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Careful selection of forest types in afforestation can increase carbon sequestration by 25% without compromising sustainability

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Afforestation is a major carbon dioxide removal technology but can negatively affect food and land systems. Here, we used an integrated assessment model to quantitatively demonstrate how the selection of forest type to use in afforestation could increase global carbon sequestration without compromising global food and land sustainability. Our findings indicate that if a carbon-intensive forest type is selected, afforestation would increase carbon sequestration by 25% compared to the level assuming the native forest type. At the same time, if implemented inappropriately at a large scale, afforestation would worsen the economy, food, and land systems due to decreased land efficiency in carbon removal compared to bioenergy with carbon capture and storage, leading to increased land expansion for carbon removal, higher food prices, and increased risk of hunger. These results suggest the need to implement carbon-intensive forest types with complementary measures to reduce the adverse impacts on food and land sustainability.

The global climate change mitigation scenarios that aim to limit global warming to 2 °C or 1.5 °C will require rapid reductions in greenhouse gas emissions and large negative emissions in the latter part of this century¹. In most global scenarios from the latest Intergovernmental Panel on Climate Change (IPCC) report¹, large-scale carbon dioxide removal (CDR) options such as afforestation and reforestation and bioenergy with carbon capture and storage (BECCS) play a vital role in removing CO₂ from the atmosphere over the next half century to achieve stringent climate goals^{2–4}. (For clarification, while afforestation and reforestation both refer to the establishment of trees on non-forest land, reforestation refers to the establishment of forest on lands that previously supported forests within the last 50 years and where the original crop has been replaced with a different one, whereas afforestation refers to the establishment of forest on lands that previously have not supported forests for more than 50 years. This study includes both actions and does not differentiate the two explicitly. The two are treated equivalently in terms of carbon accounting⁵. We use the term ‘afforestation’ for simplification hereinafter). BECCS is a CCS technology applied to a

bioenergy facility, where a relatively pure stream of CO₂ from bioenergy sources is separated, conditioned, compressed, and transported to a storage location for long-term isolation from the atmosphere⁶. In the scenarios that limit warming to 2 °C, annual volumes of carbon mitigation are estimated to be 2.75 giga tonnes CO₂ [GtCO₂] per year for BECCS and 2.98 GtCO₂ per year for afforestation at the median level in 2050⁷. The cost of mitigation is estimated to be 50–200 USD per tCO₂ for BECCS or 0–200 USD per tCO₂ for afforestation in 2030⁷. A key issue is the feasibility of implementing land-based CDR strategies that may negatively affect food security^{8–13} and biodiversity^{14–17}. The potential consequences of large-scale CDR in mitigation scenarios with stringent climate goals could be infeasible or socially undesirable due to sustainability and intergenerational equity concerns^{8,18–23}. The feasibility of land-based CDR would depend on the stringency of the climate goals, associated emissions pathways, and the impacts on other sustainability objectives. Moreover, inappropriate forest expansion, such as afforestation of naturally open habitats, could reduce habitats for non-forest organisms and negatively affect biodiversity^{14–16}. To reduce such adverse

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Table 1 | Scenario settings

Scenario	Climate mitigation	Afforestation		Selection schemes		BECCS	Food measures	Expected effects
		native forest	ecological conservation	maximised carbon sink	ecological conservation			
Conventional								
Mitigation	✓	✓	✓	✓		✓		
Afforestation (Aff-only)	✓	✓	✓	✓				Effects of forest-type selection schemes
	✓	✓	✓	✓				
	✓	✓	✓	✓				
Afforestation + Food measures (Aff-FodPol)	✓	✓	✓	✓			✓	Effects of food measures
	✓	✓	✓	✓			✓	Effects of forest-type selection + food measures (maximum C sink considering biodiversity protection and food security)
	✓	✓	✓	✓			✓	Effects of forest-type selection + food measures (maximum C sink considering food security)
BECCS-only	✓					✓		Comparison with BECCS
	✓					✓	✓	

Food measures include agricultural intensification, dietary changes, trade globalisation, and improved food distribution.

effects, food-related measures such as agricultural intensification, trade globalisation, and dietary change are expected to increase carbon sequestration through BECCS while protecting food and land sustainability^{24,25}. However, no study has investigated how afforestation and food-related measures should be designed or which forest types should be used to reduce the adverse impacts on food- and land-related sustainability.

Here we quantified how forest-type selection combined with food-related measures would affect the carbon sequestration potential and food- and land-related sustainability. For quantification, we used a framework that combines an economic model (AIM/Hub)²⁶, a land-use allocation model (AIM/PLUM)²⁷, and a terrestrial vegetation model (Vegetation Integrative Simulator for Trace gases model; VISIT)²⁸ (Supplementary Fig. 1). In the framework, we developed a mechanism to consider the type of forest used for afforestation and calculate the carbon removal potential of afforestation by assuming different forest types. The regional land demand (17 global regions; see Supplementary Table 1 for regional classifications) of different land categories estimated using AIM/Hub was input into AIM/PLUM and downscaled into the proportional area and amounts of carbon sequestered by afforestation and BECCS at half-degree grids. In AIM/PLUM, land for afforestation and other land categories were allocated to maximise profit for landowners based on the biophysically determined land productivity (yield per unit area)²⁷. The land areas and amounts of carbon sequestration used in this study are the output from AIM/PLUM, while other variables are the outputs of AIM/Hub. AIM/Hub considers emissions mitigation by setting a certain carbon budget with a global uniform carbon price in different sectors (i.e., agriculture and/or nonagricultural sectors). This approach allows the model to identify the most cost-efficient emissions pathway for a given climate target. The carbon budget for this century was set to 600 GtCO₂, corresponding to the long-term climate target of 2.0 °C. No negative emissions were allowed after global achievement of net-zero CO₂ emissions (see Supplementary Fig. 2 for the emissions pathways). Although the absence of negative emissions limits the deployment of large-scale land-based carbon removal technologies, this restriction is adopted because the model could not be solved for scenarios for achieving the 2 °C target in which negative emissions are allowed but only afforestation was deployed with neither BECCS nor changes in other socioeconomic conditions, such as lowering energy demand^{29,30}.

Nine climate-mitigation scenarios that limit warming to 2 °C were analysed, differentiated by the availability of the two main land-based CDR technologies (afforestation, BECCS), three forest-type selection schemes (*Aff-Cur*, *Aff-Div*, *Aff-Cmax*), and implementation/non-implementation of food-related measures (with or without *FodPol*), along with a conventional scenario with neither climate-mitigation measures nor food measures (see Table 1). The scenarios with different land-based mitigation technologies allow us to explore the benefits and trade-offs/adverse effects of afforestation compared to those of BECCS. For the climate-mitigation measures, either only afforestation or only BECCS was deployed to extract the pure effect of a single measure.

A scheme of forest type selection was based on the growth rates of different forest types. For each grid cell, a forest type for afforestation is selected from a set of forest types. Different types of forest were prepared for different scenarios according to the level of consideration for ecological conservation. For *Aff-Cur*, a native forest type is assumed. For *Aff-Div*—a scenario considering ecological conservation—the most carbon-intensive forest type is selected from three to six forest types that exist in the same agro-ecological zone as the grid cell, based on the idea that the ecological challenge will be lower in cases where forest types from the same agro-ecological zone are planted. Agro-ecological zoning as applied in FAO studies defines zones on the basis of combinations of soil, landform and climatic characteristics³¹. Each zone has a similar combination of constraints and potentials for land use. For *Aff-Cmax*—in which carbon sequestration is maximised without ecological consideration—the most carbon-intensive among all 12 forest types was selected for each grid cell. The forest types selected for each scenario are shown in Supplementary Fig. 3. To consider changes in the amount of carbon sequestration along with tree growth, a tree

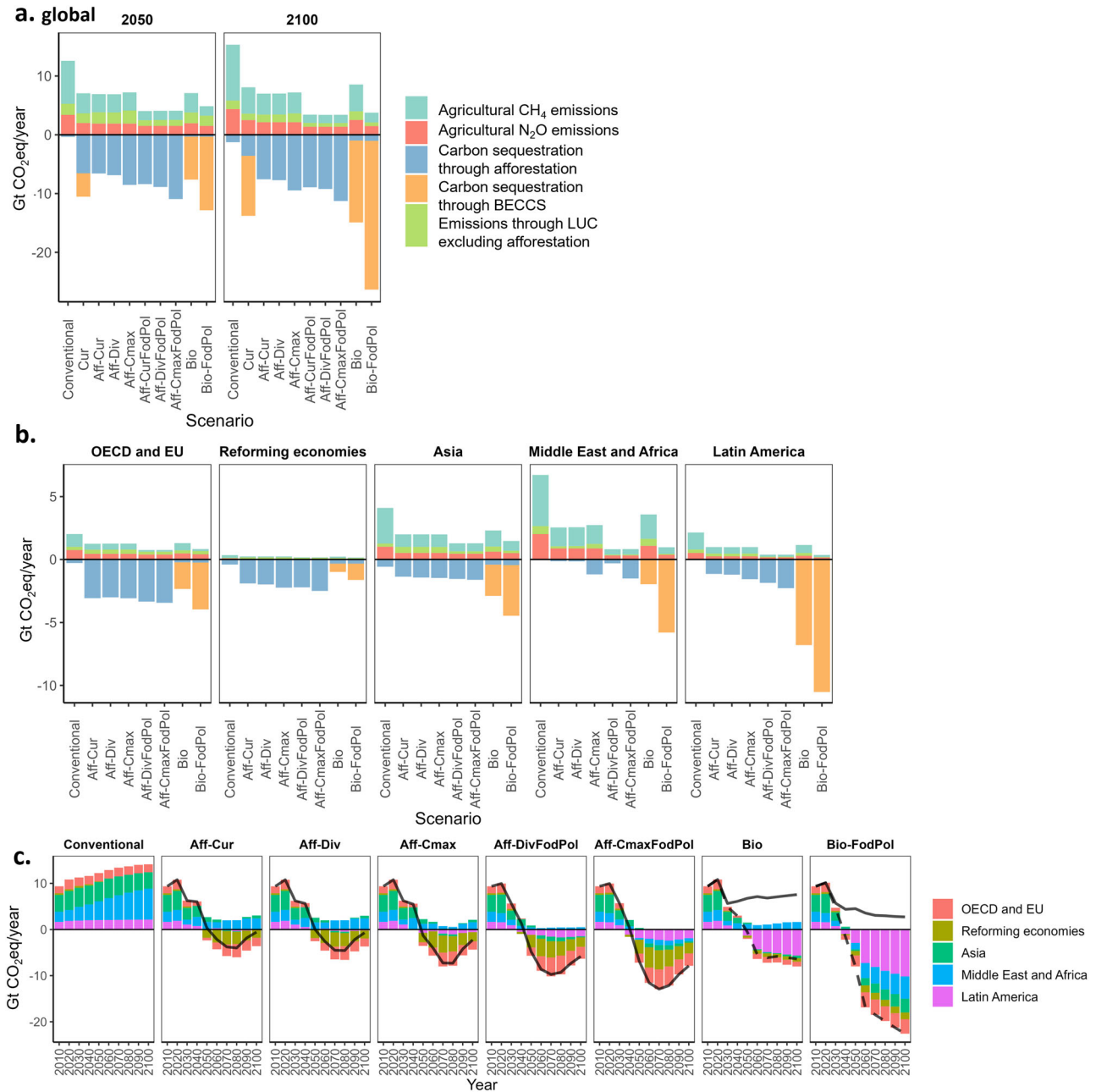


Fig. 1 | Greenhouse gas (GHG) emissions related to agriculture, forestry, and other land uses (AFOLU) and carbon sequestration through land-based carbon dioxide removal (CDR) options under different scenarios. a Emissions at the global level in 2050 and 2100 and **b** emissions at regional levels in 2100. **c** Shows the

same as **b** but over time. The black solid line in **c** shows net emissions in AFOLU. The dotted line in **c** shows the sum of net emissions in AFOLU and sequestration from bioenergy with carbon capture and storage (BECCS) CDR.

growth function (Sohngen et al.)³² was assumed. The function was parameterised for each forest type using the net primary production (NPP) calculated by VISIT. Changes in growth rates were taken from the growth function. The food-relevant measures assumed agricultural intensification, trade globalisation, and improved equity in food distribution as policy-relevant efforts, as well as dietary change as voluntary action. See the Methods section for greater detail on forest-type selection, the VISIT model, and food-related measures. See the Supplementary Notes 1 and 2 for a more detailed description of the AIM/Hub and AIM/PLUM, respectively.

Results

Increased carbon sequestration by forest-type selection

Our analysis shows that if the forest type is carefully selected from those in the same agro-ecological zone (*Aff-Div*), afforestation would increase the

carbon sequestration by 2% globally (7.7 GtCO₂ per year in 2100) compared to the native forest type (7.6 GtCO₂ per year in the *Aff-Cur*) (Fig. 1a). Moreover, a carbon-intensive forest type (*Aff-Cmax*) would increase the global carbon sequestration by 25% (9.5 GtCO₂ per year in 2100) compared to the native forest. Regional analysis shows that carbon sequestration substantially increases in all regions excluding Organisation for Economic Cooperation and Development (OECD) and European Union (EU) regions (Fig. 1b, c). For example, in the *Aff-Div* and *Aff-Cmax* scenarios, the carbon sequestration in Latin America (LAM) increases by 5.2% and 37% in 2100, respectively, while sequestration in reforming economies (REF) increases by 4.3% and 18% in the same scenarios and year compared to the case of native forest. From a regional perspective, for example in LAM, tropical and subtropical evergreen forest (forest type code #1 in Supplementary Table 2) is currently widely distributed, while tropical montane forest (#2) and

tropical subtropical dry forest (#3) increase carbon sequestration (Supplementary Fig. 3). In South Russia, northern taiga (#11, #12) is currently found, while the southern taiga (#8) is beneficial for carbon sequestration in the region. In East Asia, such as South China, mid-latitude mixed forest (#4) is currently found, while semiarid wood or low forest (#6) is beneficial.

Land intensity of carbon sequestration and its impacts on land use

The land intensity of carbon sequestration potential (LIC), which describes the potential amount of carbon sequestration per unit area, can be an important factor that determines the difference in the carbon sequestration area implemented across afforestation forest types and the types of mitigation options. It was calculated by dividing the amount of carbon sequestration potential of afforestation by the area of land allocated to afforestation. The LIC of BECCS was calculated by dividing the product of bioenergy crop yield potential, the regional share of BECCS to total electrification, and the regional share of CCS usage to bioenergy electrification by the area of land allocated to bioenergy crop production. The latter three variables were calculated based on the results of AIM/Hub. Our results show that if the carbon-intensive forest type is selected for afforestation, the LIC of afforestation becomes higher than that of the native type (Fig. 2a). In the *Aff-Div* and *Aff-Cmax* scenarios, the global mean LIC of afforestation is higher (4.1 and 5.0 tonnes CO₂ equivalent [tCO₂eq] per ha per year, respectively, in 2100) than the native forest type (4.0 tCO₂eq per ha per year for the same year) (Fig. 2a). This difference is because in some regions or grids, non-native carbon-intensive forest types are available. See Supplementary Fig. 4 for the LICs of different forest types and Supplementary Fig. 5 for the regional geographical distribution of carbon sequestration for different forest-type selections.

Notably, given the same long-term climate target, afforestation contributes less to carbon sequestration compared to BECCS. For example, even in the scenario for maximising carbon sequestration (*Aff-Cmax*), the global sequestration by afforestation (8.5 and 9.5 GtCO₂ per year in 2050 and 2100, respectively) is less than that by BECCS (7.3 and 14 GtCO₂ per year in 2050 and 2100, respectively) in the BECCS-only (*Bio*) scenario in the same years (Fig. 1a). This difference is because bioenergy crop yield is greater than afforestation yield. The mean annual carbon sequestration of BECCS is more than 10 times that of afforestation (Fig. 2c, e). As a result, the LIC of afforestation is lower than that of BECCS (Fig. 2a). In *Aff-Cmax*, the global mean LIC of afforestation is 7.7 and 5.0 tCO₂eq per ha per year in 2050 and 2100, respectively, while that of BECCS of 15 and 19 is tCO₂eq per ha per year for the same years.

Afforestation and BECCS affect land-use change differently. Where cropland and pastureland decrease with forest area expansion in afforestation-only scenarios, forestland decreases to expand cropland area for bioenergy production in BECCS-only scenarios (*Bio*) (See Fig. 3 and Supplementary Fig. 6 for global aggregated land-use change). What differs here is the change in cropland. In BECCS-only scenarios (*Bio*), the high sequestration intensity of BECCS means less competition with crop production for land, resulting in a global increase in cropland in response to increased demand for food. By contrast, in afforestation-only scenarios, afforestation increases competition with crop production for land, resulting in decreased cropland.

Regional analysis

From a regional perspective, while carbon sequestration by afforestation is high in OECD and REF countries, sequestration by BECCS is high in LAM, Asia, and OECD countries (Fig. 1b, c). These regional differences in carbon sequestration potential are the results of the geographical heterogeneity in land availability (e.g., demand for cropland and pastureland), the LIC, and the possibility to deploy renewable energy to reduce emissions from energy systems (such as energy consumption) as well as energy costs. For example, in high-latitude regions such as the OECD, EU, and REF, the LIC of afforestation is generally high because cold-tolerant forest types (e.g., coniferous forests or taiga) grow faster than tropical and temperate forests (see

Supplementary Fig. 3 for forest growth curves across forest types, and Fig. 2 and Supplementary Fig. 4 for the geographical distribution of growth ratios of afforestation), and the land available for afforestation is widely distributed in potential areas for high-growth forests. Thus, in high latitudes, the current forest types have a high carbon removal potential by afforestation, and forest-type selection increases this potential. By contrast, this is not the case in low-latitude regions. Regions with high LIC such as the Amazon and Central Africa are already forested and cannot be used for afforestation. Instead, in these regions, the LIC of BECCS is high and thus a smaller area is needed for BECCS than afforestation to achieve a given climate target. It is more effective to implement BECCS than afforestation in these regions.

Impacts of food-relevant measures

Implementation of food-relevant measures considerably increases the carbon sequestration for all scenarios of both afforestation and BECCS (Fig. 1a). For example, the *Aff-CmaxFodPol* scenario—in which forest-type selection to maximise carbon sequestration is combined with implementation of food measures—yields the maximum sequestration by afforestation (11.3 GtCO₂ per year in 2100; 19% more than without food measures; 49% more than native forest without food measures). Among the food-relevant measures analysed, dietary change substantially reduces meat consumption and increases food crop consumption. This, in turn, considerably reduces pastureland area and increases the area of land available for sequestration measures (Fig. 3a). Consequently, the area of cropland and pastureland decreases while the afforested area increases in all regions of the world, resulting in increased carbon sequestration (Figs. 2b and 3b).

Impacts on the environment and sustainability

It is important to explore the impacts of land-based options on the economy (gross domestic product; GDP), energy, and food systems because many countries have established long-term climate mitigation goals with consideration of the wide-ranging impacts of mitigation measures. In terms of economic efficiency, the afforestation-only scenarios (*Aff-only*) raised carbon prices and caused more GDP loss. This is because economic and industrial structures and energy systems are less economically efficient under these scenarios compared to the BECCS-only scenario with lower land competition and higher economic efficiency. In terms of energy systems, the price of electricity can be interpreted as an indicator for the energy system. In general, electricity price reflects the dependence of energy supply on fossil fuel and the costs and types of electrification technologies including renewable energy and bioenergy. If a large share of electricity is generated from fossil fuel which is less expensive compared to low-carbon energy technologies, the electricity price becomes relatively low. Moreover, renewable energy (solar, wind) is more expensive than bioenergy. Therefore, in the afforestation-only scenarios, a large scale of afforestation deployment reduces the amount of bioenergy and emissions reduction is achieved through deployment of renewable energy, raising the cost of power generation and price of electricity. The higher price of energy also contributes to losses in GDP (Fig. 4).

In terms of food systems, afforestation and BECCS raise the prices of land and food because both require land area. The risk resulting from afforestation is greater than from BECCS because afforestation requires more land to achieve the carbon sequestration for a given long-term climate target. The impact changes over time depending on the emissions pathways (Supplementary Fig. 2) and increases in the latter half of the century. Food measures implemented along with afforestation (*Aff-CurFodPol*) and BECCS (*Bio-FodPol*) lower the increase in carbon prices and the loss of GDP associated with afforestation and BECCS but not the risk of hunger. Yield improvements and shifts of agricultural production to more suitable locations through trade liberalisation would decrease the land demand for agricultural production and decrease food prices, while the risk of hunger increases with lower food demand associated with dietary change.

Discussion

We investigated how a forest-type selection scheme in afforestation would increase global carbon sequestration and affect global food and land systems

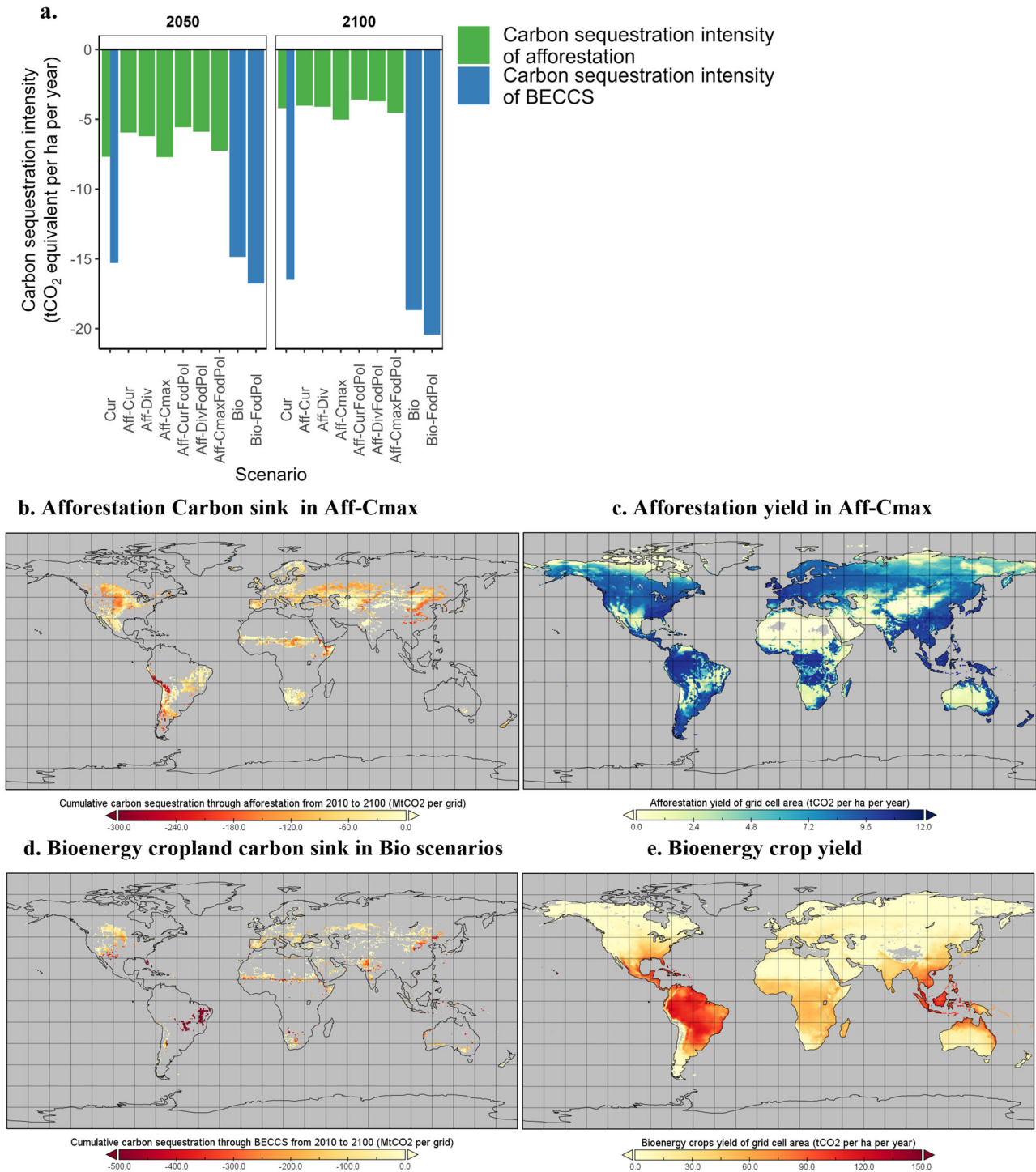


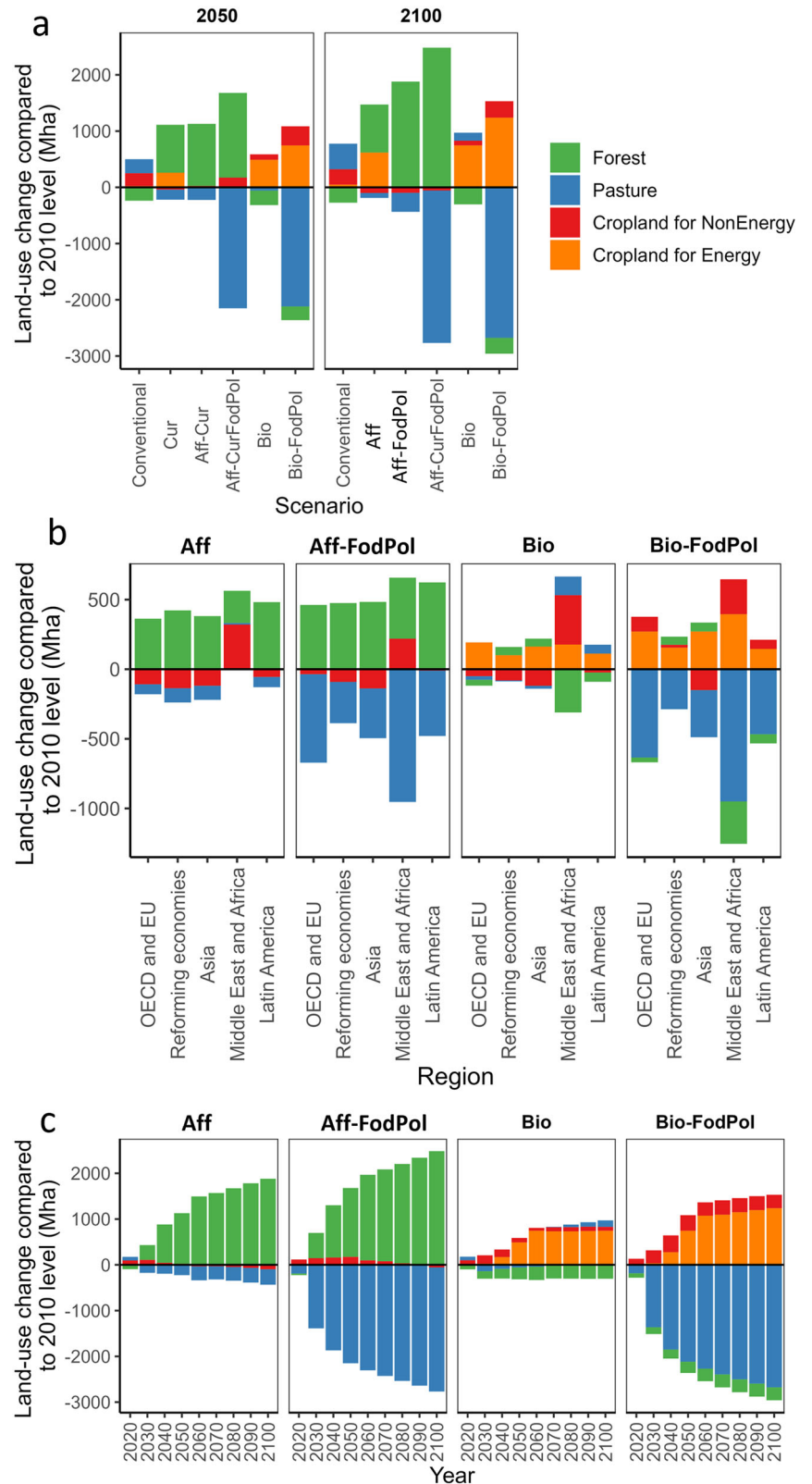
Fig. 2 | Carbon sequestration by afforestation and BECCS under different scenarios. **a** Land intensity of carbon sequestration potential (LIC); potential amount of carbon sequestration per unit area) calculated from the total amount of carbon sequestration potential and the area of land allocated to the option. Global distribution of cumulative carbon sequestration through **b** afforestation and **d** BECCS throughout this century. Global distribution of (c) growth rates of afforestation and (e) bioenergy

crop yield. Carbon sequestration through BECCS in **d** is calculated from bioenergy crop yield, the share of BECCS to total electrification, and the regional share of carbon capture and storage (CCS) usage to total bioenergy electrification. **c** Mean growth rates of afforestation in the *Aff-Cmax* scenarios throughout this century. **e** Mean yields of switchgrass and miscanthus on rainfed land⁴¹.

and sustainability. Our results indicate that afforestation with a carefully selected carbon-intensive forest type would increase the carbon sequestration by 25% at maximum compared to the native forest type; if combined with food measures, the carbon sequestration potential increases to a maximum of 49% compared to the native forest type due to lower land demand, leading to a decrease in the population at risk of hunger, as well as

less nitrogen and water usage. At the same time, if it not carefully implemented, afforestation would push up the prices of land and food, resulting in higher risk of hunger compared to BECCS due to the low land productivity of afforestation in terms of carbon sequestration. These results should not be interpreted as indicating a lower importance of future afforestation; rather, they highlight the importance of incorporating complementary policies

Fig. 3 | Land-use change compared to 2010 through different scenarios. **a** Land-use change at the global level in 2050 and 2100 and **b** land-use change at regional levels in 2100. **c** Land-use change over time from 2010 to 2100. Positive (negative) values represent a net expansion (reduction) of the land use category.



such as more productive agricultural systems or safety-net programs that compensate for the impacts of afforestation in vulnerable regions. These combined measures would be needed to increase carbon sequestration while reducing the negative impacts of afforestation on food and land sustainability. Although no integrated assessment model accounts for forest types, the consideration of multiple forest types would be beneficial for future evaluations of land-based climate mitigation.

Our results also indicate that BECCS is more effective than afforestation in terms of carbon sequestration and that afforestation has the same or greater negative impact on the economy, energy, food, and land use compared to BECCS²⁻⁴. This is because the lower LIC of afforestation requires more land for a given carbon removal toward the long-term climate target, resulting in higher prices of carbon and energy, greater land demand, and negative impacts on food security compared to BECCS, although

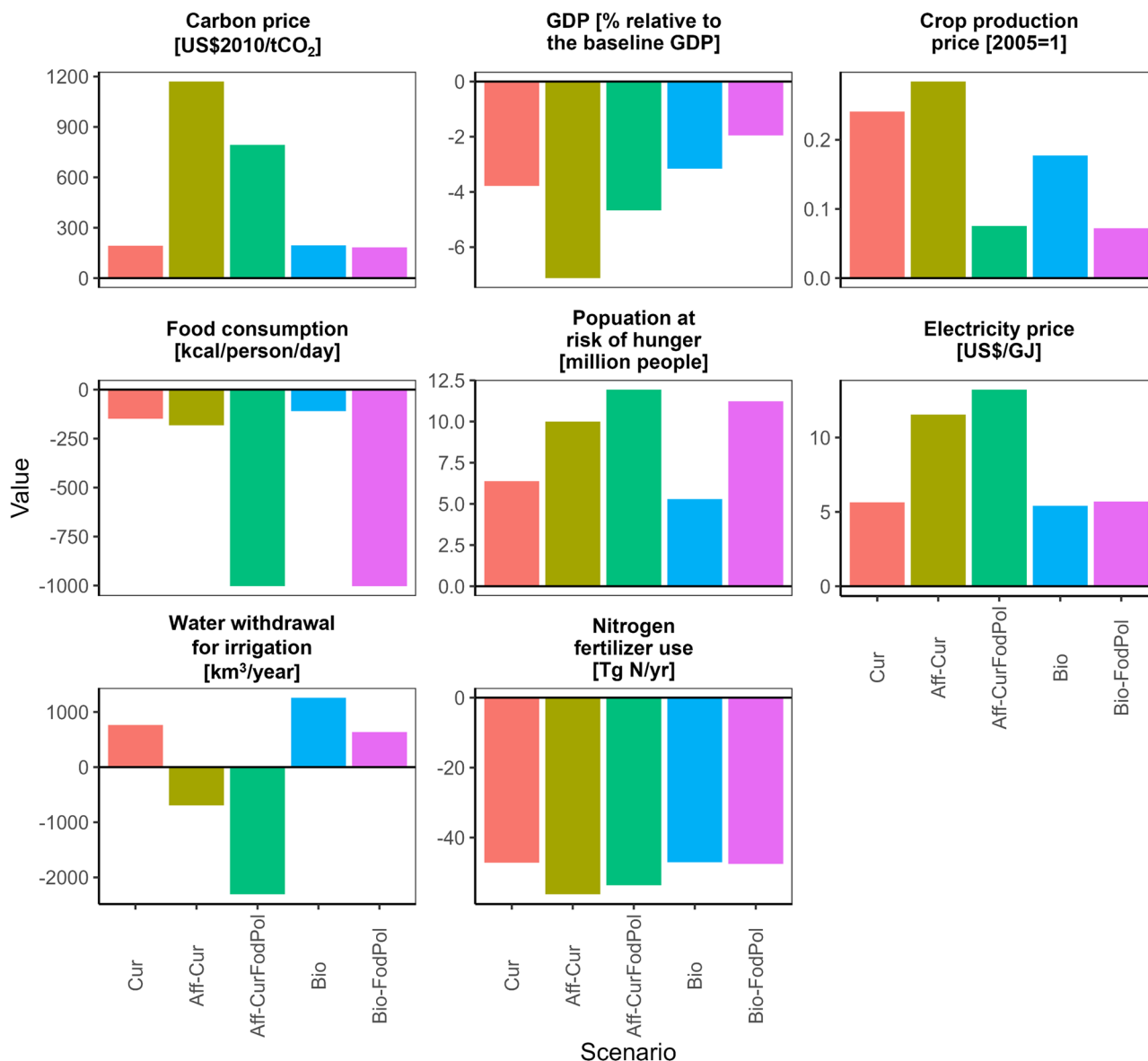


Fig. 4 | Global relative changes in multiple variables compared to the conventional scenario in 2100. See Table 1 for the scenario names and settings.

afforestation does bring some benefits from less nitrogen and water usage. Thus, both land-based CDR technologies will likely negatively impact food and land systems to a certain extent. Moreover, the social acceptability and desirability of using BECCS is uncertain^{8,10,19–23,33}. This suggests that all of the benefits and risks of implementing land-based CDR technologies should be considered when discussing climate actions and future pathways to be taken. For instance, implementing early climate actions that avoid temperature overshoot would reduce our reliance on land-based CDR technologies and emissions reductions while maintaining food and land systems, thereby reducing the risks associated with land-based CDR technologies³⁴. Given the need for CDR technologies to achieve the long-term climate target, it is important to determine a combination of land-based options and food measures to realise large-scale CDR while maintaining sustainability. The ambitious target of limiting climate change to 2 °C can be achieved through a best mix of land-based mitigation options with a better selection of forest types in proportions that minimise the trade-offs/adverse impacts on the economy, energy, food, land systems, and biodiversity.

Our analysis indicates that raising food distribution equality is key to mitigating the negative impacts of afforestation on food security. When a healthy and sustainable food diet is achieved only at the country-mean level

without improvement of food distribution equality, hunger likely increases substantially while over-consumption decreases. Although the total population at risk of hunger and the over-consuming population will decrease globally because the reduction in over-consumption is greater than the increase in hunger, regional disparities will occur. Hunger will intensify in developing countries while over-consumption will decrease in advanced countries. Accordingly, improvements in food distribution equality must be accompanied by a shift to a healthy and sustainable diet such as that proposed by EAT-Lancet³⁵. In the additional scenario assuming food distribution inequality based on past trends as in Hasegawa et al.³⁶, the population at risk of hunger was greater than in the scenario with no dietary change. This suggests that the past trend of food distribution equality improvement is insufficient and that greater reduction of inequality is needed. To avoid the increased hunger risk accompanying achievement of the EAT-Lancet target, the degree of reduction (reduction in the coefficient of variation for food distribution) must be approximately double that previously assumed³⁶.

Some limitations of this study point toward additional research avenues. First, there are available land-based CDR technologies that were not considered in this analysis. Currently, most integrated assessment models (IAMs) consider BECCS and afforestation/reforestation as land-based CDR

technologies. Other land-based CDR technologies (e.g., agroforestry, biochar, soil carbon management) have not been considered in the IAMs primarily because they are connected to sectors that are not yet included in many models, and because parameterising these technologies is speculative given that CDR technologies are not currently commercially deployed. It is therefore unlikely that these technologies can be implemented in the current model. Second, further development of a biodiversity model would help elucidate the impacts of land-based CDR on the environment³⁷. Third, the cost of food-related measures is not considered, as the data are limited but will cause some adverse effects and barriers to realisation. Fourth, the large-scale land-cover transitions from non-forest to forest vegetation associated with afforestation would decrease surface albedo and increase radiative forcing³⁸, and would require additional emissions reductions. Moreover, climate and forest interactions through fire and disturbances are complex and regionally diverse^{39,40}. The climate conditions assumed in the estimation of afforestation carbon sequestration are inconsistent with the mitigation scenario limiting global warming to 2 °C in this study. An analysis considering albedo- and climate-induced effects would bring more precise results. Fifth, this study considers the impacts on water and nutrient demand only for food systems but not for afforestation and bioenergy crops because such information for global study does not currently exist. Further study considering nutrient and water use or soil degradation associated with these land-based climate mitigation technologies would bring more precise evaluation from the land sustainability point of view. Finally, the present study is based on a single model; multiple-model analyses would generate more robust conclusions and clarify sources of uncertainty, particularly with regard to the magnitude of the effects of forest-type selection on carbon removal.

Methods

Model framework

We modelled the impacts of afforestation with different forest types on the mitigation potential of afforestation, food and land-use systems, and the environment using an integrated framework (Supplementary Fig. 1) that combines an economic model (AIM/Hub)²⁶ and a land-use distribution model (AIM/PLUM)²⁷. AIM/Hub calculates future land demand for 17 regions based on assumed socioeconomic conditions including population, GDP, and food measures (yield improvement, dietary change, trade globalisation, reduction of food distribution inequality). AIM/Hub considers emissions mitigation by setting a certain carbon budget with a global uniform carbon price in different sectors (i.e., agriculture and/or non-agricultural sectors). The model shows specific endogenous responses to the carbon price, which include adjustments to production systems, technologies, and demand and trade, among others. In the model, carbon prices lead to an increase in the land-based mitigation measures (e.g., afforestation/ reforestation) and a decrease in agricultural area (cropland and pasture) through three main channels simultaneously: the carbon tax on agricultural greenhouse gas (GHG) emissions directly increases prices and production costs of agricultural commodities depending on the GHG intensity of the production¹¹, leading to decreases in food consumption and agricultural area; the carbon tax on the carbon emissions/sequestration associated with land-use change makes expansion of agricultural land more expensive and land-based mitigation technologies more beneficial, thus shrinking agricultural land and expanding afforestation and bioenergy cropland area; and finally, the carbon tax induces an increase in the bioenergy demand from the energy system, which further increases the demands for land for bioenergy production. The resulting increases in food commodity prices decrease food consumption or shift demand to less expensive food products, with an increase in the population at risk of hunger.

The regional aggregated area of land calculated in AIM/Hub is input into AIM/PLUM to calculate the proportional areas of different land uses and amounts of carbon sequestered by afforestation and BECCS in individual grid cells (0.5° × 0.5°) so that the total area of gridded cells is equal to the land demand for each region. AIM/PLUM allocates cropland and afforested land to maximise profit to the landowner based on the

biophysically determined land productivity of the crop or tree (yield per unit area)²⁷. Afforestation is assumed to be implemented on non-forest land. The forest type selection scheme for each scenario was assumed in AIM/PLUM by setting the forest growth (tree yield) of different forest types. Yields from hydrological model H08⁴¹ were used for the bioenergy cropland productivity (yield) to calculate revenue; NPP for afforestation was calculated using the global gridded vegetation model VISIT²⁸ and used for afforestation productivity. Carbon sequestration by forests of different types and ages was calculated using forest growth curves based on land-use change over time. Withdrawal for irrigation and nitrogen fertiliser use were used as indicators measuring the effects on land-related sustainability. The indicators include water and nutrient use for food and energy crop production but not for afforestation. Due to data limitation for nitrogen fertiliser input to bioenergy crops, nitrogen fertiliser input to coarse grains (mainly maize) was used for that for bioenergy crops.

Method for estimating carbon sequestration through afforestation with different forest types

Here, we present how to calculate the amount of carbon sequestration with different forest types. NPP is the amount of biomass or carbon increased in the vegetation and soil through photosynthesis by subtracting loss due to respiratory by plants. To account for different forest types, NPP was calculated at the grid cell level for 12 forest types using the terrestrial vegetation model VISIT²⁸. VISIT is a gridded process-based model that considers above- and belowground biomass as well as soil carbon balance and simulates shifts in potential vegetation and the associated biogeochemical and hydrological cycles as a response to shifts in climate. The initial quantity of soil organic carbon was obtained by spin-up calculation for 300–4000 years under a stationary condition until the net ecosystem carbon balance at each grid approached adequately close to zero. The global total amount and spatial distribution of simulated soil carbon were comparable to those of observational data (e.g., Harmonised World Soil Database). To calculate the NPP of different forest types in the same environment, the following hypothetical experiment was performed using VISIT: all vegetation was removed from land in 2010 and afforested simultaneously with a single forest type. The same experiment was performed for all 12 forest types. The change in annual per-unit-area NPP in all land grid cells was calculated from 2010 onward. The 12 forest types used were: 1. tropical and subtropical evergreen forest, 2. tropical montane forest, 3. tropical and subtropical dry forest, 4. mid-latitude mixed forest, 5. mid-latitude broad-leaved forest, 6. semiarid wood or low forest, 7. coniferous evergreen forest, 8. southern taiga, 9. main evergreen taiga, 10. main deciduous taiga, 11. northern evergreen taiga, 12. northern deciduous taiga. See Supplementary Tables 2 and 3 for a map of agro-ecological zones and forest types for different scenarios. In calculations of future carbon sequestration through afforestation, RCP4.5⁴² was used as the future climate condition. This climate condition is not consistent with the mitigation scenario but this inconsistency would not overturn the conclusions of this study. The risk of natural disturbance through fire is considered, while other natural disturbances (e.g., strong winds, pests, and landslides) and the emissions associated with the operations required for afforestation (e.g., land preparation, tillage) are not.

To consider changes in the amount of carbon sequestration along with tree growth, carbon sequestration at different ages was calculated using the tree growth function³² shown below, the parameters of which were estimated from NPP estimated by VISIT. Parameters B and δ of the function were set to 30 and 1, respectively; parameter A was estimated for each forest type so that the forest growth rate when tree age = 20 was equal to the NPP calculated by VISIT. The maximum carbon amount was set to 300 MgC per ha. Tree age was calculated as the years since the tree was planted on the land.

$$V(\text{MgC per ha}) = \delta * \exp[A - B/\text{age}]$$

V (MgC per ha): carbon stored in trees; age: tree age; δ , A, B: coefficients

Assumptions on food-relevant measures

The food-relevant measures implemented assumed agricultural intensification, trade globalisation, dietary change, and improved equity in food distribution. Agricultural intensification and trade globalisation were assumed to be the same as those for scenario Shared Socioeconomic Pathway 1³⁶. To represent dietary change, calorie intake was set so that the EAT-Lancet target would be achieved in 2050 and maintained through 2100 in all regions. To represent more equitable food distribution, the coefficient of variation (CV) for per-capita dietary energy consumption in each country was set to reach 0.1 when per-capita GDP is USD 50,000.

Methodology for estimating the population at risk of hunger

The narrow definition of hunger is a state of food energy deprivation lasting more than 1 year; this does not include the short-lived effects of temporary crises or inadequate intake of other essential nutrients⁴³.

The population at risk of hunger is calculated by multiplying the proportion of the total population at risk of hunger by the total population. According to the Food and Agriculture Organisation (FAO) methodology⁴⁴, the food distribution within a country is assumed to obey a standard normal cumulative distribution. The proportion of the population at risk of hunger is defined as the proportion of the population below the mean minimum dietary energy requirement (M). The standard normal cumulative distribution has two parameters: the mean and the variance. The parameters of mean and variance are represented using the mean food calorie intake per person per day (cal) and the coefficient of variation of the domestic distribution of dietary energy consumption (CV), respectively.

The weight-based consumption of food goods is calculated and converted into calorie-based consumption using conversion factors for each commodity in the AIM/Hub model, and this is used as the mean food calorie intake per person per day (cal). Calories per 100 g⁴⁵ are weighted on the basis of production data in the base year and aggregated to the commodity classification to obtain the conversion factors. In this process, only the edible parts of commodities are considered for food consumption by using the edible part ratios⁴⁵. The CV is an indicator of food security observed in a household survey conducted by the FAO; it ranges from 0 to 1. FAO country data for CV are weighted across countries on the basis of population data in the base year and aggregated to regional classifications to obtain the CV s of aggregated regions.

The M is calculated for each year and country using the mean minimum dietary energy requirement in the base year at the country level⁴⁶, the adjustment coefficient for the minimum energy requirements per person in different age and sex groups, and the population of each age and sex group in each year⁴⁷. See Hasegawa et al.³⁶ for details regarding the method for estimating the population at risk of hunger and assumptions regarding CV .

Data availability

Data used in the study are available in the repository: <https://doi.org/10.5281/zenodo.10846304>.

Code availability

We compiled our calculations as open-source R packages that are available at <https://doi.org/10.5281/zenodo.10836630>.

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Author contributions

T.H. and S.F. designed the research; T.H. ran the economic and land-use model; A.I. ran the vegetation model. T.H., S.F. and T.K. carried out analysis of the modelling results; T.H. created figures and drafted the paper; and all authors provided feedback and contributed to writing of the entire manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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