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A regional assessment of land-based carbon mitigation potentials: Bioenergy, BECCS, reforestation, and forest management

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Abstract

Land-based solutions are indispensable features of most climate mitigation scenarios. Here we conduct a novel cross-sectoral assessment of regional carbon mitigation potential by running an ecosystem model with an explicit representation of forest structure and climate impacts for Bavaria, Germany, as a case study. We drive the model with four high-resolution climate projections (EURO-CORDEX) for the representative concentration pathway RCP4.5 and present-day land-cover from three satellite-derived datasets (CORINE, ESA-CCI, MODIS) and identify total mitigation potential by not only accounting for carbon storage but also material and energy substitution effects. The model represents the current state in Bavaria adequately, with a simulated forest biomass 12.9 ± 0.4% lower than data from national forest inventories. Future land-use changes according to two ambitious land-use harmonization scenarios (SSP1xRCP2.6, SSP4xRCP3.4) achieve a mitigation of 206 and 247 Mt C (2015–2100 period) via reforestation and the cultivation and burning of dedicated bioenergy crops, partly combined with carbon capture and storage. Sensitivity simulations suggest that converting croplands or pastures to bioenergy plantations could deliver a carbon mitigation of 40.9 and 37.7 kg C/m^2, respectively, by the year 2100 if used to replace carbon-intensive energy systems and combined with CCS. However, under less optimistic assumptions (including no CCS), only 15.3 and 12.2 kg C/m^2 are mitigated and reforestation might be the better option (20.0 and 16.8 kg C/m^2). Mitigation potential in existing forests is limited (converting coniferous into mixed forests, nitrogen fertilization) or even negative (suspending wood harvest) due to decreased carbon storage in product pools and associated substitution effects. Our simulations provide guidelines to policy makers, farmers, foresters, and private forest owners for sustainable and climate-benefitting ecosystem management in temperate regions. They also emphasize the importance of the CCS technology which is regarded critically by many people, making its implementation in the short or medium term currently doubtable.

KEYWORDS

afforestation, BECCS, climate mitigation, land management, land-use change, negative emissions

1 | INTRODUCTION

Despite the Paris Agreement targeting to limit global warming "well below 2°C" relative to the pre-industrial period, global carbon dioxide (CO_2) emissions are still rising (Le Quere et al., 2018). Germany, for example, has pledged to reduce its emissions by 40% in year 2020 relative to 1990 as a contribution to the Nationally Determined Contribution (NDC) of the European Union but will likely fail to deliver this target. In view of the recently announced climate package by the German government, achieving the German 2030 target also seems unlikely. In addition, even the successful implementation of all intended NDCs would leave a gap in the emission reductions to comply with the Paris target (Rogelj et al., 2016). The remaining emission budget consistent with the Paris Agreement is uncertain but probably around the order of magnitude of 200 Gt C (IPCC, 2018), an amount consumed in less than two decades under present-day emissions. A potential option to resolve this discrepancy is the implementation of large-scale CO_2 removal from the atmosphere (so-called negative emissions) which would effectively extend the budget. Indeed, scenarios consistent with the Paris Agreement typically rely on cumulative negative emissions of 150–200 Gt C by the year 2100 (IPCC, 2018; Smith et al., 2016; Wiltshire & Davies-Barnard, 2015), but even many less ambiguous mitigation scenarios require substantial amounts of CO_2 removal from the atmosphere. Most negative emissions are assumed to be land based, that is, enhancing the natural sink via avoided deforestation and reforestation, soil carbon sequestration, or bioenergy cultivation with carbon capture and storage (BECCS; Rogelj et al., 2018). Consequently, land management as a climate mitigation tool is an active area of current research (e.g. Griscom et al., 2017; Harper et al., 2018; Krause et al., 2018; Lewis, Wheeler, Mitchard, & Koch, 2019; Luyssaert et al., 2018; Smith et al., 2019).

Even though climate mitigation scenarios are typically developed at the global scale, in practice mitigation projects have to be realized regionally or locally. Land-based mitigation is particularly relevant in already intensively managed landscapes like the state of Bavaria, Germany, where the original vegetation has been largely replaced by agriculture and managed conifer monocultures. The hot and dry years of 2018 and 2019 in Central and Northern Europe raised public awareness that climate change is already underway and foresters and farmers increasingly experiment with new cultivars, which they hope will be better adapted to higher temperatures, droughts, and extreme events. For example, the fraction of deciduous forests in Bavaria increased from 22% to 36% over the last four decades (LWF, 2014). Further changes in species composition are expected as climatic thresholds of local species are surpassed (Buras & Menzel, 2019) and are recommended for adaptation by, for example, increasing the fraction of deciduous trees in forest ecosystems (Bayerisches Staatsministerium für Umwelt und Verbraucherschutz, 2017). A number of previous studies estimated the potential of German ecosystems to contribute to climate mitigation but were constrained by fundamental limitations, in particular by (a) not considering the effects of climate change or competition among trees on ecosystem productivity; (b) neglecting important components like soil carbon or substitution effects (i.e., carbon savings when wood is used to replace energy-intensive materials or prevent the burning of fossil fuels); (c) focusing on stand level; or (d) being restricted to either the forestry or the agricultural sector (e.g., Härtl, Höllerl, & Knoke, 2017; Klein, Höllerl, Blaschke, & Schulz, 2013).

Here, we use the detailed process-based ecosystem model LPJ-GUESS (Smith et al., 2014) to estimate the effects of alternative land management on carbon mitigation (negative emissions or reducing conventional fossil fuel emissions) until the year 2100 within a consistent modelling framework that considers climate change impacts, CO_2 fertilization, and vegetation dynamics (such as tree competition und forest structure). Bavaria with an area of 7 Mha and 13 million inhabitants is chosen as a case study to illustrate the novelty and advantages of our modeling approach. We estimate the potential for carbon mitigation by applying land-use projections from the land-use harmonization (LUH2) project as well as our own land-use scenarios in which we investigate the carbon mitigation potential on agricultural land and existing forests. We consider total carbon saving by not only simulating ecosystem carbon storage but also accounting for long-lived wood products and substitution effects. With our cross-sectoral study, we aim to contribute to the discussion of how best to use our available land in the context of climate mitigation, food production, ecosystem services, and biodiversity.

2 | MATERIALS AND METHODS

2.1 | Description of the LPJ-GUESS ecosystem model and modifications

LPJ-GUESS is a process-based ecosystem model simulating vegetation biogeography and dynamics as well as associated biogeochemical and water fluxes (Smith et al., 2014). Physiological processes are simulated on a daily time step, while establishment, carbon allocation, and mortality occur at the end of the year. The model represents forest gap dynamics and consequently explicitly simulates the succession of different plant functional types (PFTs) in a number of replicate patches (here: 5) per grid cell. Patches account for forest heterogeneity within a grid cell induced by stochastic processes and can be interpreted as samples of a forested landscape. Individuals of an age class within a patch (cohort) share the same properties, for example, diameter and access to water. In this study we used parameterizations of common global PFTs (temperate broadleaved summergreen and boreal needle-leaved evergreen PFTs), with a few parameters adjusted to better represent the main Bavarian species: spruce (*Picea abies*), pine (*Pinus sylvestris*), beech (*Fagus sylvatica*), and oak (*Quercus robur*, *Quercus petraea*; see Table S1). Tree establishment is determined by PFT-specific maximum establishment rates, bioclimatic limits, and plant-available light, water, and nutrients. Mortality occurs when growth efficiency falls below a PFT-specific threshold, when the tree approaches its maximum age, or when climate conditions become unsuitable. Trees may also die from wildfire, which is simulated based on fuel availability and moisture, and from stochastic disturbances (representing wind throws or insect outbreaks) which kill all trees in a patch. The average disturbance return interval was set to 935 years until 1980 based on Seidl, Schelhaas, Rammer, and Verkerk (2014) and Pugh, Arneth, Kautz, Poulter, and Smith (2019) and then gradually shortened to 409 years in 2021 (constant thereafter) in spruce-dominated forests, 672 years in other conifer-dominated forests, and 804 years in deciduous-dominated forests. Our approach of shortening the return interval accounts for the fact that conifer forests and particularly spruce forests are highly vulnerable to more frequent bark beetle outbreaks and storms (Lagergren, Jonsson, Blennow, & Smith, 2012) but that pests are also increasing in European deciduous forests (Seidl et al., 2018). It is a conservative assumption because we apply the full increase in disturbance frequency only to spruce forests and keep the shortened disturbance rates constant from 2021 on (lacking reliable estimates about future disturbance rates). Soil carbon-nitrogen dynamics in each patch are based on the CENTURY model. Nitrogen enters the ecosystem via simulated biological fixation (based on an empirical relationship with evapotranspiration; here the mid-range "central" parameters from Cleveland et al., 1999 were used), deposition, or fertilization (both prescribed). Besides natural vegetation, LPJ-GUESS represents croplands, pastures, forest monocultures, and their management (Jonsson, Lagergren, & Smith, 2015; Lindeskog et al., 2013; Olin et al., 2015). We introduced a new bioenergy crop PFT mimicking *Miscanthus* growth to represent second-generation bioenergy plantations more realistically than by using the existing maize crop PFT (see below). *Miscanthus* is a highly productive, cold-resistant C4 grass requiring low management and energy input, emitting few greenhouse gases and potentially increasing belowground carbon stocks (Kludze, Deen, & Dutta, 2011; McCalmont et al., 2017; Robertson et al., 2017). For these reasons it is considered a climate-attractive energy carrier compared to common food crops or fossil fuels, with the potential to provide negative emissions if combined with CCS. Thinning and timber harvest were implemented as selective harvest. A description of the harvesting rules can be found in the Supporting Information.

2.2 | EURO-CORDEX climate projections

We used bias-corrected climate projections from the EURO-CORDEX project (https://esgf-data.dkrz.de/search/cordex-dkrz/; Jacob et al., 2014) as forcing climate in LPJ-GUESS. These projections were bilinear remapped to the resolution of our simulations (0.025° × 0.025°) using Climate Data Operators (https://code.mpimet.mpg.de/projects/cdo/). We chose four combinations of global and regional climate models for which the necessary variables (daily surface air temperature, precipitation, incoming solar radiation) were available at 12.5 km resolution to account for uncertainties in climate projections: MPI-M-MPI-ESM-LR/REMO2009, IPSL-IPSL-CM5A-MR/RCA4, ICHEC-EC-EARTH/RACMO22E, and CNRM-CERFACS-CNRM-CM5/ARPEGE51. These four projections show a large range of simulated temperature and precipitation changes (https://www.regionaler-klimaatlas.de) and we therefore considered them to adequately represent the climate model uncertainty for a given representative concentration pathway (RCP). We decided to focus on RCP4.5 because for this case all required variables were available and it seems a realistic scenario given still-increasing emissions and assuming the large-scale implementation of CO_2 removal in this century.

The temperature increase in our climate projections ranges between 1.4 and 2.6°C by the end of the century (2071–2100) compared to the 1971–2000 period (Figure 1a). The largest temperature increase occurs in the Alps and in Eastern Bavaria (Figure 1c). Annual precipitation increases in all four scenarios (by 35–114 mm averaged over the total area), with largest increases found in Southwestern Bavaria (Figure 1d). However, plant-available water might still decrease due to increased evaporation from rising temperatures and shifts in rainfall frequency and seasonality (see Figures S1 and S2).

2.3 | Land cover datasets

We used three satellite-based datasets providing observations of present-day land cover at high resolution: CORINE Land Cover 2018 (https://land.copernicus.eu/pan-european/corine-land-cover), Climate Change Initiative of the European Space Agency (ESA-CCI) Land Cover (http://maps.elie.ucl.ac.be/CCI/viewer/), and MODIS Land Cover Type product version 6 (MCD12Q1, International Global Biosphere Programme classification scheme; https://e4ftl01.cr.usgs.gov/MOTA/MCD12Q1.006/). CORINE is a European land cover dataset at 100 m resolution available for the year 2018 while ESA-CCI (300 m, latest year 2015) and MODIS (500 m, latest year 2017) are available globally. Each LPJ-GUESS simulation was performed for all three present-day land covers. The conversion of the satellite-product land cover classes to LPJ-GUESS classes is described in the Supporting Information, with the resulting land cover maps shown in Figure 2.

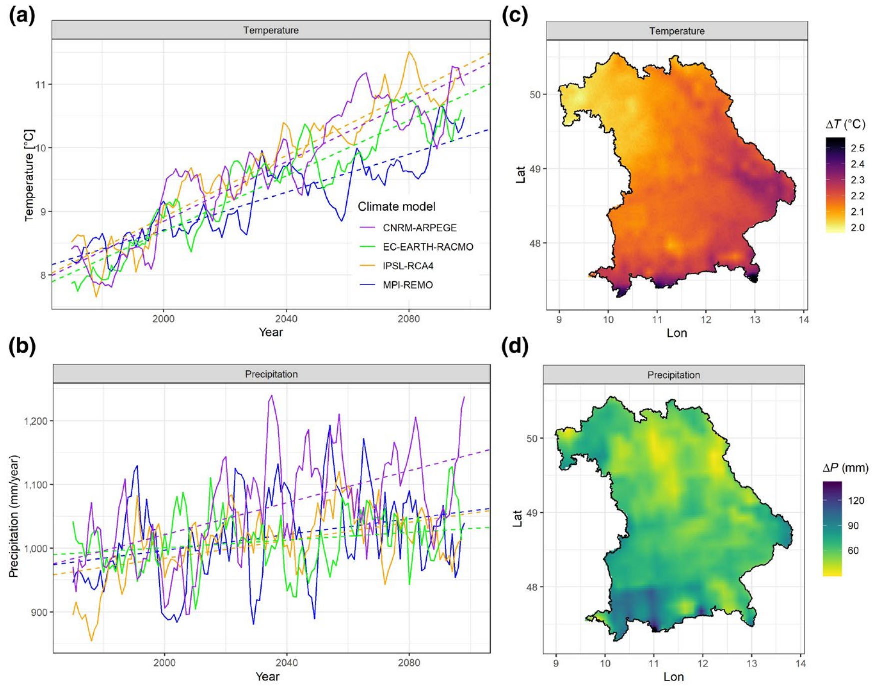


FIGURE 1 Time-series (5-year running means) of annual mean temperature (a) and precipitation (b) in our input climate data, maps of model-averaged annual temperature (c), and precipitation (d) changes between 1971–2000 and 2071–2100. Dashed lines show linear trends over the 1970–2100 period

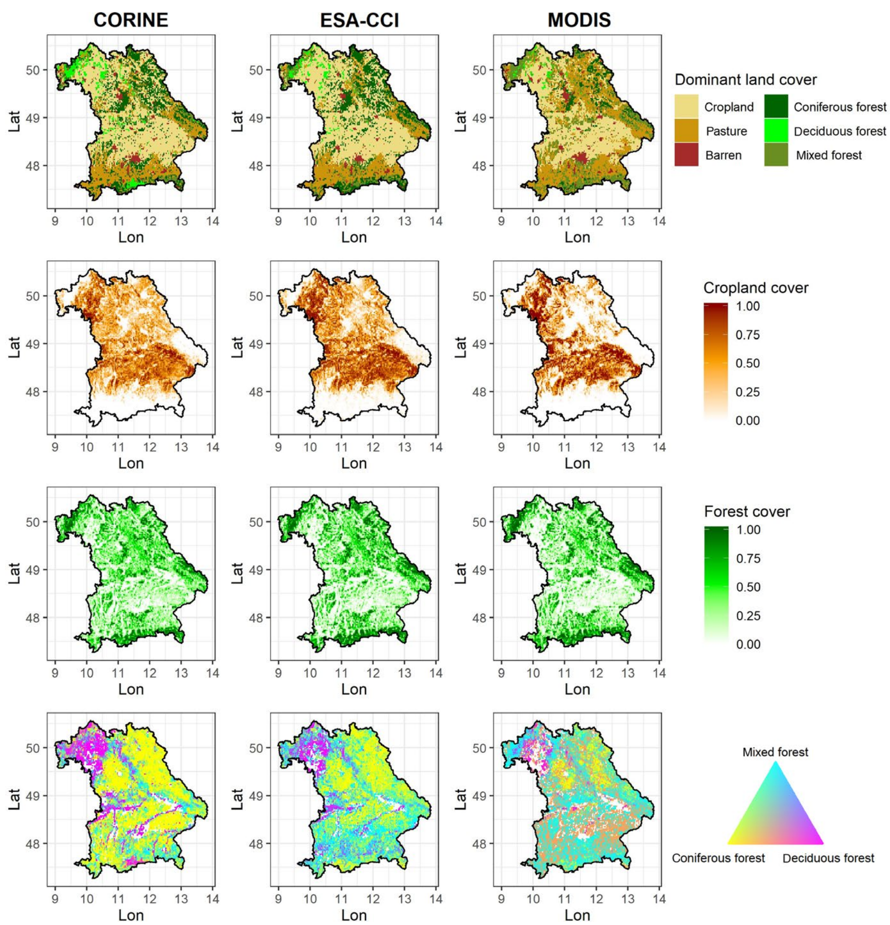


FIGURE 2 Maps of current land cover according to the three satellite-derived datasets, converted to LPJ-GUESS input data: dominant land cover, cropland fraction, forest fraction, and forest composition (top to bottom)

2.4 | Simulation setup

We performed simulations with LPJ-GUESS for Bavaria at a 0.025° × 0.025° resolution (~1.8 km × 2.8 km) for the 1901–2100 period following a spin-up of 1,000 years. Climate data (daily surface temperature, precipitation, short-wave radiation) were taken from an ensemble of RCP4.5 EURO-CORDEX simulations (see above). As no climate data were available before 1971, we used a repeating temperature-detrended 1971–1980 climate for the spin-up and years before 1971. According to RCP4.5, atmospheric CO_2 increases from 296 ppm at the start of the simulation to 411 ppm in the year 2020 and stabilizes around 538 ppm by the end of the century. Future nitrogen deposition used as model input also followed RCP4.5. We kept land cover in the reference simulations constant over the entire simulation period according to the satellite-derived datasets but allowed forest composition in mixed forests to change in response to climate change. Nitrogen application rates on croplands followed the average fertilizing rates of annual C3 and C4 crops in Bavaria according to the LUH2 data set and were kept constant at 173 and 293 kg N/ha, respectively, from year 2014 on.

2.5 | Maximum-scale land-use scenarios

In order to assess the maximum potential for carbon mitigation in Bavaria and to compare the efficiency of different management options we performed seven experiments for each of the 12 land cover—climate change combinations (Figure 3): no more wood harvest in forests, converting coniferous forests gradually into mixed forests, nitrogen fertilization of forests, reforestation on croplands, dedicated bioenergy crop cultivation on croplands (further distinguished between two different assumptions about conversion routes and with or without CCS), reforestation on

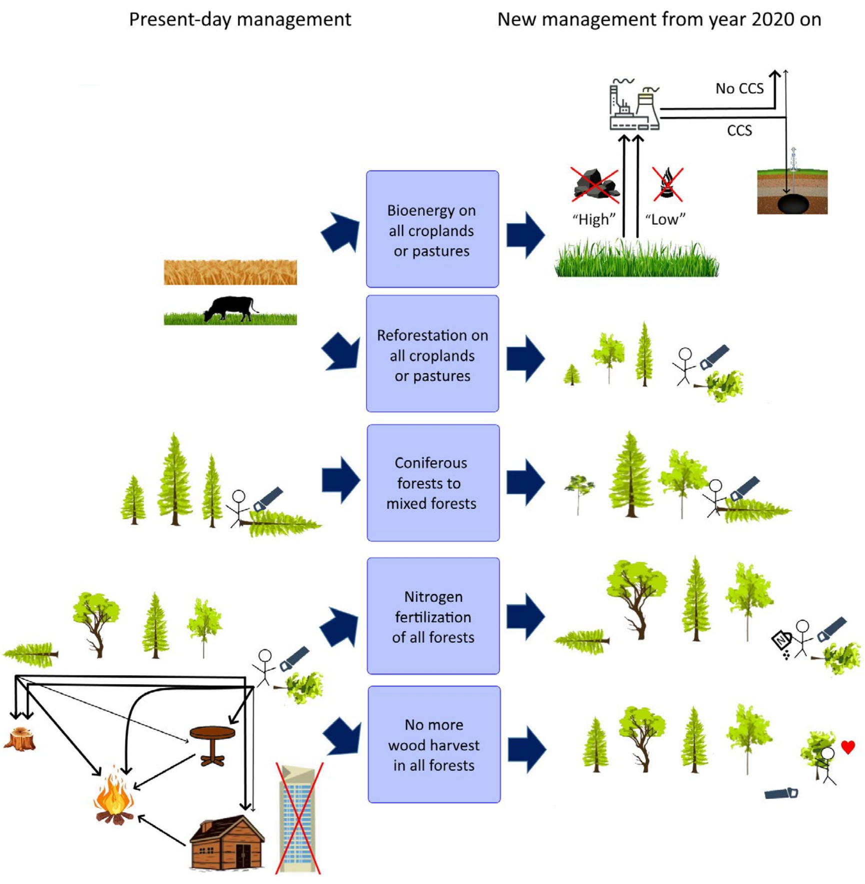


FIGURE 3 Overview of our mitigation scenarios. Existing agricultural land is converted to bioenergy plantations or reforested. Harvested bioenergy crops can be burned to replace fossil-fuel intensive materials like coal ("high" scenario) or less carbon-intensive materials like gas or used in the transport sector with lower mitigation potential ("low" scenario). The CO_2 emitted upon combustion goes to the atmosphere or is partly captured assuming CCS can be applied at the industrial scale. Harvested wood is either directly burned for energy production, transferred to medium (e.g., furniture) and long-term product pools (e.g., constructions), or left on-site (see Supporting Information for details), thereby storing carbon in the long term and preventing the production of energy-intensive materials (e.g., concrete). Each scenario was simulated in LPJ-GUESS forced by four climate projections and three land-cover maps (12 combinations). The additionally investigated LUH2 scenarios assume a combination of reforestation and bioenergy, but only a fraction of agricultural land is gradually converted. The figure has been designed using resources from Freepik.com. CCS, carbon capture and storage

pastures, and dedicated bioenergy crop cultivation on pastures (also further distinguished between two different assumptions about conversion routes and with or without CCS). All of these simulations started implementing mitigation management in the year 2020 at the maximum spatial scales (e.g., 100% of the total cropland area), thereby representing a theoretical maximum potential. We did not consider a forest clear-cut scenario (e.g., for bioenergy plantations) as this would likely not be realizable in Bavaria due to ecological concerns and current law.

To convert coniferous forests into mixed forests, establishment of deciduous trees was allowed in our simulations in conifer monocultures from year 2020 on. Suspending wood harvest was implemented by simulating no more thinning or final harvest. Forest nitrogen fertilization was applied every 5 years at a rate of 150 kg N/ha. Reforestation on cropland or pastures was implemented as natural forest regrowth, including wood harvest according to the rules described in the Supporting Information. Second-generation bioenergy crops were represented in LPJ-GUESS by a newly introduced dedicated lignocellulosic bioenergy crop with parameters chosen to mimic *Miscanthus* growth (Table S2).

2.6 | Application of land-use scenarios from the land-use harmonization project (LUH2)

Additionally, we also performed simulations with more realistic land-use projections. The LUH2 project (http://luh.umd.edu/) provides global land-use scenarios covering the 850–2100 period at 0.25° × 0.25° resolution. The projections are based on simulations from Integrated Assessment Models, harmonized to historic reconstructions. LUH2 land cover classes can easily be used by dynamic vegetation models; however, the satellite-based products offer more information about spatial heterogeneity (e.g., forest type) and are more reliable at the Bavarian scale (see Table S3). We therefore decided to use the satellite-based land cover for the historic period (before year 2015) and apply future changes (2015–2100) from these projections after remapping to 0.025° × 0.025° resolution (in combination with the RCP4.5 climate mentioned above). In cases where the coverage of a land cover class in a grid cell exceeded the [0–1] range, we did not allow the exceeding land-use change to take place. We chose a subset of LUH2 scenarios which assume large improvements in agricultural efficiency and shifts in diets thus allowing large-scale land-based mitigation as a tool to achieve ambitious climate targets (Figure S3): SSP1xRCP2.6 (a scenario of rapid and large-scale reforestation in Bavaria which is partly cancelled in the second half of the 21st century in favor of bioenergy crop plantations) and SSP4xRCP3.4 (a scenario of massive bioenergy deployment starting already today and somewhat lower reforestation rates compared to SSP1xRCP2.6). Accordingly, calculated mitigation potential is based on what is perceived by Integrated Assessment Models as realistic future land allocations, but changes in forest management (e.g., forest composition) are not considered. Increases in natural vegetation (the categories secondary forests and non-forests in LUH2) were simulated here as natural forest succession, including harvest when the harvest diameter is reached, with constant forest composition over time (assuming 100% mixed forests if no forest existed in a grid cell before).

We also performed additional simulation runs on the original resolution of the LUH2 land-use projections (0.25°) in which we applied the LUH2 land-use transitions on the initial LUH2 land cover (so land cover and land cover changes were consistent). As a result, all LUH2 transitions were possible (as the land cover fraction never exceeded [0–1]). For instance, forest expansion in SSP1xRCP2.6 by the year 2100 would be around 0.49 Mha using LUH2 initial land cover, compared to 0.44 Mha using CORINE land cover, even though LUH2 total area is around 2% (0.14 Mha) smaller. However, initial land cover as given in the LUH2 dataset is quite unrealistic in Bavaria (see Table S3): While pastures are underestimated, the fraction of natural vegetation largely exceeds the forest cover from satellite-based products and official statistics. We thus used the initial satellite land cover as our default option.

2.7 | Calculation of the carbon mitigation potential

The total carbon mitigation potential was calculated as the sum of changes in biomass carbon, litter plus soil carbon, product pool carbon, material substitution from harvested wood products (as wood can replace energy-intensive materials like concrete), energy substitution from harvested wood products (either direct energy wood or burned at the end of its lifecycle), energy substitution from burning of second-generation bioenergy crops, and—if applied—underground carbon storage via CCS, all changes compared to the baseline simulations.

Vegetation and soil carbon pools are directly simulated by LPJ-GUESS. The distribution of harvested wood to the different product pools and the decay rate differed from the standard LPJ-GUESS procedure (see Supporting Information). For the material substitution of wood products we assumed a mitigation factor of 1.5 (Knauf, Köhl, Mues, Olschofsky, & Frühwald, 2015). This means that for every ton of harvested carbon that goes to the mid- or long-lived product pool, 1.5 tons of carbon emissions are avoided because the replaced energy-intensive material is never produced. We note that the effect depends on the substituted material and higher or lower values are also found in the literature (Klein et al., 2013; Leskinen et al., 2018;

Sathre & O'Connor, 2010). For energy substitution from wood, we used a mitigation factor of 0.67 (Knauf et al., 2015; Rüter, 2011). We assumed that 90% of the short-term product pool (e.g., fuel wood and paper) is directly burned for energy production, while the remainder is oxidized without providing energy. For medium- and long-term products, we assume that only 80% are burned for energy production at the end of their lifetime (Knauf et al., 2015; Rüter, 2011).

There is very large uncertainty with the carbon mitigation potential of dedicated bioenergy crops chiefly because of different conversion routes (e.g., electricity vs. liquid biofuels vs. hydrogen production) and because the substitution effect depends on the carbon intensity of the replaced energy system (Creutzig et al., 2015; Fajardy, Köberle, MacDowell, & Fantuzzi, 2019; Kalt et al., 2019). Some scientist even question the ability of BECCS to provide net energy when accounting for emissions over the whole life cycle (Biofuelwatch, 2015; Fajardy & Dowell, 2018). The efficiency of the respective bioenergy pathway, that is, the carbon mitigation per unit biomass can be consolidated in a "displacement factor" (Kalt et al., 2019), comparable to the "mitigation factor" for wood. We analyzed the carbon mitigation potential for a "low" and a "high" scenario, following Kalt et al. (2019). In the "high" case the displacement factor declines from 0.7 in 2020 to 0.55 in 2050 followed by a slower decline to 0.4 in 2100. In this case bioenergy is assumed to initially replace CO_2-intensive fossil fuels (e.g., coal) and later in the century liquid transport fuels and natural gas. In the "low" case the displacement factor declines from 0.55 to 0.35 and 0.25 in 2050 and 2100, respectively. This represents a scenario in which bioenergy is initially used to displace natural gas-based electricity and later in the century to produce biofuels, but at a lower efficiency than for the "high" case. In addition, we tested the mitigation potential for both of these cases when combined with CCS. In both the "low" and the "high" scenario the capture rate is assumed to be 0.75 in the year 2020 but then declines linearly to 0.65 (high) and 0.55 (low) in the year 2100, accounting for the lower capture efficiency in the transport sector (Klein et al., 2014). We assume an energy penalty of 25% if CCS is applied due to the energy consumption of CCS and downstream emissions (Creutzig et al., 2015; Gough & Vaughan, 2015). Sufficient storage capacities are assumed to exist. In the LUH2 simulations we assumed an intermediate displacement factor of 0.6 in the year 2020, declining to 0.45 in 2050 and 0.3 in 2100. As the LUH2 scenarios provide no information about the application of bioenergy without CCS versus BECCS, we assume CCS being first applied in the year 2031 (Vaughan et al., 2018) and then steadily increasing to 100% in 2080. Capture efficiency decreases from 0.75 in the year 2020 to 0.6 in the year 2100 as bioenergy is assumed to be used increasingly in the transport sector.

3 | RESULTS AND DISCUSSION

3.1 | Present-day carbon stocks and future changes assuming no changes in management

Our model represents the observed current state in Bavaria adequately. According to our simulations, Bavarian ecosystems (including agricultural areas) presently store around 282 ± 6 Mt C (mean ± 1σ, 2010–2019 average) in vegetation (Figure 4). The simulated average forest biomass density is well in the range of the Third National Forest Inventory (10.8 vs. 12.4 kg C/m^2; Figure S4) and total forest vegetation carbon (without agricultural areas) is 267 ± 8 Mt C compared to 300–328 Mt C reported in other estimates (Klein & Schulz, 2011, 2012; LWF, 2014). The slightly larger observed values result most likely from high fertility of Bavarian soils in terms of nutrient and water availability that we cannot reproduce in our simulations. While total simulated wood harvest

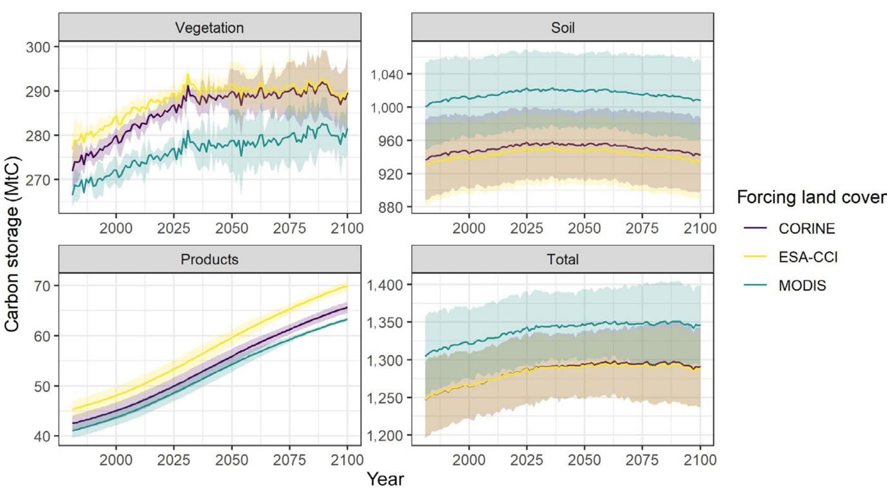


FIGURE 4 Time-series of changes in carbon pools for the baseline simulations (constant land cover and management). The line represents the mean across the simulations driven by the four climate projections and the shaded area represents the ±1 *SD* range

is substantially lower than estimated in a former study based on official statistics (1.6 vs. 4 Mt C/year; Klein & Schulz, 2012), the size of the product pool is only slightly lower (48 ± 3 vs. 58 Mt C), even though we assume carbon transferred to the fast product pool (~0.75 Mt C/year; Figure S5) to decay instantly. Spatial patterns of wood harvest intensities are likely more complex than in our simulations. While we assume constant harvest in all forests (aside from National Parks), in reality this practice will sometimes not be realized because of inaccessibility or indifference of the forest owners (more than half of Bavarian forests are private property). The simulated fraction of energy wood versus material wood is roughly 50%, similar to existing calculations (Mantau, 2012), even though we cannot simulate the economy-driven trend toward more energy usage observed over the past few years. Total simulated litter plus soil carbon over the 2010–2019 period is 971 ± 53 Mt C, including agricultural areas. Total forest soil carbon is significantly higher than another estimate (545 ± 35 vs. 347 Mt C in the upper 150 cm in Klein & Schulz, 2011), which is likely mainly a result of LPJ-GUESS simulating the entire soil column. Depending on the forcing climate, simulated soil carbon densities of mixed forests range between 15.4 and 18.8 kg C/m^2 (18.8–21.7 kg C/m^2 for spruce monocultures and 7.1–15.9 kg C/m^2 for other monocultures), compared to 9.8 or 14.3 kg C/m^2 reported in empirical estimates (Klein & Schulz, 2011; Wiesmeier et al., 2013).

Total terrestrial carbon storage increases throughout the 21st century in the baseline simulations by 7.5 ± 8.7 Mt C (mean ± 1σ across 12 simulations—the combination of four climate projections and the three land covers) over the 2020–2100 period (Figure 4). Vegetation carbon increases until the year 2030 but then remains relatively constant for all three land-cover sets. However, uncertainty from the different climate projections increases substantially in the second half of the century. The largest vegetation carbon increase occurs in MODIS/CNRM-ARPEGE (+10 Mt C), while ESA/IPSL-RCA4 results in the largest biomass loss (−6 Mt C). Initial soil carbon content is particularly dependent on land cover but in all three land-cover sets there is an increase until around year 2025 followed by a gradual decrease afterward. Carbon storage in the product pool increases throughout the entire century. This is a result of increased wood harvest converted to medium and long-term products (Figure S5) driven by enhanced tree productivity. Overall, total wood harvest increases by 18% between 2010–2019 and 2091–2100, while crop and pasture harvest increase by 28% and 9%, respectively. This implies that under constant demand and management as well as regulated markets (to avoid overproduction), land could potentially be made available for the purpose of land-based mitigation without preventing local timber and food production and without indirect land-use emissions from more food import.

3.2 | Carbon mitigation simulations based on land-use harmonization (LUH2) scenarios

Total simulated carbon mitigation is smaller for SSP1xRCP2.6 (the scenario relying on both reforestation and bioenergy) than for SSP4xRCP3.4 (the more bioenergy-focused scenario; 206 ± 17 Mt C vs. 247 ± 21 Mt C; see Figure 5), with carbon mitigation via CCS (i.e., CO_2 captured upon oxidation and subsequent underground storage) being the most important component in both scenarios (83 ± 7 and 109 ± 11 Mt C; Figure 6). However, while vegetation and soil carbon uptake also play an important role in SSP1xRCP2.6 (49 ± 4 and 11 ± 2 Mt C, respectively), bioenergy substitution is particularly important in SSP4xRCP3.4 (89 ± 9 Mt C). Putting these numbers into perspective, they are equivalent to around 9–11 years of present-day emissions in Bavaria, 0.10%–0.13% of the global remaining emission budget to stay "well" below 2°C (IPCC, 2018), or 0.13%–0.15% of the negative emissions likely needed to achieve the 2°C target of the Paris Agreement (Smith et al., 2016; Wiltshire & Davies-Barnard, 2015). This compares to Bavaria representing 0.055% of the ice-free land area and 0.17% of the global population. It is important to keep in mind that historic per capita emissions in

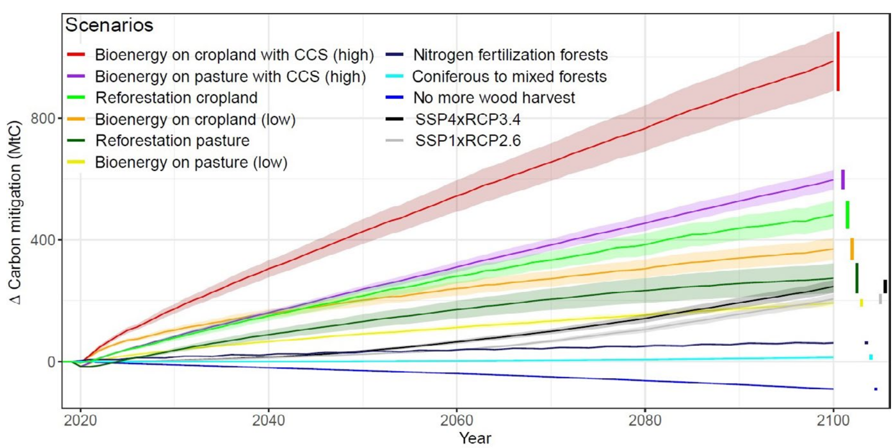


FIGURE 5 Time-series of total carbon mitigation in mitigation scenarios (compared to the baseline simulation). Shaded areas and bars on the right show the ±1 *SD* range. Note that the cropland and pasture scenarios bioenergy (high) and bioenergy with CCS (low) are not shown here for clarity. CCS, carbon capture and storage

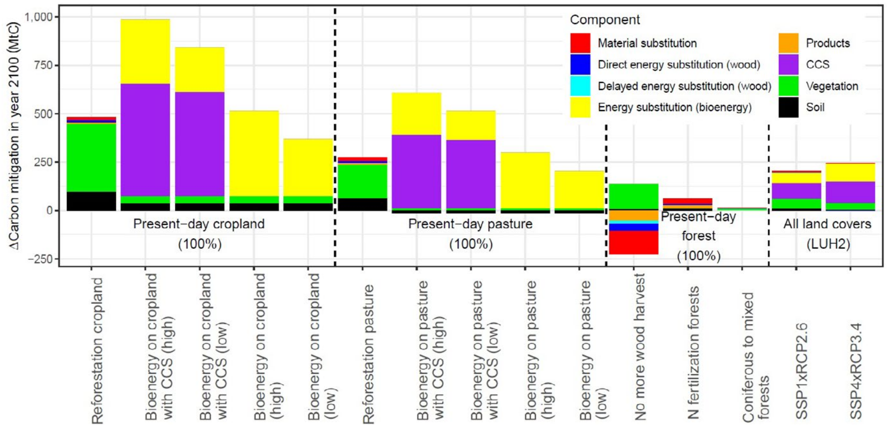


FIGURE 6 Relative contributions of different processes to total carbon mitigation in the year 2100. Carbon mitigation can be achieved via additional storage in biomass, soil, woody products, carbon capture and storage (CCS), or substitution effects when harvested biomass is used for constructions or fuel. Dedicated bioenergy crops are assumed to be burned directly while wood can be burned directly for energy or after usage. Bars show average carbon mitigation across the 12 combinations of climate projections and land cover sets. Carbon mitigation is relatively low for the LUH2 scenarios because here only a fraction of the agricultural land is used for carbon mitigation and most mitigation activities are only realized after the year 2020. LUH, land-use harmonization

Germany were above the global average, and will likely remain high in the next decades. Clearly rapid reductions in fossil fuel emissions are needed in Bavaria even in the presence of large-scale land-based mitigation to achieve the targets of the Paris Agreement.

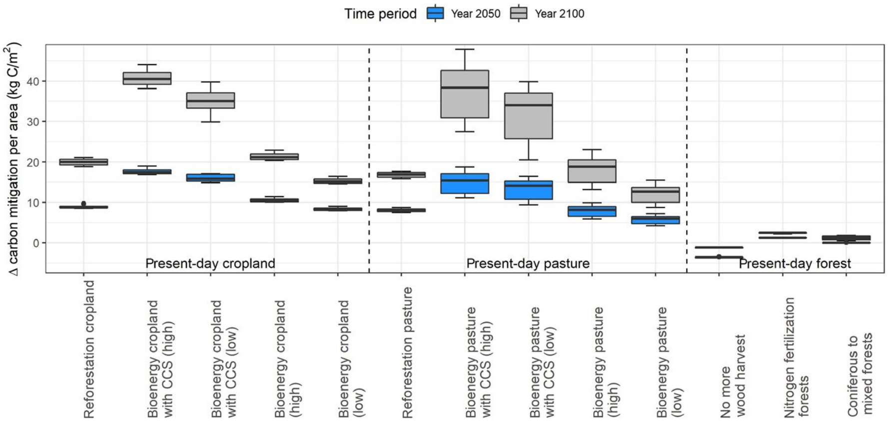
Total carbon mitigation is slightly larger (4%–8%) in the sensitivity simulations in which we used the original LUH2 spatial resolution and initial LUH2 land cover (see Section 2) compared to the standard setup forced by satellite-based estimates (Figure S6). While there is little difference between the two options in terms of mitigation via bioenergy and CCS, the LUH2 approach yields substantially larger vegetation and soil carbon uptake. One likely reason is that in the LUH2 case there is no mismatch between initial land cover and land cover change, that is, land-based mitigation can be applied at the full scale. Both approaches include some questionable assumptions (e.g., initial land cover is implausible in LUH2; reforestation with conifers as often assumed using satellite-based land cover seems unlikely) so the mean of both approaches (210 and 256 Mt C) might provide the best estimate of the realistic carbon mitigation potential in Bavaria.

3.3 | Reforestation competitive with bioenergy but not with BECCS

Our own scenarios allow us to explore the potential contribution of different management options in more detail. Abandoned agricultural fields could be either cultivated for bioenergy crops or reforested. Converting all cropland to dedicated bioenergy plantations in the year 2020 would, in our simulations, deliver a carbon mitigation of 370–987 Mt C by the year 2100 (Figure 5), with large uncertainties arising from assumptions about conversion routes and carbon intensity of the replaced energy system (i.e., the displacement factor) and whether bioenergy is combined with CCS. The "high" scenario, representing a case where bioenergy chiefly replaces carbon-intensive fossil fuels (e.g., coal), could deliver 987 ± 96 Mt C if combined with CCS, and 516 ± 49 Mt C without CCS. In contrast, the "low" scenario yields 843 ± 96 and 370 ± 35 Mt C, respectively. Most of this carbon mitigation is achieved via fossil fuel substitution and—if applied—carbon storage via bioenergy CCS, while vegetation and soil carbon uptake are relatively small (Figure 6). Simulated *Miscanthus* yields are in relatively good agreement with site observations, even though the variability across sites is clearly underestimated (Figure S7). If croplands are instead converted to mixed forests in our simulations, carbon mitigation is mainly achieved via increases in biomass, with smaller contributions from soil carbon, wood products, and associated substitution effects. The total carbon uptake in this case is larger (482 ± 45 Mt C) than for the "low" bioenergy scenario without CCS but substantially smaller than for the "high" BECCS scenario, emphasizing the importance of the precise bioenergy usage when assessing bioenergy versus forests as climate mitigation options.

Converting all pasture land to bioenergy plantations has a smaller potential for carbon mitigation than all croplands—up to 597 ± 31 Mt C for the "high" scenario with CCS and 193 ± 11 Mt C for the "low" scenario without CCS (Figure 5). Natural forest succession could deliver 274 ± 48 Mt C, again lower than for reforestation of croplands. The reasons for the generally lower numbers are the smaller pasture area

FIGURE 7 Per-area carbon mitigation of the different management options by the years 2050 (blue) and 2100 (gray). Hinges correspond to the first and third quartiles, whiskers extend to the total range without outliers (within 1.5 interquartile range from the hinges)



(23.2% vs. 34.4% fractional coverage on average) but also that per-area carbon mitigation is 8%–20% smaller than for cropland (Figure 7), including much larger variability across simulations. Pastures generally have larger soil carbon stocks and consequently less soil carbon uptake potential following land cover transitions (Krause, Pugh, Bayer, Lindeskog, & Arneth, 2016). In addition, pastures may be located at less productive locations and may also have different soil nitrogen contents, thereby affecting plant growth compared to croplands following land conversions. Surprisingly, despite the smaller area, reforestation of pastures yields slightly larger product pools and substitution effects than croplands (Figure S8), indicating differences in harvest rates or forest composition. In fact, young forests on former croplands are around 21% less productive than on former pastures in the same grid cell (2021–2025 period), which is likely a result of reduced soil nitrogen availability from more intensive harvest (Krause et al., 2016). In contrast, *Miscanthus* yields are independent from former land use. Interestingly, vegetation carbon uptake via reforestation levels off around 2070 on former pastures (carbon mitigation via substitution effects still takes place though), while on former croplands the increase continues until 2100 (Figure S8). This occurs because on former pastures shade-intolerant pioneer species reach their peak biomass around 2060 (with losses thereafter balanced by growth of shade-tolerant trees), while on the former, croplands continue to accumulate carbon for some more decades (thereby limiting the growth of shade-tolerant trees).

It is important to point out that CCS is currently far from being deployable on a commercial scale (Bui et al., 2018), pilot CCS projects have been abandoned all over Europe, and its feasibility is currently not further investigated in Germany chiefly due to low governmental and societal acceptance (Vogele, Rubbelke, Mayer, & Kuckshinrichs, 2018). Consequently, assuming that bioenergy will be combined with CCS currently seems unrealistic, at least for the next few decades. This indicates that reforestation might be the better option compared to bioenergy (Figures 5 and 7), in agreement with DeCicco and Schlesinger (2018) but contradicting the findings of Albanito et al. (2016) and Evans, Ramage, DiRocco, and Potts (2015). However, the permanence of carbon storage (forests are prone to disturbances and direct human interventions) and the timing of carbon mitigation (at least for former pastures reforestation is relatively more efficient in the first decades compared to bioenergy) also need to be considered. In addition, estimating the carbon mitigation potential of BECCS is particularly challenging. While our simulations suggest that CCS contributes most to the overall carbon mitigation of BECCS (emphasizing the importance of the technology and the assumed capture efficiency), energy substitution is also important but was neglected in previous studies (Harper et al., 2018; Humpenoder et al., 2014; Krause et al., 2018). CCS is particularly uncertain due to the large range of capture efficiencies (including processing losses and sometimes transport losses) assumed in the literature, for example, 48%–90% (Klein et al., 2014), 52% (Smith & Torn, 2013), 60% and 77%–87% (Harper et al., 2018), or 80% (Krause et al., 2018), compared to our time-depending value of 55%–75% (see Section 2). Additional carbon mitigation is achieved via belowground biomass and soil carbon accumulation, even though the contribution to total carbon mitigation is relatively small (0%–20%) in comparison to energy substitution, in agreement with other studies (Clifton-Brown, Breuer, & Jones, 2007; Zatta, Clifton-Brown, Robson, Hastings, & Monti, 2014). However, simulated belowground vegetation carbon is smaller (~4.9 tC/ha) than the range (7.5–15.0 tC/ha) reported for four *Miscanthus* sites in Germany (Kahle, Beuch, Boelcke, Leinweber, & Schulten, 2001). Bioenergy cultivation on croplands in LPJ-GUESS increases soil carbon, in agreement with previous observations (McCalmont et al., 2017; Zatta et al., 2014). In contrast, former pastures in our simulations release soil carbon, with observations ranging from depletions in the first years (McCalmont et al., 2017), no change (Zatta et al., 2014), or soil carbon accumulation (Clifton-Brown et al., 2007). There is also large uncertainty in bioenergy crop yields, which can be expected in the future, especially on a commercial scale (Krause et al., 2018; Searle & Malins, 2014). While our simulated yields (unfertilized and rain-fed) are very similar across suitable sites (7–10 t ha^{-1} $year^{-1}$), reported yields in Bavaria range between 4 and more than 20 t ha^{-1} $year^{-1}$ under intensive management (Figure S7).

3.4 | Limited mitigation potential in the forestry sector

Carbon mitigation potential is in our simulations generally much lower in existing forests than on agricultural land. The cessation of wood harvest in all forests from 2020 on results in a net carbon release of 90 ± 3 Mt C (−3.6 kg C/m^2). This occurs because decreases in wood product storage (−53 Mt C), immediate and delayed energy substitution (−41 and −14 Mt C, respectively), and material substitution (−119 Mt C) outweigh additional carbon uptake in vegetation and soils (+128 and +9 Mt C, respectively; Figure 6). Similar results have been reported by Klein et al. (2013), Klein and Schulz (2012), and Schulze et al. (2020). The finding that managed forests are superior climate mitigation options than unmanaged forests sounds surprising in view of a recent study emphasizing the need of tropical forest renaturation rather than tree plantations for climate protection (Lewis et al., 2019). A major difference, however, is that tropical tree plantations produce much shorter-lived wood products compared to managed forests in Bavaria. Nevertheless, product pool storage and substitution effects (especially energy substitution) were likely underestimated by Lewis et al. (2019).

Forest nitrogen fertilization in our simulations achieves a carbon mitigation of 62 ± 4 Mt C (2.5 kg C/m^2). While vegetation carbon is hardly affected, mitigation is mainly achieved via soil carbon uptake, increases in wood products, and associated substitution effects. The reason is that the increased tree productivity results in more extraction of living biomass, which is partitioned between soil and product pools. However, potential nitrous oxide (N_2O) emissions from increased nitrogen input could substantially reduce the net effect of nitrogen fertilization. While N_2O emissions from fertilizer application might be higher in deciduous forests than in coniferous forests (Eickenscheidt, Brumme, & Veldkamp, 2011), assuming the default IPPC emission factor of 1% and a 296 times greater warming potential than CO_2 (Hastings et al., 2009), potential cumulative N_2O emissions correspond to a carbon equivalent of 16 ± 0.5 Mt C. The carbon mitigation potential of nitrogen addition to forests could thereby be reduced by around 26%.

The gradual conversion of all coniferous monocultures into mixed forests (as recently urged to accelerate by the German Forest Protection Association) offers only minor carbon mitigation potential (14 ± 7 Mt C). This is partly because conifer monocultures represent only a fraction of total forest area (Table S3). However, per-area carbon mitigation is also small (1.2 kg C/m^2) compared to most other mitigation options (Figure 7). One likely reason is that while deciduous trees are better adapted to future climate conditions, they also tend to grow slower and are less commonly used for long-lived constructions (reducing product pools and substitution effects), thereby limiting the net carbon benefit of this option and emphasizing the need to explore new ranges of application for hardwood which would also help to make mixed forests economically competitive. It should also be noted that LPJ-GUESS likely underestimates the mortality of trees, especially conifers, in a warmer climate because the response to water stress is only represented in a simplified way. The necessary implementation of plant hydraulics is current work in progress, as is the refinement of parameters for European tree species. Additionally, LPJ-GUESS does not yet explicitly account for bark beetle outbreaks or wind throws, which are instead assumed to be accounted for by the general disturbance events. On the other hand, planting species possibly better adapted to future climate conditions (e.g., Douglas fir) represents a management option not accounted for in this study.

3.5 | Conflicts with food production, biodiversity, and other constraints

It should be emphasized that a full assessment of different land management options cannot only consider theoretical carbon mitigation potentials. Importantly, land-based mitigation efforts should neither jeopardize food security (Smith et al., 2019) nor trigger indirect land-use emissions at other locations (Popp, Lakner, Harangi-Rakos, & Fari, 2014). Even under optimistic assumptions, only a fraction of the agricultural land will be available for mitigation purposes in reality. For instance, European reforestation targets via agricultural land abandonment will not be achievable without substantial crop yield increases and reductions in meat consumption (Lee et al., 2019). Some of these yield increases, however, could be driven by climate change and increasing CO_2 fertilization: crop and pasture production increase by 20.4 and 7.4%, respectively (2020–2100 average compared to the 2010–2019 period) in our baseline simulations. Assuming constant demand and management, reforestation on the combined freed-up land could thus deliver around 59 Mt C (assuming linear carbon uptake as forests grow), while *Miscanthus* plantations could mitigate 45–123 Mt C, depending on the assumed displacement factor and the availability of CCS.

Another major concern is the detrimental impact of extensive bioenergy plantations on biodiversity. While *Miscanthus* is believed to increase species richness compared to conventional crops (Teagasc and AFBI, 2011), this is likely not the case for plantations on former grasslands which have high biodiversity

(Ichii et al., 2019). For example, Hof et al. (2018) found comparable threats to biodiversity in a low and a high warming scenario because bioenergy cropland expansion in the former largely compensated for enhanced climate change impacts in the latter. Forests, both existing and newly planted ones, are usually perceived as biodiversity friendly. However, whether reforestation will have a positive impact on biodiversity depends on former land use, management intensity, and forest composition (Cunningham et al., 2015; Hua et al., 2016). For example, forest nitrogen fertilization would not only increase N_2O emissions but also exacerbate drinking water pollution and eutrophication in aquatic systems (Galloway et al., 2004).

Other ecosystem functions could also be affected. For instance, large-scale reforestation reduces surface albedo (Krause et al., 2017), thereby causing local warming in mid-high latitudes (Li et al., 2015). Additionally, financial costs of different land-use strategies need to be considered (BECCS has been estimated to be ~50% more expensive than reforestation for the same CO_2 removal; Smith et al., 2016) as well as complex land ownerships and the current legislation hindering pasture land conversions in Bavaria.

4 | CONCLUSIONS

In our study, we investigate the potential for land-based carbon mitigation on a regional scale following an innovative multi-sectoral modeling approach. We consider a range of mitigation processes ultimately ascribed to photosynthetic carbon fixation: directly via carbon storage in biomass, soils, wood products, and geologic reservoirs via bioenergy CCS (negative emissions); or indirectly when wood is used to replace energy-intensive materials or when biomass is burned for energy production (thus preventing fossil fuel emissions).

We find that Bavaria offers prospects for carbon mitigation, but the realistically achievable potential can likely offset only a few years of ongoing emissions. Our simulations reveal that all relevant components, including energy and material substitution, need to be considered to assess the efficiency of different mitigation options. Largest per-area mitigation potentials are found for reforestation or bioenergy crops on agricultural land, while the forestry sector provides limited opportunities via alternative management. Bioenergy would likely have to be combined with CCS to exceed the mitigation potential of reforestation, but its implementation in the short or medium term seems currently doubtable. Without shift in the societal perception of CCS, technological advances, and financial investments, the planting of trees likely represents the better option than the cultivation of bioenergy crops in cases where fields are no longer needed for food production. However, even assuming large-scale agricultural abandonment and high per-area carbon mitigation (e.g., via BECCS), rapid reductions in fossil fuel emissions are inevitable to achieve the Paris target.

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CONFLICT OF INTERESTS

The authors declare no competing financial interests.

AUTHOR CONTRIBUTIONS

A.K. and A.R. designed the study. A.K. conducted the simulations, led the analysis, and wrote the first draft. All authors contributed to the interpretation of the results and to the writing of the manuscript.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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