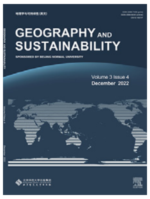
Geography and Sustainability 3 (2022) 347–357

Contents lists available at ScienceDirect

Geography and Sustainability

journal homepage: www.elsevier.com/locate/geosus



Comparing the climate change mitigation potentials of alternative land uses: Crops for biofuels or biochar vs. natural regrowth☆

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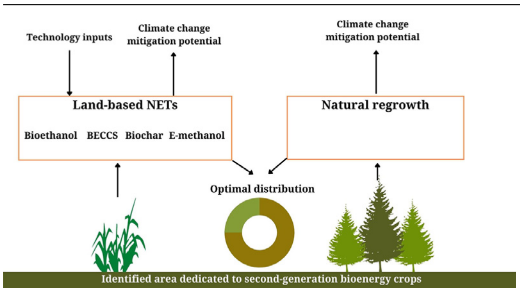
HIGHLIGHTS

- Large-scale depolyment of land-based options are needed to mitigate climate change.
- 13.80 Mha can produce 178 Mton dry biomass annually from dedicated crops.
- The climate change mitigation potentials can be up to 257 $MtCO_2$-eq. yr^{-1}.
- The largest mitigation is from bioethanol with CCS and e-methanol.
- Natural regrowth achieves higher mitigation than bioethanol without CCS.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 29 August 2022
Received in revised form 15 November 2022
Accepted 15 November 2022
Available online 18 November 2022

Keywords:
Negative emission technologies
Natural regrowth
Land management
Bioenergy systems
Carbon neutrality

ABSTRACT

Using biomass from dedicated crops for energy production and natural vegetation regrowth are key elements in future climate change mitigation scenarios. However, there are still uncertainties about the mitigation potentials that can be achieved by the different land-based systems and how they perform relative to each other. In this study, we use harmonized future land use datasets to identify global land areas dedicated to second generation bioenergy crop production in 2050 under different climate scenarios. We then assess the global climate change mitigation potentials of using biomass for producing bioethanol with (BECCS) or without carbon capture and storage, biochar, or a synthetic fuel (e-methanol). For the latter, the electricity required to produce hydrogen for e-methanol synthesis is sourced from either wind power or the projected average electricity mix in 2050. Mitigation potential from natural regrowth on the identified land is also quantified. For all the cases, we modelled emissions of greenhouse gases from the life-cycle stages and use parameterized models to estimate local biomass growth rates. The identified land areas range from 1.95 to 13.8 million hectares and can provide from 30 to 178 mega ton (Mt) dry biomass annually from dedicated crops. Climate change mitigation potentials range from 11 to 257 $MtCO_2$-eq. yr^{-1}, depending on technological option and land availability. The largest mitigation is delivered by BECCS, but e-methanol can achieve similar findings when hydrogen is sourced from wind power. If hydrogen is produced from grid electricity, e-methanol can result in net positive emissions. E-methanol can also deliver more final energy than bioethanol (4.04 vs. 1.27 EJ yr^{-1}). Natural vegetation regrowth can generally achieve higher mitigation than bioethanol, but less than biochar. An optimal combination of BECCS and natural vegetation regrowth can achieve a larger mitigation, up to 281 $MtCO_2$-eq. yr^{-1}, indicating that integrated solutions can help to achieve successful land management strategies for climate change mitigation.

☆ Given his role as Associate Editor-in-Chief of this journal, Wenwu Zhao had no involvement in the peer-review of this article and had no access to information regarding its peer-review. Full responsibility for the editorial process for this article was delegated to Carla Sofia Santos Ferreira.

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https://doi.org/10.1016/j.geosus.2022.11.004

1. Introduction

Most of the future climate change mitigation scenarios include negative emission technologies (NETs), referring to the net removal of carbon dioxide from the atmosphere (Minx et al., 2018). Bioenergy for production of biofuels or heat and power is a form of land-based NETs when it is associated with carbon capture and storage (BECCS), and it is assumed to play a key role in future scenarios consistent with a temperature stabilization at low levels due to its cost-efficiency and feasibility when compared to other NETs (Hanssen et al., 2020; Vaughan et al., 2018). Similarly, afforestation and natural vegetation regrowth are options that can deliver negative emissions (Cook-Patton et al., 2020; Doelman et al., 2020). However, large-scale mitigation potentials require biomass from dedicated biomass crops or expansion of new forest areas, which can induce land use competition with food security or nature conservation (Boysen et al., 2017; Seddon et al., 2021; Vera et al., 2022), especially under increasing trends of population growth and land-degradation (Prăvălie et al., 2021; Smith et al., 2020). Among other measures based on land use planning efficiencies (Kuang et al., 2020; Yao et al., 2022), dietary shifts towards plant-based diets and improvements in the agrifood sector have the potential to release large areas of grazing lands and croplands from food and feed production, which can be dedicated to the implementation of NETs (Bauer et al., 2020; Hayek et al., 2021; Næss et al., 2021). Deploying NETs on abandoned agricultural land can reduce its negative effects on food security and nature conservation, as it prevents the use of existing cropland or natural areas. This land has been under intensive management with usually low ecosystem service value, and the growth of both perennial grasses for BECCS or natural vegetation regrowth can improve many indicators connected to soil quality and ecosystem services (Robertson et al., 2017; Werling et al., 2014).

Bioenergy crops can be used for different renewable energy options (fuels, electricity, biochar) with the opportunity to replace fossil fuels. Bioenergy crops can grow on poorer quality land and require less water and management efforts than food-crops (Yang et al., 2018). Biomass can be fermented into bioethanol (BE), a drop-in biofuel with a relatively mature technology (Morales et al., 2021). BE produced from lignocellulosic materials typically has lower life-cycle GHG emissions than BE produced from food crops, and it can also be combined with CO_2 removal by capturing the carbon released from fermentation (Field et al., 2020). BECCS can additionally boost the climate change mitigation of BE and achieve negative emissions through permanent storage of part of the carbon sequestered during biomass growth, with estimates of global potentials up to 5 Gt CO_2-eq annually by 2100 (Roe et al., 2019). Biomass can also be used to produce biochar via pyrolysis, a stable form of carbon that can be used as soil amendment. Biochar has good resistance to decomposition, so that the carbon remains stored in the soil for decades or even centuries (Schmidt et al., 2021). Co-products from the pyrolysis process are bio-oil and syngas, which can be used for heat and power generation if the process is coupled with combined heat and power (CHP) (Tisserant et al., 2021). Biochar is considered one of the most affordable NETs for future large-scale deployment of carbon dioxide removal (CDR) from the atmosphere (Lehmann et al., 2021; Smith, 2016). Several studies taking a life-cycle assessment (LCA) perspective and a consideration of the biochar-induced soil effects generally show the positive benefits of biochar not only from a climate change mitigation perspective, but also in terms of improved yields and soil quality (Tisserant and Cherubini, 2019).

An emerging option is the possibility to transform biomass into synthetic fuels. An example is via biomass gasification into a mix of CO and CO_2 and then add hydrogen (H_2) to produce e-methanol (Hepburn et al., 2019; Ueckerdt et al., 2021). Although it is not a NET as the carbon is not stored away from the atmosphere but it is released from fuel combustion, it is considered here as it is a promising carbon capture and utilization (CCU) technology that is frequently seen as a solution to replace fossil fuels (Hepburn et al., 2019). The fuels have high energy density and are easier to handle than pure hydrogen fuels. E-methanol is a possible contributor to decarbonize sectors where electrification is challenging, such as aviation, shipping, the chemical industry, and heavy road transport. However, their climate mitigation effectiveness critically depends on the source of hydrogen (i.e., the carbon intensity of the electricity, when hydrogen is produced from electrolysis) (Ueckerdt et al., 2021).

A land-based alternative to the production of bioenergy crops is natural regrowth (NR). This option aims to a spontaneous vegetation regrowth (and hence sequestration of atmospheric carbon) on previous cropland, and it is the most common nature-based solution to simultaneously address the climate and biodiversity crises (Cook-Patton et al., 2020; Harper et al., 2017). Many national and international entities have prioritized NR of forests for carbon sequestration and improve ecosystem services in rural and urban areas, essentially because of its simplicity, affordability and promising results (Cook-Patton et al., 2020; Nolan et al., 2021; Pan et al., 2021).

In general, these alternative land-based options of climate change mitigation have been studied on an individual basis for both single projects and their large-scale potentials, but a consistent comparison of their climate benefits under given land availability constraints are missing. Such an analysis is instrumental to evaluate the geographical suitability of the different solutions and to identify the best implementation in an area and its contribution to global climate change mitigation. It will also help to bridge global environmental goals with local implementation strategies.

There are large uncertainties and variations in the estimated future available land for bioenergy crops in the literature, as it depends on several factors connected to socioeconomic developments, dietary changes and production efficiencies (Brown et al., 2021; Gomes et al., 2021). For instance, estimates of land available for bioenergy crops range from 34 to 180 Mha (Roe et al., 2019), which will result in very different outcomes in terms of climate change mitigation potentials. These predictions are inherently uncertain because they depend on future policies, economy, social and technological development (Alexander et al., 2017; Robinson et al., 2018). Harmonizing different scenarios provided by integrated assessment and climate models is a solution to offer a standard basis to different studies and secure their comparability and consistency. This is the goal of the LUHv.2 Harmonized Global Land Use database, which provides gridded maps of future land use scenarios in a framework that is consistent with the different shared socioeconomic and representative concentration pathways (SSP-RCPs) (Hurtt et al., 2020).

This study identifies the global cropland areas used for energy crops in 2050 under different SSP-RCP scenarios from the LUHv.2 dataset and quantifies the corresponding bioenergy crops yields using a site-specific database (Li et al., 2020). We then assess the life-cycle emissions, energy potentials, and climate change mitigation benefits of the use of biomass for production of bioethanol (with or without CCS), biochar, and e-methanol (where electricity for hydrogen production is sourced from either the average grid mix or from wind power) (Fig. S1). An additional case where the identified land areas for bioenergy crops are instead left to natural vegetation regrowth is considered. Background data specific to each SSP-RCP scenario are used for electricity consumption, life-cycle emissions, and estimates of land availability for bioenergy crops. Finally, the climate change mitigation potentials of these solutions are compared, both in terms of their global potentials and their performances at an individual grid level.

2. Materials and methods

2.1. Identification of land for bioenergy crops

The database used to identify cropland for bioenergy crops in 2050 is the LUH2-ISIMIP2b Harmonized Global Land Use database (LUHv.2) (Hurtt et al., 2020). This dataset includes land use projections for different SSP-RCP combinations, representative of alternative socioeconomic pathways and stringency of the climate change mitigation targets that describe plausible global developments (Riahi et al., 2017). The database uses scenarios provided by Integrated Assessment Models (IAMs), and the land dedicated to bioenergy crops is identified by the parameter "crpbf total", which is the fraction (between 0 and 1) of the total cropland area in each grid where second-generation biofuel crops are grown. IAMs are models that are used to understand how human development and societal choices affect each other and the natural world, including climate change and the land use sector (Riahi et al., 2017). The data are downloaded as global matrices at a resolution of 0.25°, but re-aggregated at a 0.50° resolution. Of the possible SSP-RCP combinations available from the dataset (see Table S1 in the Supplementary Information (SI)), the scenarios SSP1-RCP2.6, SSP4-RCP3.4, and SSP4-RCP6.0 are those with the largest areas expected to be dedicated to second-generation bioenergy crops, and thus selected for our analysis. SSP1-RCP2.6 is a sustainable development scenario where the radiative forcing by 2100 is 2.6 W/m^2, corresponding to a global average temperature increase of 1.76 °C relative to pre-industrial levels. This scenario is developed by the Integrated Model to Assess the Global Environment (IMAGE) (van Vuuren et al., 2017). SSP4-RCP3.4 is, on the other hand, described as a scenario of global inequality, where the radiative forcing by 2100 is 3.4 W/m^2 and the temperature increases to around 2.18 °C by 2100. SSP4-RCP6.0 has a less stringent climate policy and a larger expansion of global cropland than SSP4-RCP3.4, with a radiative forcing level in 2100 of 6.0 W/m^2 and a temperature increase to 3.16 °C. Both SSP4 scenarios are developed using the Global Change Assessment Model (GCAM) (Calvin et al., 2017). Table S2 in SI shows some key characteristics of the different scenarios, and Fig. S2 shows the identified land areas for the three scenarios.

2.2. Biomass yields

A bioenergy crop yields (BCY) database is used to estimate yields of perennial grasses (miscanthus and switchgrass) and short rotation coppice (eucalyptus, poplar, and willow) (Li et al., 2020). These are the most common types of second-generation bioenergy crops (e.g., non-food crops) and are the most promising in terms of potential yields, simplicity of management, and adaptability to different climates. The yields are computed under low demand for fertilizers, considerable CO_2 abatement potential, and are suited for a wide range of climatic zones. In general, eucalyptus grows in tropical and subtropical zones, while willow and poplar are better suited for temperate climates. Switchgrass thrives in temperate zones, while miscanthus is suited for multiple temperature environments and grows in tropic, sub-tropic, and subarctic regions. Feedstock characteristics are presented in Table S3.

The global BCY database is grid-specific and it has a 0.5° resolution. It is produced from expanding observed yields from field studies by a random forest model. For short rotation coppice, the yields are given as annual average. For each grid, we select the biomass type that can deliver the highest yields according to site specific climatic conditions, and compute the total biomass supply from each crop for a given SSP-RCP scenario (Table S1).

The amount of carbon sequestrated through NR is estimated using a recently produced database (Cook-Patton et al., 2020). Regrowth is here defined as the transition from less than 25% tree cover, to more than 25% cover in areas where forests have historically occurred. Based on a collection of 11,360 publications of NR studies, it estimates the above-ground carbon captured in Mg C ha^{-1} yr^{-1} without silvicultural measures. The resolution is 30 arc seconds, but the matrix is aggregated at 0.50° resolution to fit the other databases.

2.3. Life cycle assessment

All strategies except NR require activities such as cultivation, collection, drying, technological conversion, transport, and use. All these activities cause direct and indirect emissions of greenhouse gasses (GHGs) to the atmosphere, which can reduce the climate change mitigation potentials (and the magnitude of negative emissions) of the different options. Calculation of emissions from the life-cycle is based on the sum of activity emissions and are connected to the management of 1 ha of dedicated cropland (the functional unit). Fig. S1 shows a schematic overview of the life-cycle system of the land-based solutions, and Table S4 summarizes their inventory data. These foreground data are coupled with the background inventory database ecoinvent v.3.6 to capture indirect emissions (Wernet et al., 2016).

The identified cropland in the SSP-RCP scenarios is cultivated under rainfed conditions. Cultivation fuel emissions are calculated using data from Fazio and Monti (2011) and Monti et al. (2009) for miscanthus, and from Morales et al. (2015) for eucalyptus. For simplification, switchgrass is assumed to require the same inputs as miscanthus, and poplar and willow as eucalyptus. The electricity and thermal energy demand to dry the wet mass are also considered (Manouchehrinejad and Mani, 2019). The thermal energy is assumed to come from burning organic residues. The biomass is transported 400 km with 18-ton diesel trucks. In the rest of the study, all emissions from the plantation activities are indicated as "cultivation emissions".

2.4. Carbon intensity of the electricity mix

The mix of the electricity production is an important component of the total life-cycle emissions, and it changes over time. The SSP Public Database estimates the future annual global energy demand for different energy sources for electricity production (Bauer et al., 2017). This dataset is used for the estimation of the electricity mixes in 2050 (global average) that are specific for each SSP-RCP scenario, which is combined with the life-cycle emissions for each specific electricity source from the ecoinvent database (Wernet et al., 2016). This makes the global carbon intensity of the electricity mix in 2050 to be 174, 86, and 393 g CO_2-eq kWh^{-1} for SSP1-RCP2.6, SSP4-RCP3.4, and SSP4-RCP6.0, respectively. The data are shown in Supplementary Tables S5, S6, and S7.

2.5. Climate change mitigation potential of the alternative options

In this study, the climate change mitigation potential of the different options is computed as the net sum of positive and negative CO_2 emissions through the life-cycle of a technology or solution. Both CO_2 stored in geological deposits (BECCS) or soils (biochar) and avoided CO_2 emissions contribute to climate change mitigation (Fig. S1). Carbon emissions from land clearing are not considered because the identified land areas are mostly derived from former cropland as a result of progressive dietary changes and increasing efficiencies in agricultural production (Hurtt et al., 2020).

The conversion factors for the different crop species determine the BE production potential per kg of dry matter (shown in Table S8). Approximately one-third of the carbon content is converted to ethanol through fermentation (Morales et al., 2021). Plant emissions related to conversion into bioethanol are taken from previous studies (Lask et al., 2019; Morales et al., 2021), and they are mostly due to the demand for chemicals and auxiliary energy. The avoided emissions from replacing gasoline with BE are 70 Mt CO_2-eq EJ^{-1}.

BECCS concerns post-combustion capture and storage of the carbon emitted from bioenergy production. In this study, it is connected to the CO_2 emitted from the bioethanol production plant, where one third of the carbon from the dry matter (DM) is converted into BE and the rest

Table 1
Overview of identified land allocated to various bioenergy crops (higher yield per grid cell) and natural vegetation regrowth in the different future land use scenarios.

	SSP1-RCP2.6		SSP4-RCP3.4		SSP4-RCP4.6	
Bioenergy crops	Land area (Mha)	Dry mass (Mt DM)	Land area (Mha)	Dry mass (Mt DM)	Land area (Mha)	Dry mass (Mt DM)
Eucalyptus	1.02	16.9	4.26	65.4	2.40	37.1
Miscanthus	0.87	12.7	6.45	89.1	3.63	50.7
Poplar	0.014	0.10	0.13	0.9	0.11	0.80
Switchgrass	0.00	0.00	0.01	0.08	0.003	0.03
Willow	0.05	0.39	2.97	22.2	2.02	15.4
Total	1.95	30.1	13.8	178	8.17	104
Global average yield (t ha^{-1} yr^{-1})		15.4		12.9		12.7
Natural regrowth						
Total CO_2 sequestration (Mt CO_2)		13.2		86.9		107
Global average rate (tCO_2-eq ha^{-1})		9.60		10.6		22.0

goes to the capturing process (Morales et al., 2021). The carbon is stored in geological reservoirs, and, together with emission savings from gasoline replacement by BE, contributes to negative emissions (Field et al., 2020). An average capture efficiency of post-combustion is 90%, which is projected to reach 92% by 2050. This results in 60% of DM carbon in the original biomass being captured by CCS. In our analysis, the amount of carbon captured varies with the composition of the species in the different scenarios considered. The electricity demand for carbon capture is taken from Jackson and Brodal (2019).

Biochar is produced through pyrolysis of biomass. In our analysis, we assume a pyrolysis process at 500 °C with a carbon yield of co-products of 45.7% biochar, 42.6% tar (bio-oil), and 11.7% syngas (Tisserant et al., 2021). The pyrolysis is coupled with combined heat and power (CHP) production from combustion of bio-oil and syngas to recover electricity and heat at 28.5% and 71.5% efficiency, respectively, in line with standard values for steam cycle CHP plants (Sipilä, 2016). The electricity replaces grid electricity mix (with the carbon intensity specific of each SSP-RCP scenario in 2050), and the heat is assumed to replace heat from natural gas (after the amount used to cover the energy demand for the pyrolysis). The biochar is assumed to lose 30% of the stored carbon after being applied to the soil, and the rest is treated as a long-term sequestration corresponding to a negative emission. Emissions from the pyrolysis-CHP system are derived from both simulations and emission factors measured from a medium-scale pyrolyzer (Tisserant et al., 2021).

For e-methanol production, biomass is combusted to CO_2 and 92% of it is captured for production of methanol (a synthetic fuel) after reaction with hydrogen. E-methanol is produced through an exothermic process when gaseous hydrogen and CO_2 react and form liquid methanol and water (Borisut and Nuchitprasittichai, 2019). The energy required for these processes is indicated in Table S4 and is taken from Njakou Djomo et al. (2013). The energy from biomass combustion generates 1.25 kWh electricity for each kg of feedstock, which is used in the hydrogen electrolysis. The rest of the electricity for the electrolysis is assumed to be taken either by the grid (with the specific mix of sources in each SSP-RCP scenario) or by wind power (results are given for both cases). The amount of electricity required for electrolysis is taken from Valente et al. (2020). The produced e-methanol replaces gasoline.

3. Results

3.1. Land dedicated to bioenergy crops

The different future land use scenarios identify land areas in 2050 dedicated to second generation bioenergy crops of 1.9 Mha (SSP1-RCP2.6), 13.8 Mha (SSP4-RCP3.4), and 8.2 Mha (SSP4-RCP6.0) (Table 1). SSP1-RCP2.6 has the smallest land areas dedicated to bioenergy crops, while the other two scenarios generally show the same patterns in the identified land areas but differ in the fraction of land per grid cell (Fig. S2). In general, miscanthus and eucalyptus are the crops with the highest yields per grid cell. Eucalyptus is mostly favored in tropical and humid climates, while miscanthus in temperate climates. There are variations in terms of locations of the identified bioenergy cropland in future scenarios (Fig. 1). In SSP1-RCP2.6, they are mostly located in South America and sub-equatorial Africa (Fig. 1a). These places are typically highly productive, and this scenario can achieve the highest global average yields of bioenergy crops (15.4 t ha^{-1}, against 12.8 t ha^{-1} of the other two scenarios). In SSP4-RCP3.4/4.6, the bioenergy crops are more widely spread across the continents (Fig. 1c, e), where they are allocated a larger share of the land in North America, Europe, Asia, South America and Africa. The annual bioenergy crop production is 30 Mt in SSP1-RCP2.6, 178 Mt in SSP4-RCP3.4, and 104 Mt in SSP4-RCP4.6. On the same areas, natural vegetation regrowth could occur, with carbon sequestration rates varying from about 1 tC ha^{-1} yr^{-1} at high latitudes to more than 5 tC ha^{-1} yr^{-1} in the most productive areas of the tropics (Fig. 1b, d, f). In total, natural vegetation regrowth can sequester 13.2 MtCO_2 in SSP1-RCP2.6, 86.9 MtCO_2 in SSP4-RCP3.4, and 107 MtCO_2 in SSP4-RCP4.6 (Table S9). So, NR has the largest mitigation potential (and the highest global average rates per hectare) in SSP4-RCP6.0, while for bioenergy crops the most productive scenario is SSP4-RCP3.4. This happens because a large share of the land under SSP4-RCP6.0 is less suited for bioenergy production (for which yields are low), but not for natural vegetation regrowth. Some differences in land areas for the same scenario between bioenergy crops and natural vegetation regrowth are because some locations are not productive for bioenergy crops (or there are missing values in the original database).

Table 2
Average climate change mitigation potential per unit of biomass available for chosen technologies in each scenario. Units: t CO_2-eq. tonne^{-1} dry matter.

Strategy	SSP1-RCP2.6	SSP4-RCP3.4	SSP4-RCP6.0
BE	−0.36	−0.36	−0.35
BECCS	−1.41	−1.45	−1.36
Biochar	−0.82	−0.79	−0.90
E-methanol (wind power)	−1.29	−1.33	−1.20

3.2. Climate change mitigation potentials

The climate change mitigation potential in 2050 on the identified land areas for the different scenarios and land-based options are compared in Fig. 2, in terms of both normalized values per hectare (Fig. 2a) and total annual mitigation (Fig. 2b). The figure shows the breakdown of the contributions from the individual life-cycle stages. Values are expressed as annual emissions, so that negative values represent a sequestration of CO_2 from the atmosphere and positive values an emission. A summary of the global average climate change mitigation potential per unit of biomass in the different scenarios is shown in Table 2.

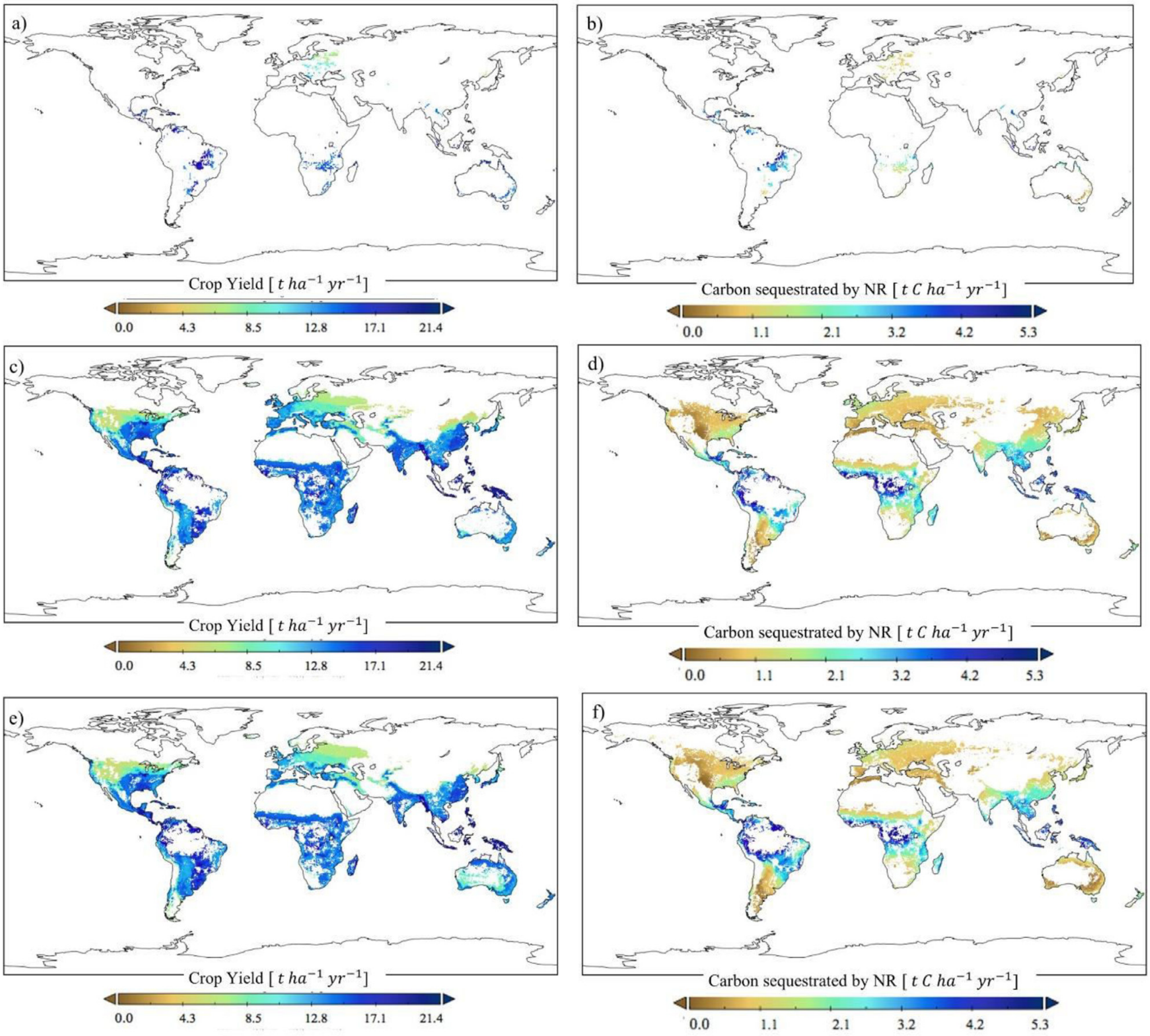

Fig. 1. Yields of bioenergy crops and annual average carbon sequestration rates by natural vegetation regrowth on land areas identified by the LUHv.2 database as those dedicated to bioenergy crops in 2050. Bioenergy crop yields and natural regrowth rates are given for scenarios SSP1-RCP2.6 (a, b), SSP4-RCP3.4 (c, d), and SSP4-RCP6.0 (e, f). Yields are given for each grid cell where the fraction of identified land is non-zero (Fig. S2).

On average, the largest climate change mitigation potential that can be achieved from one hectare of land is −22 t CO_2-eq from BECCS (bioethanol and CCS) in SSP1-RCP2.6. Life-cycle emissions from the cultivation and processing phases are largely overwhelmed by the benefits of CCS and replacement of other fossil-based energy sources (gasoline, in this case). The benefits are still large in the other scenarios, but lower, as SSP1-RCP2.6 is the one with the largest global average yields. When bioethanol is not associated with CCS, only the benefits from gasoline substitution remain and the mitigation is reduced of about one fourth. Biochar can also deliver negative emissions (between 10 and 13 t CO_2-eq. ha^{-1}), mostly thanks to the carbon stored in the soil and to a smaller extent to the replacement of electricity and heat from valorization of the co-products from pyrolysis. The latter changes with the different scenarios as the 2050 electricity mix that is replaced changes with the scenario that is considered. For example, climate benefits are relatively larger for SSP4-RCP6.0, which has a global average electricity mix with a relatively high carbon intensity, and smaller for SSP4-RCP3.4, which has the cleanest electricity mix of the ones considered thanks to the larger deployment of CCS (Tables S5–S7). Large variability is found for the mitigation options based on e-methanol, as they heavily depend on the electricity source used to produce the H_2 required in the production process. In case such electricity is taken from the grid, a mitigation of climate change is only found with the SSP4-RCP3.4 scenario, which has the most decarbonized grid. In SSP1-RCP2.6, the net emissions are around zero, and in SSP4-RCP6.0 positive (net emissions of 25 t CO_2-eq. ha^{-1}). This scenario is the one with the highest carbon intensity of the electricity mix (392 g CO_2-eq. kWh^{-1}), as it is the one with the smallest policies and ambitions to stabilize climate change at low levels. On the other hand, SSP4-RCP3.4 has a global average emission factor for the electricity that is more than 4 times smaller (86 g CO_2-eq. kWh^{-1}). Even if they are both SSP4, the stricter climate policies in line with the RCP3.4 trajectory require a decarbonization of the electricity sector. Such massive decarbonization is not needed in SSP1-RCP2.6, because in this scenario energy consumption is more reduced and more efficient, there are lower emissions from the other sectors and more negative emissions from the land sector in general. This is why this scenario has a slightly higher carbon intensity for grid electricity (174 g CO_2-eq. kWh^{-1}), despite being more ambitious in climate change mitigation. When e-methanol can rely

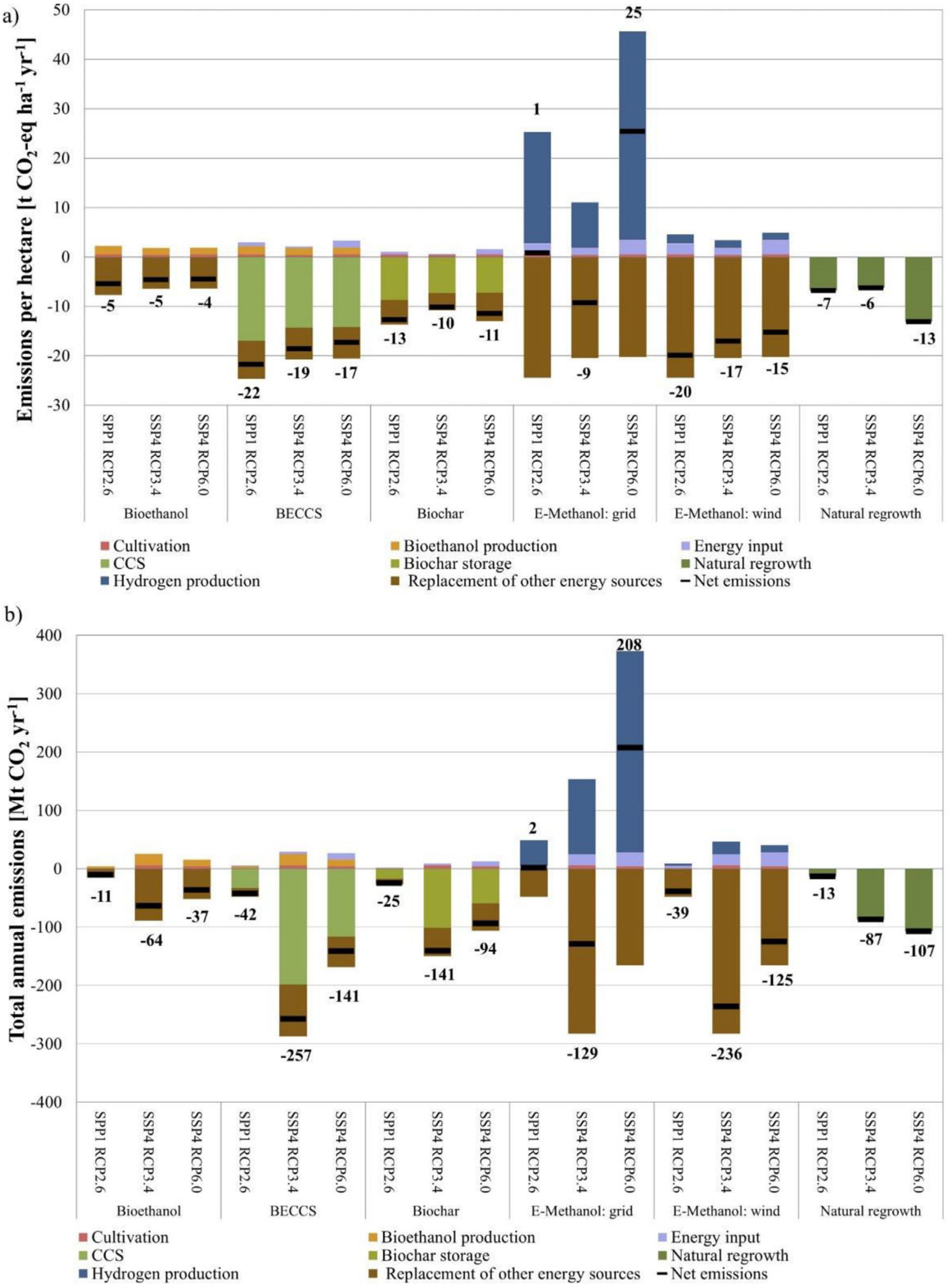

Fig. 2. Climate change mitigation potential from the different land-based options. Results are shown as annual emissions (negative values indicate carbon sequestration) averaged per unit of land (a) and total annual mitigation in each scenario (b). The number next to each bar shows the net value.

on the use of a clean electricity source (wind power) to produce H_2, the climate change mitigation performances clearly improve and become similar to those of BECCS. Natural vegetation regrowth can achieve average mitigation benefits that range from −6 to −13 t CO_2-eq. ha^{-1}, depending on the scenario considered (and hence productivity of the corresponding land areas). In general, NR offers larger mitigation than bioethanol without CCS, and is comparable with biochar systems.

The annual mitigation potential that can be achieved is sensitive to the amount of land available in the different scenarios (Fig. 2b). As the scenario with the largest land availability is SSP4-RCP3.4, the largest mitigation is achieved for BE (−64 $MtCO_2$-eq. yr^{-1}), BECCS (−254 $MtCO_2$-eq. yr^{-1}), biochar (−141 $MtCO_2$-eq. yr^{-1}), and e-methanol (between −129 and −236 $MtCO_2$-eq. yr^{-1}). For NR, land areas are located in places that are highly productive in the SSP4-RCP6.0 scenario, and

Table 3
Optimal distribution of land areas between NR and cropland for the different technological solutions in all land use scenarios.

	SSP1-RCP2.6		SSP4-RCP3.4		SSP4-RCP6.0	
	% NR	% Cropland	% NR	% Cropland	% NR	% Cropland
Bioethanol	65.99	34.01	48.89	51.11	53.66	46.34
BECCS	14.25	86.75	12.60	87.40	21.31	78.69
Biochar	30.53	69.47	25.32	74.68	38.25	61.75
E-methanol (wind)	10.45	89.55	13.95	86.05	23.71	76.29

as discussed above this is the case where the largest amount of negative emissions is achieved (−107 MtCO$_2$-eq. yr^{-1}). As a benchmark, energy related CO$_2$ emissions in 2021 are 33 Gt (IEA, 2021). Bioethanol and NR approximately have the same potential in SSP1-RCP2.6 (−11 and −13 Mt CO$_2$-eq., respectively), while NR clearly outperforms bioethanol in the other scenarios. BECCS has the most considerable climate change mitigation potential in all scenarios (−42, −257, and −141 Mt CO$_2$-eq in SSP1-RCP2.6, SSP4-RCP3.4, and SSP4-RCP6.0, respectively), and the carbon captured by CCS contributes to the largest share of the mitigation potential (up to −198 Mt CO$_2$-eq in SSP4-RCP3.4). Biochar achieves a mitigation potential higher than NR under all future scenarios, despite the contribution from energy replacement varies with the difference in grid electricity mixes.

E-methanol powered from wind is the second-best solution, after BECCS, in all scenarios (−39, −236, and −125 Mt CO$_2$-eq, in SSP1-RCP2.6, SSP4-RCP3.4, and SSP4-RCP6.0, respectively).

In terms of energy produced, the bioethanol potential ranges from 0.22 EJ yr^{-1} (SSP1-RCP2.6) to 1.27 EJ yr^{-1} (SSP4-RCP3.4), and it is dependent on the amount of biomass crops from each scenario (Supplementary Table S11). Higher final energy is delivered by e-methanol (from 0.68 to 4.04 EJ yr^{-1}). When produced from H$_2$ derived from clean electricity sources, the e-methanol pathway can produce more energy and achieve a larger climate change mitigation potential than bioethanol (but not BECCS). An energy output (electricity and heat) is also produced by the biochar system, which ranges from 0.11 to 0.63 EJ yr^{-1}. As a benchmark, today's primary bioenergy demand is around 50 EJ yr^{-1} (IEA, 2021). More details of the individual land-based options and a breakdown of the contributions to the net mitigation is shown in Tables S10–S13.

3.3. *Optimal distribution of solutions*

To maximize climate change mitigation, the optimal distribution to the identified land areas of bioenergy crops or natural vegetation regrowth can be explored for different combinations of the solutions (Fig. 3 for the SSP4-RCP3.4 scenario). The larger the mitigation potential of the technology, the smaller is the land allocated to natural re-growth. When bioenergy crops are used for production of bioethanol (without CCS), there is an approximately equal split between cropland for bioenergy crops and natural vegetation regrowth (Fig. 3a). Natural regrowth dominates in the tropics, southeast Asia and Europe, while cropland for bioenergy crops is more widespread in North America and Central Asia. When bioethanol is coupled with BECCS (Fig. 3b), bioenergy crops largely dominate over natural regrowth (87% vs. 13%). Bioenergy crops mostly gain land in temperate climates. A similar result is obtained when bioenergy crops are used for production of e-methanol where H$_2$ is produced from wind power (Fig. 3c), as this option achieves a similar mitigation potential than BECCS.

The optimal distribution of land areas between NR and the various technologies in all scenarios is shown in Table 3. There are variations in the fraction of land assigned to NR among scenarios. When compared to bioethanol, NR has the largest fraction in SSP4-RCP2.6, followed by SSP4-RCP6.0 and then SSP4-RCP3.4. This is because of the differences in yields of bioenergy crops and natural regrowth rates in the different land areas identified by the alternative future land uses. For BECCS, the amount of land where NR achieves larger potential can be up to 21% in SSP4-RCP6.0. With biochar, the land allocated to NR ranges from about 25% (SSP4-RCP3.4) to about 38% (SSP4-RCP6.0). The fractions of allocated land for e-methanol (H$_2$ from wind power) are similar to those of BECCS.

It is also possible to estimate mitigation potentials resulting from the optimal combination of land-based options (Fig. 4). As shown above, the mitigation potentials vary with the scenarios, and the same happens with the different possible combinations of options. In all scenarios, the integration of BECCS and NR can deliver the largest negative emissions, which are 10% to 15% higher than the negative emissions alone. In SSP4-RCP3.4 the combination of NR and e-methanol can achieve a mitigation potential similar to that of BECCS alone. Biochar combined with NR reaches almost the same level of mitigation potential in SSP4-RCP6.0 and SSP4-RCP3.4, mostly because of the larger potential from NR in SSP4-RCP6.0. SSP4-RCP6.0 is the scenario that benefits the most from combining technological solutions with NR. The global climate mitigation potential increases by 44% relative to BECCS only. This combination increases the potential by 2% and 9% for SSP1-RCP2.6 and SSP4-RCP3.4, respectively. The significant increase in SSP4-RCP6.0 is due to the large NR potential. By combining BECCS and NR, land-based technologies using land dedicated for second-generation bioenergy crops can mitigate up to 0.24%, 1.30%, and 0.42% of annual global emissions in Mt CO$_2$-eq for 2050 SSP1-RCP2.6, SSP4-RCP3.4 and SSP4-RCP6.0, respectively, when compared to the SSP Database estimations in the respective IAMs (Table S2). All climate change mitigation potentials of the optimal distributions are shown in Table S12.

4. Discussion

This study attempts to perform a comparison of the potentials of land-based climate change mitigation options that are fundamentally different and contrasting. We compare these options within a consistent framework, taking a land-based perspective and annual-based accounting of emissions to achieve results that are comparable across spatial and temporal scales. First, we identify common land areas from future scenarios to rely on a common basis of land availability, and then growth rates of perennial crops for bioenergy and natural re-vegetation are considered using databases that rely on local climatic conditions. The technological dimension is then simulated in detail with a transparent and reproducible approach to estimate effective climate change mitigation potentials at global level and for specific grids. Of course, the potentials estimated here are highly dependent on the land areas identified in the future scenarios, as different land availability can give different results. In general, results normalized to global average values and the maps of the optimal potentials provide an overview of the relative potentials and spatial explicit factors.

The area of dedicated bioenergy cropland from the LUHv.2 scenarios used in this study range from 1.95 to 13.80 Mha in 2050, which are rather conservative if compared with other studies. For example, a literature review estimated between 34 and 180 Mha by the end of the century (Roe et al., 2019), which obviously result in higher global potentials of BECCS than this study. This difference is, among others,

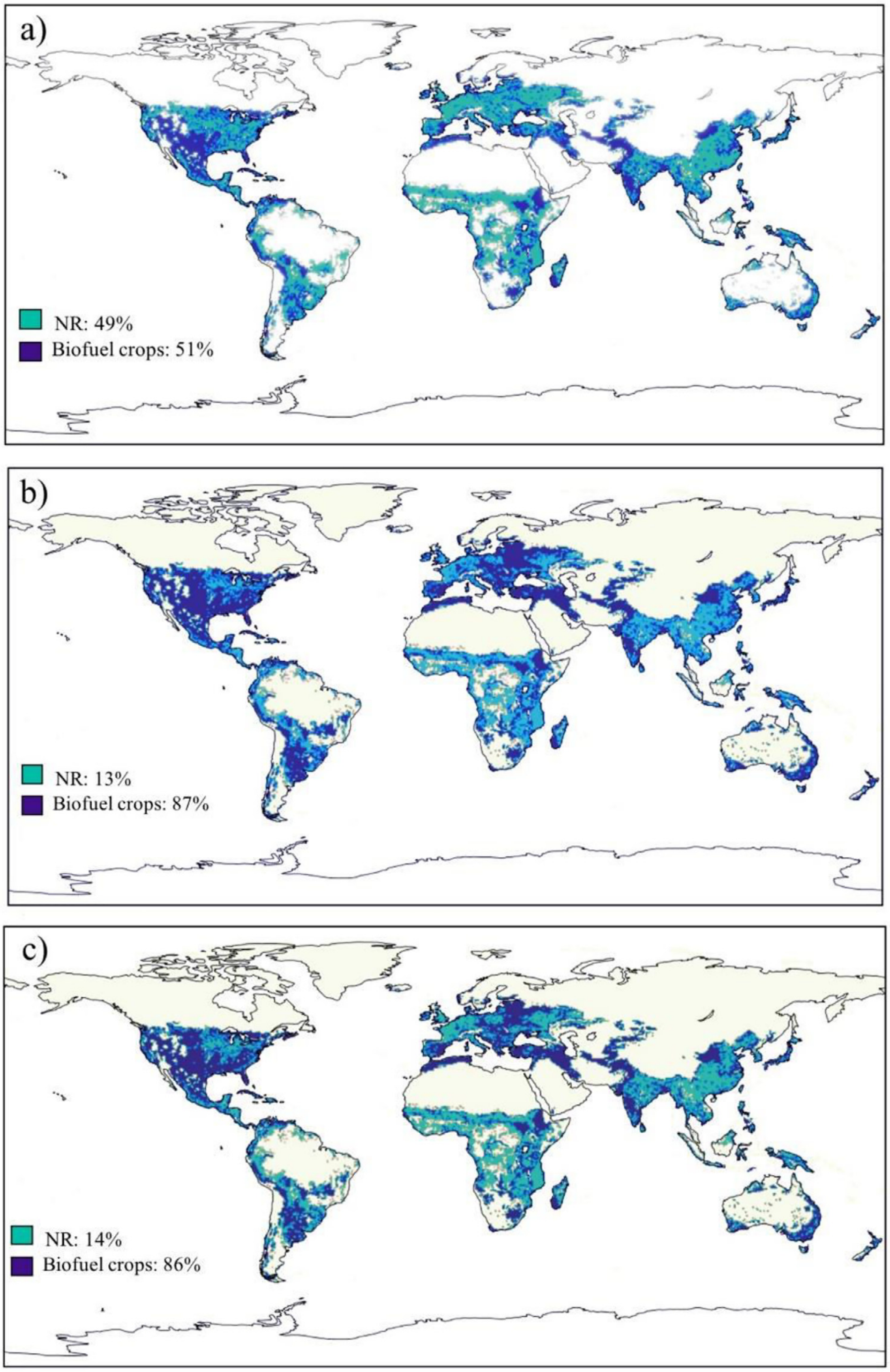

Fig. 3. Optimal spatial distribution for maximization of climate change mitigation between NR and cropland for bioenergy crops for different technologies in SSP4-RCP3.4 in 2050. The technologies are: (a) bioethanol (BE), (b) BECCS and (c) e-methanol (wind). Each grid cell is attributed to NR or the technological option on the basis of which of the two options deliver the largest mitigation potential. Note that the percentages of the different options do not represent the number of grids but the real land areas, as many of the grids only have a small percentage of identified land areas (Fig. S2).

a result of different timescales (2050 vs. 2100) and modeling assumptions of the land use systems and its future dynamics to meet a given climate target. For example, more ambitious climate targets, especially when associated with future socioeconomic pathways more dependent on energy-intensive lifestyles and production systems (such as SSP5), require a high demand of renewable energy from dedicated crops to fuel the economy and reduce use of fossil fuels (Popp et al., 2017).

This study shows that the contribution of emissions from cultivation of bioenergy crops is small compared to the total potential mitigation in all solutions. The cultivation processes emit from 31.5 to 37.95 kg CO_2-eq per ton DM, which is close to other studies estimating perennial cultivation emissions without fertilizer use, e.g., 30.18 kg CO_2-eq per ton (Krzyżaniak et al., 2020), 33.83 kg CO_2-eq per ton (Sanscartier et al., 2014), and 40 kg CO_2-eq per ton (Morales et al., 2015). Our mitigation potentials of biochar are from −10 to −12 t CO_2-eq ha^{-1}, slightly higher than the findings of a previous study (−4.59 t CO_2-eq ha^{-1}) (Tisserant et al., 2021). This difference is mainly due to the fact that in our analysis we use dedicated bioenergy crops as biochar feedstock instead of biomass residues, which have higher yields. Our estimates of average mitigation potentials from biofuels (from 4 to 5 t CO_2-eq

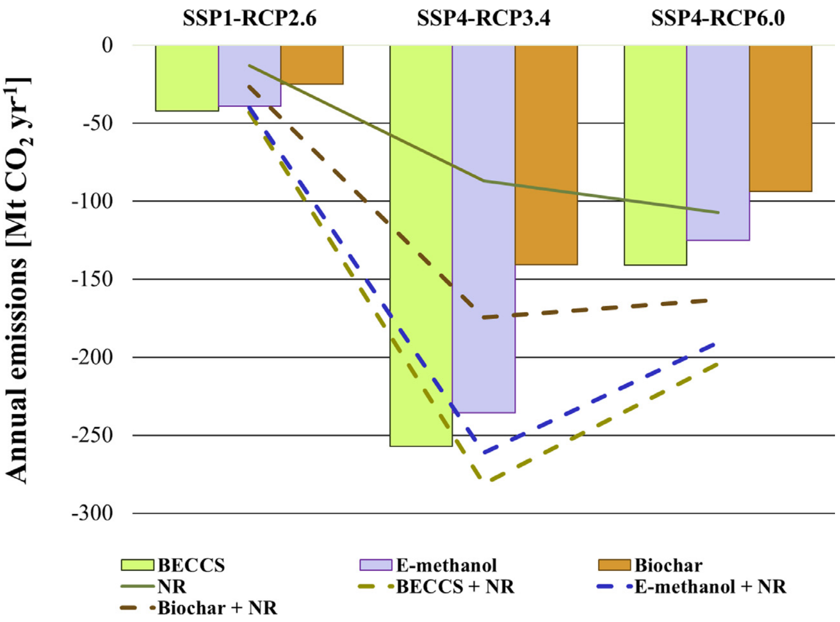

Fig. 4. Climate change mitigation potential given in Mt CO_2-eq. yr^{-1} from the individual and optimal combination between technologies: BECCS, biochar, e-methanol and NR. The bars show the climate change mitigation potential of a technology alone, while the full and dashed lines illustrate the combined potentials from integration of two options.

ha^{-1}) are consistent with those from other studies, which range from 2 to 5 t CO_2-eq. ha^{-1} (Field et al., 2020; Næss et al., 2023; Yang et al., 2018). Similarly, mitigation potentials from biofuel-based BECCS between 15 and 40 t CO_2-eq. ha^{-1} have been reported (Field et al., 2020; Hanssen et al., 2020; Næss et al., 2023), and the values found in our study are at a lower end of this range (17–22 t CO_2-eq. ha^{-1}). This is because the higher estimates of the range are achieved with technologies that maximize biofuel production and carbon capture but that are still at an immature stage. Their mitigation benefits can be quantified in the order of 15 t CO_2-eq. ha^{-1} (Field et al., 2020), which, if added to our estimates, would increase the overall mitigation potential to values close to the maximum range. Currently, there is little data available about the climate change mitigation potential of e-methanol, and a comparison with existing studies is challenging. The current literature primarily focuses on the potential cost, efficiency, and uncertainties connected to e-methanol rather than the global potential of a certain production pathway (IRENA, 2021; Ueckerdt et al., 2021).

The numerical results are heavily dependent on the uncertainties present in the original datasets used. The Scenario SSP1-RCP2.6 is developed using the IMAGE3.0 integrated assessment model. IMAGE is a model framework describing the future agriculture and energy systems, changes in future land cover, the carbon and hydrological cycle, and climate change (Doelman et al., 2018). Scenarios SSP4-RCP3.4 and SSP4-RCP6.0 are, on the other hand, developed with GCAM, coupling representations of energy, water, land, economy, and climate (Chen et al., 2020). The divergence among scenarios developed from different models for the same SSP-RCP can, in some cases, be more significant than the difference between scenarios for different SSP-RCP combinations (Alexander et al., 2017). However, this aspect does not affect the numerical results within the scenarios chosen in this study.

The biomass yield database is based on a random-forest algorithm to upscale observations of the five different species considered. This algorithm is conservative when assuming where the soil is adequate for the growth of bioenergy crops, and the yields are found to be generally lower than other estimates from parameterized yield models (Li et al., 2020; Næss et al., 2022). Further, yields are based on current climatic conditions, and future changes in temperature, precipitation, atmospheric CO_2 levels and frequency of extreme events can influence biomass productivity. A global average reduction in yields of bioenergy crops associated with future climatic conditions in 2050 is found to range between 2.5% and 7.5%, with some areas in the tropics experiencing yield losses due to unfavorable growing conditions and some areas at high latitudes showing higher yields thanks to an extension of the growing season (Næss et al., 2021). The biomass species considered in the yield database are the most common species connected to bioenergy crops, but there might be other species that are more suitable in a given location. More local specific considerations are needed when identifying the best crop to be deployed.

The natural regrowth data are based on historical data and were produced by a machine learning algorithm applied to more than 13,000 georeferenced measurements of carbon accumulation (Cook-Patton et al., 2020). These data might lose accuracy in predicting vegetation growth rates far into the future. In general, the data have been validated for a 30-year average and its use by 2050 is at the edge of this period. This is largely a negligible issue for the low climate change scenarios, but in the scenario with higher expected warming (SSP4-RCP6.0) growth rates can potentially diverge. More knowledge is required to refine estimates of growth rates of natural vegetation under future climatic conditions.

Our analysis does not consider possible soil carbon changes associated with the establishment of bioenergy crops, or following natural vegetation regrowth. Soil carbon data are highly uncertain, and robust global datasets are not currently available to support global studies. On an average global scale, carbon accumulation in soils following NR is estimated negligible or negative in most biomes, but with large confidence intervals (Cook-Patton et al., 2020; Hong et al., 2020). In general, bioenergy crops increase soil organic carbon, but at uncertain rates (Albanito et al., 2016; Don et al., 2012; Whitaker et al., 2018). So, consideration of carbon accumulation into soil can increase the climate change mitigation potential of the options that are based on bioenergy crops.

The study also used a global average electricity mix in 2050, without considering regional variations. Biomass production in places with cleaner or dirtier electricity systems can thus affect the results, especially for those cases that are highly reliant on electricity (e-methanol and, to a smaller extent, biochar). The mitigation can be also dampened by possible rebound effects connected to the additional energy produced, but this is an issue that affect all new technologies introduced in the market and it requires cross-sectoral coordinated governance for its prevention and changes in life-styles (Brockway et al., 2021).

The technologies considered in this analysis are also at different stages of development. While bioethanol and biochar are advanced and mature technologies, CCS and e-methanol are still at a pre-commercial stage and further research is needed to overcome some existing remaining technical barriers for securing their competitiveness in the market. In general, they are expected to become commercially available technologies during the 2030s (IEA, 2021), consistently with our projected negative emissions pathways for 2050.

5. Conclusions

Most future scenarios for climate change mitigation include land-based negative emission technologies. The aim of this study was to compare the most relevant land-based mitigation options that can be deployed on the cropland areas identified for second generation bioenergy crops in 2050 in three future land use scenarios. All strategies can achieve net negative emission potentials. Mitigation benefits of bioenergy are usually smaller than those of natural vegetation regrowth, which in turn are smaller than those from biochar. The introduction of BECCS makes it become the most dominant and effective NETs, but e-methanol, a relatively novel technology, can achieve similar emission reductions of BECCS when a renewable electricity source is used to produce the H_2 required in its synthesis. This is a promising outcome, as high mitigation can be achieved without the technical and socioeconomic issues connected with the long-term carbon capture and storage of BECCS. However, the successful mitigation of the e-methanol pathway has as pre-requisite a massive decarbonization of the electricity system. Overall, an optimal combination of the different land-based mitigation options can secure the achievement of the highest mitigation potentials.

Prior to this study, a proper comparison of the climate change mitigation potential of different land-based options was missing. Despite of its limitations, our work provides a common framework for the comparison and can inform about the relative performances and the best solutions for given local contexts. New studies can apply the same settings to other technologies, and expand the comparison. The analysis also sheds light on the conditions by which one option can maximize the delivery of negative emissions. A natural progression of this work is to analyze the implications for biodiversity and other ecosystem services, social impacts, water use, or other environmental aspects of these alternative land use options. This will help to identify the technology and the management practice that can be used to mitigate climate change while preventing possible environmental and social damages, and ultimately support the design of solutions that can co-deliver for multiple challenges.

Declarations of Competing Interests

The authors declare that there are no known competing financial interests or personal relationships that influenced the work reported in this paper.

Acknowledgments

X.H. and F.C. thank the support of the Norwegian Research Council through the projects Mitistress (Grant No. 286773) and BEST (Grant No. 288047), W.Z. of the National Natural Science Foundation of China (Grant No. 42271292) and State Key Laboratory of Earth Surface Processes and Resource Ecology (Grant No. 2022-ZD-08).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.geosus.2022.11.004.

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