native tree species[37]. Integrating field-level knowledge of the impact of the quality of bioenergy croplands and planted forests on biodiversity into the model approach will enable us to consider land use that minimizes the negative effects on biodiversity and provides positive impacts on biodiversity.

Conclusion

Our results suggest that climate change mitigation prevents loss in biodiversity relative to a baseline scenario, regardless of the choice of land-based CDR measures (in this case, BECCS and afforestation), but the studied land-based CDR measures would reduce biodiversity to some extent.

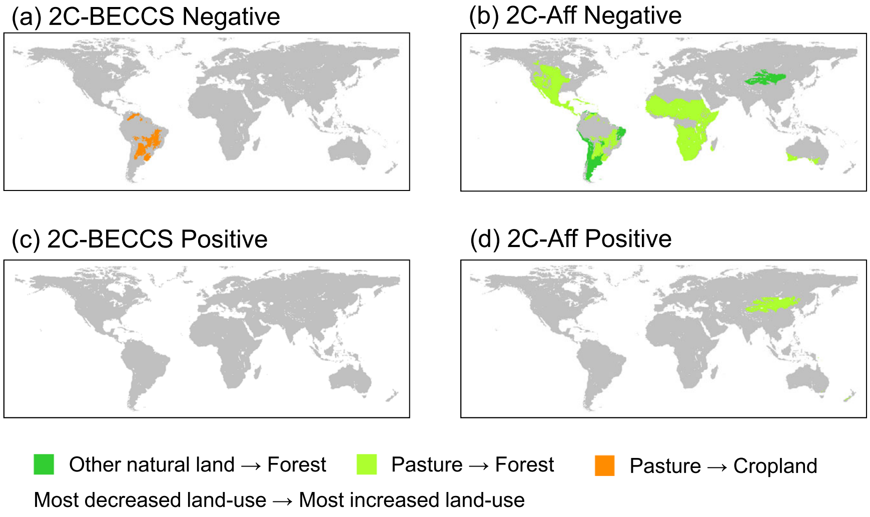


Fig. 4 | Ecoregions that are susceptible to land-use change due to implementation of mitigation measures and the types of land-use change that affect those ecoregions. a, **b** Ecoregions containing more than 15% sensitive grids where species richness is lower under the **a** 2C-BECCS scenario and **b** 2C-Aff scenario than under the baseline scenario. **c**, **d** Ecoregions containing more than 15% sensitive grids where species richness is higher under the **c** 2C-BECCS scenario and **d** 2C-Aff scenario than under the baseline scenario. Legend means that the pattern of "most decreased land use category → most increased land use category" comparing the current and the mitigation scenarios (2090s). Future species richness were calculated using LU-model that used future land-use data as land-use variables but current climate data as climate variables.

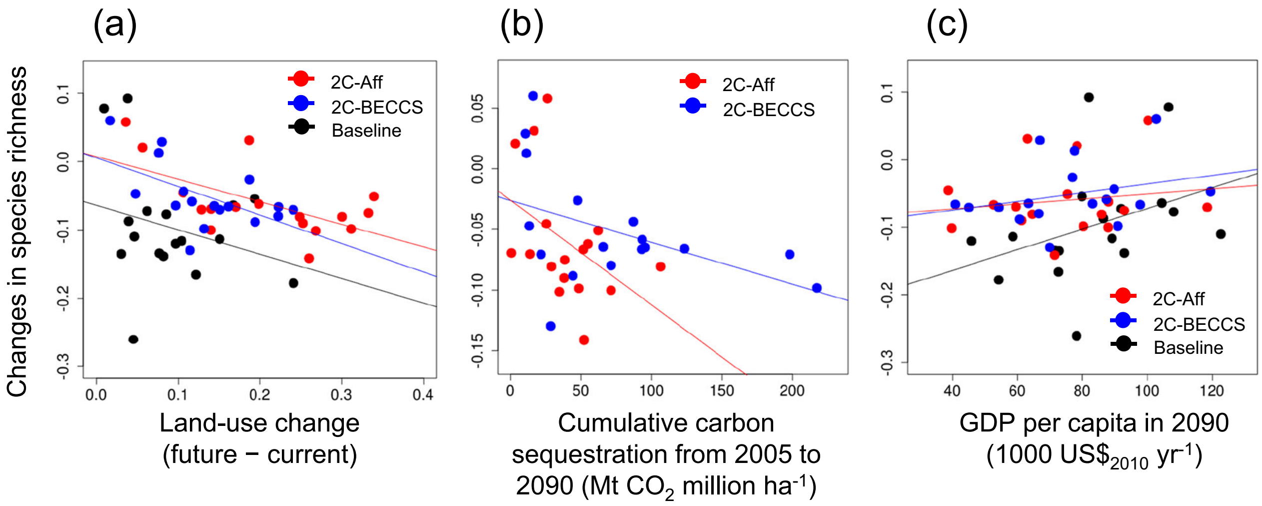


Fig. 5 | Relationships between changes in species richness and the degree of land-use change, contribution to carbon sequestration, and GDP per capita. a The degree of land-use change in 2090. **b** Contribution to carbon sequestration from 2005 to 2090. **c** GDP per capita in 2090. Changes in species richness were calculated as ([NS$_{2090}$ − NS$_{current}$]/NS$_{current}$), where NS$_{current}$ and NS$_{2090}$ indicate the current number of species and the number in 2090, respectively. Black dots and line indicate values and regression line for the baseline scenario, red dots and line indicate values and regression line for the 2C-Aff scenario, and blue dots and line indicate values and regression line for the 2C-BECCS scenario. Each dot means 17 economic regions in AIM/Hub.

Interestingly, the implementation of BECCS resulted in less global biodiversity loss than that of afforestation because less area is impacted by land-use changes. Regionally, the impacts of the mitigation measures differ. Economic regions that contribute more to carbon sequestration will experience more negative impacts on biodiversity. Grassland ecosystems in North, Central, and South America, Sub-Saharan Africa, East Asia, and Oceania are likely to be changed with the implementation of mitigation measures introducing BECCS or afforestation. In land-use change in these regions, utilization of already artificially modified cropland and pastures will help to conserve biodiversity. Natural areas should be used as little as possible because they are highly endemic and, once destroyed, are expected to be difficult to restore.

To achieve the long-term temperature goal on an equitable basis, it is important to consider the most suitable measures for each region while simultaneously considering the efficiency of carbon sequestration and biodiversity conservation. Recently, carbon sequestration through restoration of natural vegetation and implementation of appropriate management (e.g., NbS) have attracted attention as appropriate choices for land-based climate change mitigation. The appropriate introduction of such approaches may reduce the regional disparity of impacts.

Finally, it is necessary to reduce anthropogenic GHG emissions to the greatest extent possible without relying too much on land-based CDR. Although BECCS and afforestation may be a great help in mitigation pathways that aim for achieving the 1.5 °C and 2 °C targets, these measures may lead to lower mitigation ambition in other sectors[38]. As mentioned in the introduction, DACCS might be an alternative option, but there would be trade-offs that would need to be comprehensively assessed and judged. Efforts to reduce GHG emissions will contribute to maintain global biodiversity because reduced emission will result in less land-use change. It is necessary to examine measures that could balance biodiversity conservation and climate change mitigation and to verify the effectiveness of these measures.

Methods

Evaluation of global biodiversity change

We assessed the impacts of mitigation measures on global biodiversity, focusing on two dimensions of biodiversity change: biodiversity loss (gain) and biodiversity alteration. When environmental conditions of an area become unsuitable for some species that originally inhabited it, local species diversity decreases as a result of the loss of these species. Changes in environmental conditions also have potential to facilitate the migration of non-native species that prefer altered environments. The expansion of non-native species may increase local biodiversity, but it may also cause species replacement, which decreases the intactness of local biodiversity and leads to homogenization of regional biodiversity[39,40]. To clarify these benefits and disadvantages of biodiversity change due to climate change mitigation, we evaluated the impacts of mitigation measures on global biodiversity using two criteria: species diversity within local sites and temporal replacement of local species composition[41,42]. We adopted the number of species (species richness) at a local scale as an index of species diversity within local sites and the Jaccard similarity index as an index of temporal replacement of local species composition. The details of these indices are also described in the "Evaluation of the impacts of mitigation measures on biodiversity" section.

Global mitigation pathways and future scenarios

To evaluate the impacts of mitigation measures on biodiversity, we designed three mitigation scenarios and a baseline scenario using the AIM modeling framework coupled with other modeling tools[16,17,43]. The baseline scenario assumes no GHG emission reductions. Mitigation scenarios assume emission pathways for CDR where CO_2 emissions by 2100 will be about 100 $GtCO_2$ (Lower-2 °C pathway[18]). We considered three mitigation scenarios depending on the degree of implementation of BECCS and afforestation: BECCS scenario (2C-BECCS), afforestation scenario (2C-Aff), and optimal use of BECCS and afforestation scenario (2C-Opt, Supplementary Table 1). The 2C-Opt scenario is a kind of default mitigation scenario, which is allowed to use BECCS and afforestation as mitigation measures, and an emissions constraint is imposed on all energy and land-use sectors, but a carbon price cap of US\$200/tCO_2 is introduced in the land-use sector[44]. The 2C-BECCS scenario assumes that CDR is mainly achieved through the introduction of BECCS, and the forest area is not less than that of the baseline scenario. The 2C-Aff scenario assumes CDR is mainly achieved through the introduction of afforestation and making the demand for biofuels almost zero. To maintain comparability among the three mitigation scenarios, the cumulative carbon emissions budget is constrained at 900–1000 $GtCO_2$ in all scenarios. Although the emissions differ slightly, the global mean temperature in 2100 is almost same in the mitigation scenarios. The socioeconomic scenario for all of the scenarios is based on the "middle-of-the-road" SSP2 storyline, which has intermediate challenges for adaption and mitigation[45]. Global population, GDP, CO_2 emissions, radiative forcing, land use, and primary energy supply data are summarized Supplementary Fig. 5.

Projection of land-use allocation under future scenarios

Regional aggregated land demand under each scenario was projected using the AIM/Hub model[16]. AIM/Hub is a global model in which all economic activities including supply, demand, investment, and trade are described by individual behavioral functions that respond to changes in the prices of production factors and commodities, as well as changes in technology and preference parameters on the basis of assumed population, GDP, and consumer preferences. The model classifies the world into 17 aggregated regions (Supplementary Fig. 6) and projects aggregated land demand for each region. Land is categorized into one of three ecological zones and the land market operates in each zone via a multi-nominal logit function where differences in substitutability across land categories are reflected in the land rent[46].

Aggregated land-use allocations projected by AIM/Hub were downscaled into 0.5 arc degree grid cells using the integration Platform for Land-Use and environmental Modeling (AIM/PLUM)[17]. The land allocation was based on economic efficiency, where a landowner was assumed to decide the mix of land uses to obtain the highest profit. In AIM/PLUM, land use is classified 12 categories (Supplementary Table 2) and the proportions of each land-use type are stored in each grid cell for 2005 and 10-year increments from 2010 to 2100.

Projection of change in biodiversity under the scenarios

The impacts of mitigation measures on global biodiversity were projected using the AIM/BIO model[15]. AIM/BIO includes a set of equations linking the environment (land-use and climate conditions) and species distributions established using the Maxent algorithm[47] for 8428 species in five taxonomic groups (vascular plants, amphibians, reptiles, birds, and mammals). Although Maxent can apply complex nonlinear functions (called features) to the relationship between dependent (environmental) and independent (species distribution) variables, AIM/BIO uses only linear and quadratic features to avoid producing an overly complex model[15]. As environmental variables, 19 bioclimatic variables calculated using monthly minimum temperature, maximum temperature, and precipitation and five land-use variables (cropland, pasture, forest, other natural land, and settled land) were used in AIM/BIO. A species-specific set of environmental variables was identified for each species by selecting the most parsimonious combinations of variables based on the corrected Akaike information criterion (AICc)[48]. We projected current and future (2030, 2050, 2070, and 2090) potential habitats of 8428 species under four scenarios (three mitigation and one baseline) by applying the climatic and land-use conditions assumed in each scenario to the equation of each species calculated in Ohashi et al.[15].

For the land-use variables, we used land-use allocation downscaled by AIM/PLUM. We merged 12 land-use categories projected by AIM/PLUM into the five categories (cropland, forest, pasture, other natural land, and settled land) used in AIM/BIO (Supplementary Table 2). Because bioenergy crops and afforestation for GHG mitigation activity did not exist in land-use data in the current condition, we considered bioenergy crops to be cropland and afforestation as forests as described in Ohashi et al.[15].

In this study, we assumed the use of second-generation bioenergy crops, including Miscanthus and switchgrass, as bioenergy crops in the BECCS scenario. Bioenergy cropland and food cropland are expected to differ in terms of crop species and management practices, and therefore, the impact on biodiversity is also expected to differ. However, the small area of current bioenergy cropland makes it difficult to assess the large-scale impacts of bioenergy cropland on biodiversity. Therefore, in this study, both bioenergy cropland and food cropland were treated equally as cropland in the broad sense, and we focused on the impact of conversion to different types of land use, for example forests or pasture to bioenergy cropland (cropland). Previous field-based studies have reported that the biodiversity in second-generation herbaceous bioenergy cropland is not lower than that of food cropland and have also reported the positive impacts on biodiversity when intensively managed or abandoned cropland is converted to bioenergy cropland[49,50]. In contrast, negative impacts on biodiversity have been reported for the conversion of natural vegetation such as tropical forests, natural grassland, and wetland to bioenergy cropland[50]. Thus, it is important to assess the impact of converting different types of land use, such as forests and pasture to bioenergy cropland (cropland).

Afforestation is also expected to have different effects on biodiversity depending on the quality of the planted trees (e.g., monocultural vs naturalistic forests). However, there is no clear information on the current spatial extent of monocultural plantation, and it is difficult to model the impact of the differences in forest types on biodiversity on a broad scale. It is known, however, that biodiversity decreases when highly natural grassland and peatlands are converted to afforestation, but it often increases when afforestation is conducted on grasslands with high management intensity[51–53], indicating that biodiversity is also greatly affected by the original type of land use before conversion to afforestation. Therefore, for the effects of afforestation, we focused on the effects of conversion from a different land-use type, such as from cropland and pasture, to forest rather than on forest quality. We used data for 2005 (the starting year of AIM/Hub) as the current land-use condition and data for 2030, 2050, 2070, and 2090 for future land-use conditions.

For the climate variables, we calculated 19 bioclimatic variables using a dataset of monthly maximum temperature, minimum temperature, and precipitation provided by WorldClim v2.1 (https://www.worldclim.org/)[19].

We used historical climate data in WorldClim (1970–2000) as the current climatic conditions and data from the 2030s (2021–2040), 2050s (2041–2060), 2070s (2061–2080), and 2090s (2081–2100) for future climatic conditions. For the climate scenario, we selected the scenario that was most consistent with the changes in radiative forcing calculated by AIM/Hub: SSP3-7.0 as the basis for climatic conditions under the baseline scenario and SSP1-2.6 for the three mitigation scenarios. SSP1 and SSP3 have different land-use and energy conditions, and the climate outcomes should differ even under same level of radiative forcing. This original ScenarioMIP design[54], however, is based on the assumption that there will be relatively minor differences in the climate outcomes, and the global and continental scale implications will therefore be small. To evaluate the uncertainty of projected future climatic conditions, we used future climatic data based on three of the General Circulation Models (GCMs) included in the Coupled Model Intercomparison Project Phase 6 (CMIP6)[55]: GFDL-ESM4, IPSL-CM6A-LR, and MRI-ESM2-0. We downloaded the dataset of monthly maximum temperature, minimum temperature, and precipitation at a resolution of 10 arc minutes from the WorldClim database and averaged the values at a resolution of 0.5 arc degrees. Then, we calculated 19 bioclimatic variables using these data.

Projected potential habitat for each species represents the full range where each species could be distributed under specific land-use and climate conditions. However, the actual range of each species is more limited for various reasons, such as historical changes in geographic and climatic conditions. Thus, we evaluated the current potential habitat as regions within current native ranges of each species as described in Ohashi et al. [15]. We also discarded regions on a landmass that has not been connected to other landmasses since the last glacial maximum period[15]. We determined the native range of each species using information provided by the IUCN database (https://www.iucnredlist.org/).

Although altering environmental conditions has the potential to cause species to shift their habitats, successful habitat shifts depends on the species' ability to disperse and track their ecological niche. Therefore, we projected future potential habitats considering the dispersal ability of each species. First, we projected the potential habitat of each species under current climatic and land-use conditions. Then, we estimated a potential migration range of each species for the next time step by generating a buffer of the dispersal distance of each species as calculated in Ohashi et al.[15]. The potential habitat of the next time step was estimated by masking the potential distribution range with the dispersal buffer. For the subsequent time step, the potential habitat was estimated by applying the same procedure.

In the future projections, the impacts of land-use change and climate change on biodiversity are mixed, and the magnitude of each impact cannot be compared. Therefore, to confirm the individual effects of land-use change and climate change, we prepared hypothetical future sub-scenarios, namely land-use change only (LU-model) and climate change only (CC-model) using the same procedure as in Ohashi et al.[15] (Supplementary Table 3). In the LU-model, only land use was changed according to the mitigation or the baseline land-use scenarios, while climate condition remained constant as the current state. In the CC-model, only the climate condition was changed according to the mitigation or the baseline scenarios, while land use remained constant as the current state. Model projection was performed for a total of six combinations of the scenarios, combining these two sub-scenarios with three main scenarios (baseline, 2C-BECCS, and 2C-Aff; Supplementary Table 1). The projection procedure for the sub-scenarios was the same as that used for the main scenarios. Individual impacts of land-use change and climate change on biodiversity were evaluated as $[(\mathrm{NS}_{\mathrm{Mitigation}} - \mathrm{NS}_{\mathrm{Baseline}})/\mathrm{NS}_{\mathrm{Current}}]$ in 2090, where $\mathrm{NS}_{\mathrm{Mitigation}}$ and $\mathrm{NS}_{\mathrm{Baseline}}$ indicate the number of species under the mitigation and the baseline scenarios, respectively, and $\mathrm{NB}_{\mathrm{Current}}$ indicates the current the number of species.

To evaluate which land-use changes due to the implementation of mitigation measures affect biodiversity, we compared current and future land-use changes for grids where biodiversity was particularly decreased/increased under the mitigation scenarios as compared to the baseline scenario in the LU-model. For the grids where differences in species richness between the mitigation and the baseline scenarios were <-0.1 or >0.1 respectively (i.e., more sensitive grids), the most occupied land-use categories were calculated for the current and future (2090) timeframe, and land-use changes from the current to the future were visualized using a Sankey diagram. In addition, ecoregions that are susceptible to land-use change due to mitigation measures and the patterns of land-use change that affect them were evaluated. The spatial extent of ecoregions was defined by combining the IUCN regions used by AIM/BIO to determine the native distribution range of species and the modified ecoregions originally proposed in Olson et al.[36] (https://www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world, Supplementary Table 4) to consider the characteristics of region, climate, and species endemism. We first calculated the differences in the occupancy ratio of each land-use category between the current and the future (mitigation scenarios) for sensitive grids. Then, we extracted the land-use categories that most increased/decreased in the mitigation scenarios. Finally, for each ecoregion, the most common increasing/decreasing land-use types were extracted and mapped. Only ecoregions where the number of sensitive girds was more than 15% of total number of grids of each ecoregion were evaluated as sensitive ecoregions to land-use change.

Evaluation of the impacts of mitigation measures on biodiversity

Species diversity within local sites was evaluated by the number of species (species richness) for each grid. We calculated the number of species for each grid using the projections of current and future potential habitats of 8428 species. For the projections of future potential habitat, we combined the projections of the three GCMs for each species. Only grids determined to be the potential habitat by two or more GCMs were considered as potential habitat for each species. The number of species in each grid was calculated for 2005, 2030, 2050, 2070, and 2090.

Temporal replacement of local species composition was evaluated with the Jaccard similarity index. The Jaccard similarity index (J) is calculated as $J = c/(a + b + c)$, where a is the number of species that occur only in the current period, b is the number of species that occur only in the future, and c is the number of species that occur in both the current and future periods. A lower similarity index means greater compositional changes in the local community. We calculated the similarity index for 2030, 2050, 2070, and 2090, and assessed temporal changes in the similarity index.

Social and regional equity of the impacts of mitigation measures on biodiversity

To assess social and regional equity of mitigation measures, we examined the relationship between mitigation efforts or economic conditions and biodiversity loss for the 17 economic regions. For the mitigation efforts, we focused on the intensity of land-use change and amount of carbon sequestration of each region. Intensity of land-use change was evaluated by using the differences in occupancy ratios of five land-use categories between the current period and 2090 for each grid. The value of the category that had the largest difference value was considered to be the intensity of land-use change for the grid. The amount of carbon sequestration through BECCS and afforestation of each region was calculated by AIM/Hub. Total CO_2 emissions captured from bioenergy use and stored in geological deposits and the deep ocean were considered as the contribution to carbon sequestration in the 2C-BECCS scenario. Total CO_2 sequestered through afforestation was considered as the contribution to carbon sequestration in the 2C-Aff scenario. As the index of economic conditions of each region, we used the GDP in 2090 projected in AIM/Hub.

Data availability

The data used to create the figures are shared in the public repository: https://doi.org/10.5281/zenodo.10969647.

Code availability

The code used for data analysis and creating the figures are shared in the public repository: https://doi.org/10.5281/zenodo.10969647.

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Author contributions

A.H., S.F., K.Ta., and T.M. contributed to the conception of the work; A.H. ran the biodiversity model, with contributions from H.O. and K.Ts.; S.F. ran the economic model; T.H. ran the land-use model; A.H. carried out analysis of the modeling results, with input from all authors; A.H. created the first draft; all authors contributed to discussion of contents and revising of the entire manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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