Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

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Estimates of climate change mitigation potentials from land-based solutions in 2050

Master's thesis in Energy and Environmental Engineering
Supervisor: Francesco Cherubini
Co-supervisor: Xiangping Hu
June 2022

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Problem description

This thesis is written in the form of a scientific article, with the intention to be submitted to and hopefully accepted by the journal "Geography and Sustainability" in the Special Issue "Carbon neutrality potentials from geographical perspectives" summer 2022. For this reason, the thesis is not written in the form of a traditional master's thesis.

The background for this study is the following:

The continuing increase in emissions of fossil fuels presents a major challenge for meeting the international goal of limiting warming to 2 °C relative to the pre-industrial era, particularly if stringent climate change mitigation strategies are not introduced rapidly. The different Shared Socio- economic Pathways (SSPs) indicate that forest areas and bioenergy crops should expand around 500 – 1000 Mha by 2100. Most of this land is supposed to come from marginal land not in use for agriculture and from changes in diets that will lead to declines in the extension of cropland and pastureland. A key question that arises is how much carbon dioxide can be sequestered by planting new forests or bioenergy crops. Different locations will have a different land-based mitigation benefits. Robust and informed land management planning is essential to identify the most relevant areas where negative emissions are the largest.

Anticipating where future changes in land cover may occur requires mapping of land that will be available. This is inherently uncertain, but the possibility to use harmonized future land cover projections allows to use consistent data across the studies. This project work will review areas of bioenergy crops in future land use scenarios from SSP-RCP combinations and estimate yields of the most important bioenergy crop types. Climate change mitigation potentials and estimates of negative emissions from production of biofuels coupled with CCS, e-fuels and biochar will be explored, quantified, and compared to each other and natural regrowth. The project will integrate knowledge of industrial ecology and environmental science, work with spatially explicit and large datasets, and explore solutions to real-world problems.

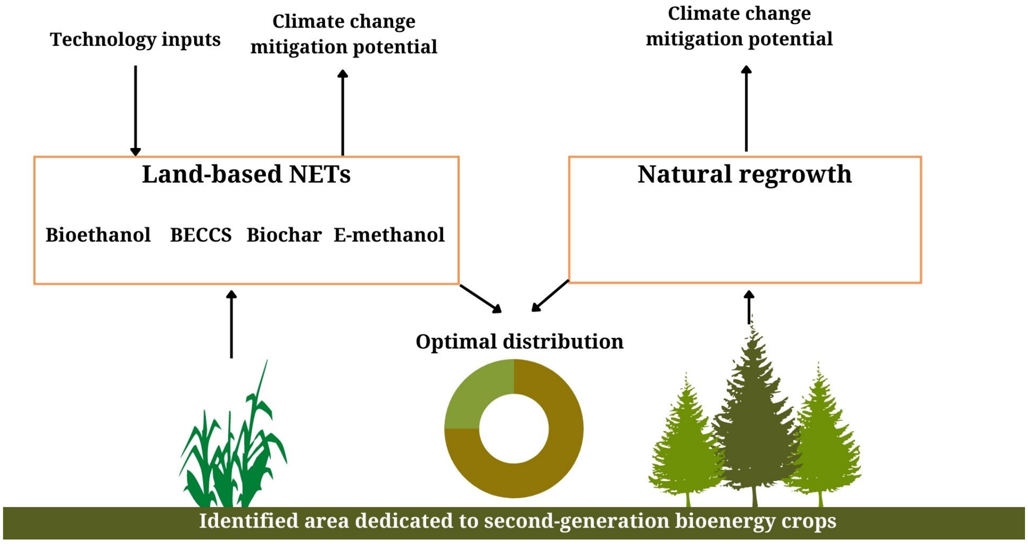
Highlights

- Cropland for second-generation bioenergy in three 2050 scenarios is identified.
- The scenarios offer different amounts of area, biomass, and mitigation potential.
- BECCS is the most promising technology, followed by e-methanol using wind power.
- For optimal climate change mitigation, natural regrowth is combined with BECCS.
- Management of this cropland can mitigate 1.3 percent of global emissions in 2050.

Abstract

Identifying cropland dedicated to energy crops and estimating the potential given by the management of these, is essential for developing climate change mitigation strategies. This study is a continuation of the project work carried out fall 2021 and provides a scenario analysis of the dedicated land in 2050, using databases to identify the area and potential yield in three scenarios. The identified area ranges from 1.95 to 13.80 Mega hectares and can provide from 30.10 to 178.00 Mega ton dry mass annually. From the yield and area available, this study evaluates natural regrowth and the possibility of using second-generation energy crops for bioethanol, bioenergy with carbon capture and storage (BECCS), biochar with combined heat and power, and e-methanol. All solutions are shown to reach net negative emissions in at least one scenario; however, the life cycle performance of some technologies, especially e-methanol, strongly depends on the emissions from the energy source. The most significant climate change mitigation potential of -257 Mt CO_2-eq yr^{-1} is reached using BECCS in scenario SSP4-RCP3.4. Due to spatial differences in natural regrowth potential and crop yield, optimal management comes from combining BECCS with natural regrowth in all scenarios, which reaches -281 Mt CO_2-eq yr^{-1} in SSP4-RCP3.4. Dependent on the scenario, this combination can remove between 0.23 and 1.3 percent of the global anthropogenic emissions in 2050. Despite some limitations from dependency on the databases and the simplification of using global average values of energy supply emissions, this study shows the importance of choosing the right management option for the cropland dedicated to second-generation bioenergy crops in the future. It also lies a foundation that enables comparison of the technologies and strategies on the same premises, eliminating barriers in previous literature. This can contribute to more robust and informed land management in the future.

Graphical abstract



Key words: Negative emission technologies; Natural regrowth; Land management; Bioenergy systems; Carbon neutrality

Norwegian summary

Identifisering av land dedikert til avlinger for bioenergi og en estimering av biomassens potensiale for forhindring av klimaendringer er nødvendig for å utvikle strategier for å dempe den globale oppvarmingen. Denne studien er en scenarioanalyse av de dedikerte områdene i 2050 ved hjelp av databaser for å identifisere arealet og vekstutbytte. Det identifiserte området er mellom 1.95 og 13.80 Mha og kan gi mellom 30.10 og 178.00 Mt tørr biomasse årlig. De evaluerte mulighetene i denne studien er naturlig gjenvekst og muligheten for å bruke biomassen til bioetanol, bioenergi med karbonfangst og lagring (BECCS), biokull kombinert med CHP og e-methanol. Alle strategiene viser seg å ha et negativt utslippspotensiale i minst ett scenario, men de totale livssyklus utslippene er sterkt avhengig av utslippene som følger av energibehovet til prosessene. Det største potensialet får man ved å bruke BECCS i scenario SSP4-RCP3.4 på -257 Mt CO_2 yr^{-1}. På grunn av geografiske forskjeller i potensiale for avlinger og naturlig gjenvekst, vil den optimale fordelingen mellom BECCS og naturlig gjenvekst føre til et potensiale av -281 Mt CO_2 yr^{-1} in SSP4-RCP3.4. Avhengig av scenario kan denne kombinasjonen føre til et utslippsredusjojnspotentiale på mellom 0.23 og 1.3 prosent av de globale utslippene i 2050. Denne studien viser viktigheten av å velge den riktige strategiene for å utnytte de begrensede landområdene i fremtiden. Den legger også et sammenlikningsgrunnlag for de teknologiske løsningene ved å legge de samme premissene for alle strategier. Den fjerner dermed barrierer fra den eksisterende litteraturen og bidrar til muligheten for robust og informert ressursforvaltning.

Preface

This thesis is the conclusion of my MSc in Energy and Environmental analysis, carried out at the Department of Energy and Process Engineering, at the Norwegian University of Science and Technology. It is written in the form of a scientific article, with the intention to be submitted and hopefully accepted in the "Geography and Sustainability" journal in the Special Issue "Carbon neutrality potentials from geographical perspectives" the summer 2022. It is a continuation of the project work carried out fall 2021.

I would like to express gratitude towards my supervisor Prof. Francesco Cherubini for excellent guidance the last year. Also, a special thanks to my co-supervisor Xiangping Hu for contributions, good advice and discussions during this period. I would also like to thank Otávio Cavalett and Marcos Djun Barbosa Watanabe for their help, collecting data in Ecoinvent and providing other inventory data.

And for my boyfriend. Thank you for all the patience, advises and support during this period. I would also like to thank all my classmates at Energi og Miljø for making this 5-year period social and fun as well as educational.

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Nomenclature

Units	
CO_2-eq	carbon dioxide equivalents
ha	hectares
kWh	kilo Watt hours
J	joules
t	metric ton
E	Exa $= 10^{18}$
Abbreviations	
BCY	Bioenergy Crop Yields
BE	Bioethanol
BECCS	Bioenergy with carbon capture and storage
CCS	Carbon Capture and Storage
CHP	Combined heat and power
DM	Dry mass
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
LC	Life cycle
NET	Negative Emissions Technology
NG	Natural Gas
NR	Natural Regrowth
RCP	Representative concentration pathway
SSP	Shared socioeconomic pathway

Table 1: Nomenclature

1 Introduction

Most future climate change mitigation scenarios include negative emission technologies (NETs), referring to the net removal of carbon dioxide from the atmosphere (Dooley et al. 2018). Particularly, land-based NETs, where bioenergy is used as, for instance, biofuel, generation of heat and power, or carbon capture and storage, are assumed to play essential roles in global climate change mitigation due to their cost-efficiency and feasibility (Shukla et al. 2019; Dooley et al. 2018). Previous research has established that bioethanol (BE), bioenergy with carbon capture and storage (BECCS), and biochar coupled with combined heat and power (CHP) can have significant climate change mitigation potential (Shukla et al. 2019, Roe et al. 2019; Tisserant et al. 2019). More recent studies have also examined the potential of hydrocarbon fuels such as e-methanol to be a promising technology (Ueckerdt et al. 2021; IRENA et al. 2021). However, large-scale land use can compromise food security by reducing the availability of land suited for food production, generating social impacts. This is an increasing problem as the population grows and land-degradation expands (Sims et al. 2010). Ecological impacts from land degradation and increased resource use is also a related problem. Land use often lead to biodiversity loss, which is a critical global issue already, with species extinction rates at 100-1000 times the natural rate. It also leads to perturbation of the nitrogen cycle, which is close to exceeding the planetary boundary (Rockstrøm et al. 2009). Wise management of areas is, therefore, necessary to secure efficient use of resources and with as little environmental and social impact as possible. Required information for informed land management is among others, an estimation of the global life cycle (LC) emissions related to the strategies and their feedstock and land use efficiency.

Biomass can be fermented into BE, with the opportunity to replace fossil fuels. This is part of most climate stabilization scenarios because it requires few changes in technology and is relatively affordable. The production of BE is well understood and widely commercialized, using mostly food-crops such as corn and sugarcane as feedstock, which compromises with food (Shukla et al. 2019). Deng et al. 2015 estimate the global biofuel potential in 2070 to reach from 40 to 190 EJ of final energy, where 75% comes from more sustainable energy crops. The BE can also be combined with carbon dioxide removal, which removes the unused carbon from fermentation (Field et al. 2020; Roe et al. 2019). BECCS is a widely-recognized technology for climate change mitigation, but is yet to be built in large-scale units because of financial, social, political, and ecological challenges (Gustafsson et al. 2021). In AR5, the IPCC was concerned about the challenges and risks related to the upstream activities of BECCS as well as implications regarding CCS technology (Masson-Delmotte et al. 2021). Using different feedstocks, Roe et al. 2019 estimate a global potential at 1.1 Gt CO_2-eq annually for BECCS.

Carbon can also be stored in biochar, used for soil amendment, a product of incomplete biomass combustion. The product has good resistance to decomposition, which keeps much of the carbon stored in the soil for decades or even centuries (Olsson et al. 2019). Co-products from the pyrolysis are tar and syngas, which can be used for heat and power generation if the process is coupled with a CHP (Tisserant et al. 2019). Biochar is considered one of the most affordable NETs for future large-scale deployment of CDR (Tisserant et al. 2021). Matuštík et al. 2020 review assessment studies of the environmental impact of biochar, concluding that biochar brings significant benefits in a GHG perspective. The sequestrated carbon will usually overcompensate the GHG emissions related to the production and handling of the feedstock (Matuštík et al. 2020). Tisserant et al. 2021 estimate that biochar with CHP from Norwegian forest residues results in -4.59 t CO_2-eq ha^{-1} annually.

Organic feedstock can be transformed into fuels in several ways, one method is synthesizing hydrogen and captured CO_2 into e-methanol (Ueckerdt et al. 2021). The fuels have high energy density and are easier to handle than pure hydrogen fuels. E-methanol is therefore considered a possible contributor to decarbonizing 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 carbon intensity of the input electricity and the source of CO_2 (Ueckerdt et al. 2021).

A land-based alternative to NETs, with little energy demand, is natural regrowth (NR). This is purposely restoring forest cover, eliminating obstacles for regrowth, but otherwise with low management efforts. Many national and international institutions have prioritized NR of forests for carbon sequestration because of the simplicity and affordability, with promising results (Cook-Patton et al. 2020). Although many studies have assessed the LC emissions of these solutions, there is a lack of studies quantifying and comparing their potentials at a global scale, based on the same premises. This is necessary for evaluating the geographical appropriateness of the different solutions and to identify the best solution for an area to contribute to the most significant global climate change mitigation.

Attention to disadvantages related to using food crops for energy has stimulated the interest in alternative feedstocks (Sims et al. 2010). Various studies indicate that lignocellulosic feedstocks, including energy crops, such as short rotation forests and purpose-grown vegetation, have considerable deployment potential (Shukla et al. 2019; Eisentraut 2010; Sims et al. 2010). Energy crops can grow on poorer quality land and require less water and management efforts than food-crops. Studies have shown that, for instance, BE produced from lignocellulosic materials typically has lower LC GHG emissions than BE produced from food crops, in addition to other sustainability benefits (Su et al. 2020).

Despite the benefits related to energy crops, it still requires land for cultivation, which is a limited resource. In studies estimating the potential of land-based NETs, land availability is therefore often considered a limiting factor for bioenergy and climate change mitigation potential (Tisserant et al. 2019; Shukla et al. 2019). There are large uncertainties and variations in the estimated future available cropland in the literature (Li et al. 2020; Chini et al. 2020). For instance, Roe et al. 2019 estimate 34-180 Mha of land available for bioenergy cropland, which will result in very different amounts of global mitigation potential, while Næss et al. 2021 estimate 83 Mha of abandoned cropland available for second-generation bioenergy crops. Such estimations are challenging because of different assumptions and uncertainties in future policies, economy, social- and technological development (Eitelberg et al. 2015), as well as types of areas included in the consideration. Harmonizing different scenarios provided by integrated assessment- and climate models might be a solution. This is done in the LUH2-ISIMIP2b Harmonized Global Land Use database, which provides the land availability in different shared socioeconomic- and representative concentration pathways (SSP-RCPs).

This study aims to create a common ground where the global cropland used for energy crops in 2050 is identified. Further, the goal is to quantify this area's collectible climate change mitigation potential through different land-based solutions. The databases LUH2-ISIMIP2b Harmonized Global Land Use for the Years 2015-2100 from Chini et al. 2020 and the Bioenergy Crops Yields (BCY) database from Li 2019 were used to identify the land areas dedicated for second-generation bioenergy cropland in three different 2050 scenarios. Further, the LC emissions for each technology at a global scale were quantified, considering the available land, the area used, and global grid emissions. Finally, the solutions were compared, and the optimal distribution between the technologies and NR was found.

2 Methods

2.1 Identification of land for bioenergy crops and natural regrowth.

Two databases are utilized to access the data required to identify cropland for bioenergy crops in 2050. [1] The LUH2-ISIMIP2b Harmonized Global Land Use database (LUHv.2) for the Years 2015-2100 from Chini et al. 2020 is chosen because of the access to SSP-RCP combinations derived from the LUH2 methodology. The database uses scenarios provided by REMIND-MAgPIE from Integrated Assessment Models (IAMs). The SSP-RCP combinations describe plausible global developments that lead to different projections of the future, which contain broad uncertainty (Riahi et al. 2017). The data is downloaded in matrices in the form of 0.25x0.25 degree gridded global maps (Chini et al. 2020), but is aggregated into 0.50x0.50 degrees. In this study, the parameter used is the **"crpbf total"**, the fraction of total cropland area grown as second-generation biofuel crops in 2050 between 0 and 1.

This study will investigate management potentials in the scenarios SSP1-RCP2.6, SSP4-RCP3.4, and SSP4-RCP6.0, where large areas will be dedicated to second-generation bioenergy as seen in Table S.1 (Chini et al. 2020). SSP1-RCP2.6 is a sustainable development scenario where the radiative forcing declines to 2.6 W/m2 and temperature increases to 1.76°C in 2100, relating to the 1850 levels. This scenario is developed by the IMAGE model. SSP4-RCP3.4 is, on the other hand, described as a scenario of inequality, where the radiative forcing declines by 3.4 W/m2 and temperature increases to around 2.18 °C in 2100 (Riahi et al. 2017; Shukla et al. 2019). SSP4-RCP6.0 has a less stringent climate policy than SSP4-RCP3.4, and there is a larger expansion of global cropland, the radiative forcing declines to 6.0 W/m2 and temperature increases to 3.16 °C in 2100. Both SSP4 scenarios are developed using the GCAM model. Table S.2 in the Supplementary presents some characteristics of the different scenarios.

The Bioenergy Crops Yields (BCY) database from Li 2019 provides information about bioenergy crop yields and the best crop species composition generated by a random forest model in matrices in the form of 0.50x0.50 degrees gridded global maps (Li 2019). The five species are Eucalyptus, Miscanthus, Poplar, Switchgrass, and Willow. This study uses the parameters: **"Best Crop Type"**, which tells which species of the five are the best fit for the chosen region based on climatic and soil conditions, and **"Yields for Best Crop"**, which tells how many tons of DM are available from one hectare (Li 2019).

The amount of carbon sequestrated through NR is estimated using the database from Cook-Patton et al. 2020. Regrowth is here defined as the transition from less than 25%

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[1] The two databases were used to identify the bioenergy cropland in this fall's project work (Løvenskiold n.d.) as well, the sections might therefore contain similarities.

tree cover, to more than 25% cover in areas where forests historically has 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 civil-cultural measures but with the removal of disturbances from 2020 to 2050. The resolution is at 30 arc seconds, but the matrix is aggregated into 0.50x0.50 degrees to fit the other databases.

The collected data are treated in matrices. The grid cells in "crpbf_total" are multiplied with the respective grid cells in the "Yields for Best Crop" forming a global map. The result is the available biomass for bioenergy yield per hectare each year in each grid cell [t DM ha^{-1} yr^{-1}]. The same method is used for the Natural Regrowth data set, where the potential tons of carbon sequestrated by NR at each location in each scenario is presented in [t C ha^{-1} yr^{-1}].

2.2 Life cycle inventory

All strategies except NR require cropland activities such as cultivation, collection, drying, and transport. Calculation of emissions from the LC of the solutions is based on the sum of activity emissions and results in an estimate of the **total climate change mitigation potential** and the mitigating **potential of 1 ha dedicated cropland** from the strategy in the chosen scenario. The chosen scenario determines the available land area and the carbon intensity of the LC of the used energy sources. In Supplementary, Figure S.1 provides an overview of the system, and Table S.3 summarizes the inventory data for all technologies.

2.3 Carbon intensity of the electricity mix

The SSP Public Database estimates the annual global energy demand for different energy sources for electricity production (Bauer et al. 2017). Together with LC emissions data from Ecoinvent, the carbon intensity of the electricity mix is calculated. The global carbon intensity of the electricity grid in 2050 is estimated to be 173.9, 85.6, and 392.7 g CO_2-eq kWh^{-1} for SSP1-RCP2.6, SSP4-RCP3.4, and SSP4-RCP6.0 respectively. The calculations are presented in Supplementary Tables S.4, S.5, and S.6.

2.4 Cultivation

The cropland identified in the data sets is assumed to be ready for cultivation; there are therefore no changes in soil organic carbon. Further, the crops are rainfed, and no fertilizer is used during cultivation (Chini et al. 2020, Li et al. 2020). Therefore, the emissions in this life stage are from fuel for cultivation, energy for drying, and fuel for transportation.

Cultivation fuel emissions are calculated using data from Fazio et al. 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 amount of energy as Miscanthus, and Poplar and Willow require the same as Eucalyptus. The electricity and thermal energy demand to dry the wet mass are taken from Manouchehrinejad et al. 2019. The thermal energy is assumed to come from burning organic residues and is therefore considered zero-emission. The DM is transported 400 km during the LC with 18-ton HGV diesel trucks. Table S.3 in the Supplementary presents the cultivation inventory data. In the rest of this study, all emissions from the plantation activities have the collective designation "cultivation emissions".

2.5 Feedstock characteristics

The BCY data set contains information about five perennial species, three fast-growing trees, Eucalyptus, Poplar, and Willow, and two grasses, Miscanthus, and Switchgrass. All have low demand for fertilizer, considerable CO_2 abatement potential, and are suited for a wide range of climatic zones (Li et al. 2020). Eucalyptus grows in tropical and subtropical zones (Lewandowski et al. 2006), while Willow and Poplar are better suited for temperate climates (Meyer et al. 2021). Switchgrass thrives in temperate zones, while Miscanthus is suited for multiple temperature environments and grows in tropic, sub-tropic, and sub-arctic regions (Lewandowski et al. 2006). Almost half of the weight (%wt) consists of carbon in all species, ranging from 46% to 49.80%. This project work does not consider the rotation periods, despite that this might vary, this is because the BCY database quantifies annual yields. Feedstock characteristics are presented in Supplementary in Table S.7.

2.6 Bioethanol

The conversion factors for the different crop species determine the BE energy extractable per kg DM and are presented in Table S.7. The amount of emissions related to conversion into bioethanol is taken from Lask et al. 2019 and Morales et al. 2021 and is a result of used chemicals and energy demand in the conversion. Approximately one-third of the carbon content in the DM is converted to ethanol through fermentation (Morales et al. 2021). The avoided emissions from replacing gasoline with BE are estimated to be 70 Mt CO_2-eq EJ^{-1} final energy (Chum et al. 2011)

2.7 BECCS

BECCS uses post-combustion CCS to capture the carbon emitted from bioenergy production (Field et al. 2020), in this study, after bioethanol production. The result is negative emissions because of gasoline replacement by BE and additional negative emissions from carbon capture (Field et al. 2020). One-third of the carbon from the DM is converted into BE; the rest goes to the capturing process (Morales et al. 2021). The capture efficiency of state-of-the-art post-combustion CCS is 90% (Teir et al. 2010), assumed to reach 92% by 2050 in this study. This results in 60% of the DM carbon being captured by CCS. The amount of carbon sequestrated from DM is determined by the composition of the species in the scenario. The electricity demand for capturing is taken from Jackson et al. 2019. Table S.3 in the Supplementary presents the relevant characteristics of the BECCS plant considered in this study.

2.8 Biochar

Biochar is produced through pyrolysis of DM at 500 °C, where the products have a carbon yield of 45.70% (biochar), 42.60% (tar), and 11.70% (syngas) (Tisserant et al. 2021). The pyrolysis is coupled with combined heat and power (CHP) production. This study uses Aspen Plus-derived emissions from the pyrolysis-CHP system combined with emission factors measured from a medium-scale pyrolyzer by Sørmo et al. 2020. While the biochar is a solid material used for fertilizing the soil, the tar and syngas are burned to recover electricity and heat at 28.5% and 71.5% efficiency, respectively, in line with standard values for steam cycle CHP (Sipilä 2016). The electricity replaces grid electricity, and the heat is assumed to replace heat from natural gas, which among others, covers the energy demand for the pyrolysis. The biochar is assumed to lose 30% of the stored carbon after being applied to the soil (Matuštík et al. 2020). This study leaves out the effect biochar application has on the soil. Table S.3 in the Supplementary presents all Inventory data.

2.9 E-methanol

The DM goes through combustion, where 95% of the carbon is assumed to be released into the air (Lanzerstorfer 2019). Further, 92% of the released carbon is captured by post-combustion CCS. The energy required for these processes is presented in Table S.3 in Supplementary and is taken from Djomo et al. 2013. From combustion, the energy released generates 1.25 kWh electricity for each kg of feedstock, which is used in the hydrogen electrolysis. The amount of carbon captured determines the possible amount of e-methanol produced. The electrolysis is powered by either the grid or wind power together with the generated electricity. The amount of energy required for electrolysis is taken from Valente et al. 2020. E-methanol is produced through an exothermic process when gaseous hydrogen and CO_2 react and form liquid methanol and water (Borisut et al. 2019). The produced e-methanol replaces gasoline, reducing the emissions with 70 Mt CO_2-eq per EJ gasoline replaced (Morales et al. 2021).

2.10 Natural regrowth

NR is defined as spontaneous recovery (from less than 25% of tree-cover to more than 25%) of forest and savanna biomes (Cook-Patton et al. 2020). Although potential disturbances are removed, this study excludes emissions from the management of the forests. Carbon sequestrated from NR is measured in annual tons of carbon captured per hectare by above-ground biomass through photosynthesis. The data is based on the Cook-Patton et al. 2020 database, which is an estimation of NR from 2020 to 2050.

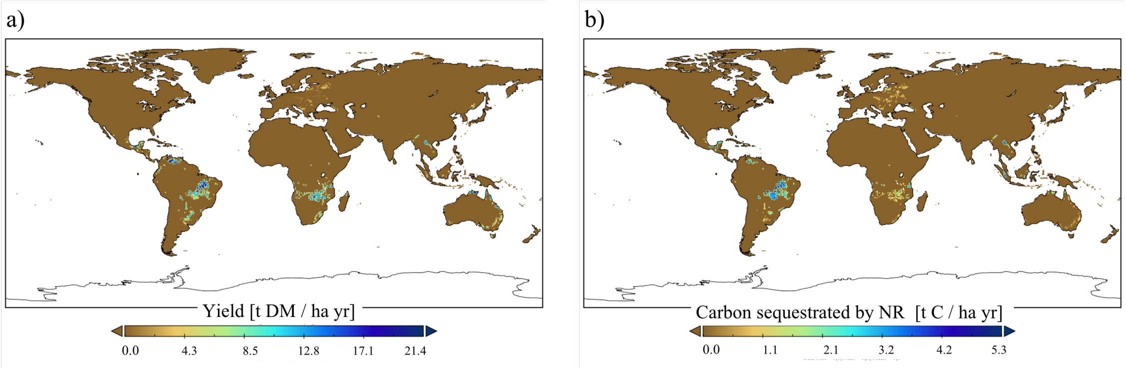
2.11 Climate change mitigation potential

In this study, the term "climate change mitigation potential"is defined as the net sum of positive and negative CO_2 emissions through the LC of a technology or solution. Negative emissions include both captured and avoided CO_2 emissions. Avoidance of emissions and capturing CO_2 are different processes, however, they both contribute to climate change mitigation. It is therefore sufficient to collect them in the same category in this study. In this study, emissions from biomass and biofuel combustion are considered zero, because of the short rotation period, and the CO_2 released during combustion is considered the same as the CO_2 captured in the crops. All LC emissions depend on the inventory data presented in Supplementary in Table S.3 and the amount of DM available, and the carbon intensity of the electricity mix in each scenario.

3 Results

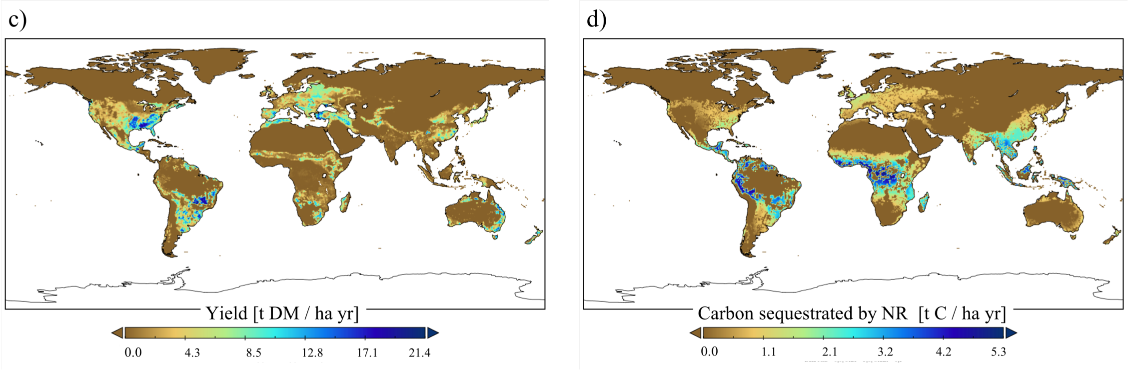
3.1 Identification of dedicated land

Figure 1 is the product of harmonizing the four parameters taken from the databases to identify the cropland and illustrate it in the three three different scenarios. In the Supplementary, information and visuals of the four parameters are presented in Figures S.2, S.3, S.4, and S.5 and Table S.8.



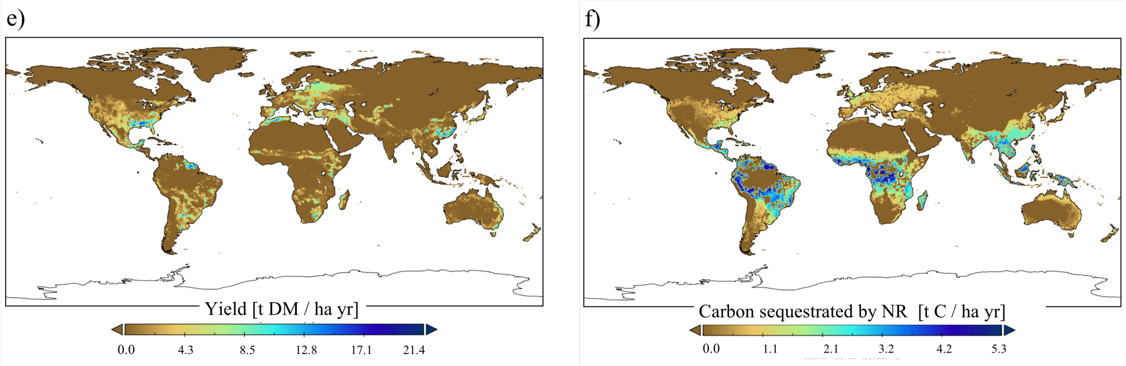
(a) SSP1-RCP2.6 Bioenergy crop yields.

(b) SSP1-RCP2.6 Natural Regrowth.



(c) SSP4-RCP3.4 Bioenergy crop yields

(d) SSP4-RCP3.4 Natural Regrowth



(e) SSP4-RCP6.0 Bioenergy crop yields

(f) SSP4-RCP6.0 Natural Regrowth

Figure 1: Harmonization of the three databases. Shows the graphics of the areas and yields for second-generation bioenergy crops [t DM / ha yr] and the NR potential [t C / ha yr] at the same locations. (a) SSP1-RCP2.6 Bioenergy crop yields. (b) SSP1-RCP2.6 NR. c) SSP4-RCP3.4 Bioenergy crop yields (d) SSP4-RCP3.4 NR (e) SSP4-RCP6.0 Bioenergy crop yields (f) SSP4-RCP6.0 NR.

Figures 1a and 1b illustrate that most of the crops grown in SSP1-RCP2.6 are located in South America and Africa, at locations where the NR potential is relatively low. What stands out from Figure 1a is that although the cropland extension in SSP1-RCP2.6 is small, the yield is high at the used land. The bioenergy crops are more evenly distributed among the continents in SSP4-RCP3.4 and SSP4-RCP6.0, where a larger share of the crops are grown in North America, Europe, and Asia as well as South America and Africa. In these scenarios, a large area share has a lower yield and larger natural regrowth potential (Figures 1c, 1d and 1f). In SSP4-RCP6.0, NR generally has a large potential; also, in the areas where the yields are low (Figure 1e and 1f). In all scenarios, NR has the most significant carbon sequestration potential in South America and Central Africa (Figures 1b, 1d, and 1f). These results can indicate that the cropland in SSP1-RCP2.6 is more informed chosen than in the other two. From the data behind Figure 1, the amount of DM, area, and carbon sequestrated is quantified and presented in Table 2.

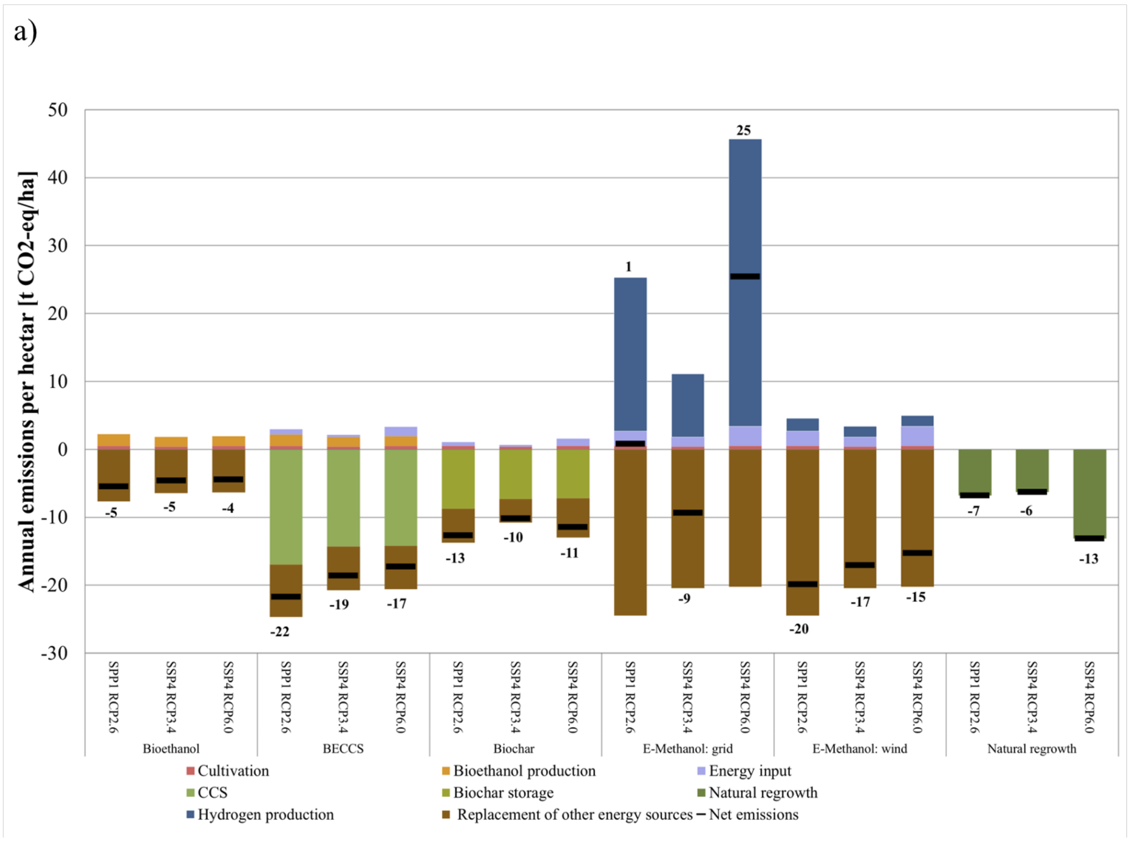
Table 2: Quantification of the global available dry mass and area. The annual amount of DM available [Mt], area use [Mha], and natural regrowth potential [Mt CO_2-eq] in each scenario as a result of combining the four parameters.

	SSP1-RCP2.6		SSP4-RCP3.4		SSP4-RCP6.0	
	Mt DM	**Mha**	**Mt DM**	**Mha**	**Mt DM**	**Mha**
Eucalyptus	16.90	1.02	65.40	4.26	37.10	2.40
Miscanthus	12.70	0.87	89.10	6.45	50.70	3.63
Poplar	0.10	0.014	0.90	0.13	0.80	0.11
Switchgrass	0.00	0.00	0.08	0.01	0.03	0.003
Willow	0.39	0.05	22.20	2.97	15.40	2.02
Total	30.10	1.95	178.00	13.80	104.00	8.17
Global average density [t/ha]	15.40		12.90		12.70	
	Mt CO_2	**Mha**	**Mt CO_2**	**Mha**	**Mt CO_2**	**Mha**
Total Natural regrowth	13.24	1.38	86.88	8.22	107.34	4.86
Global average NR [t CO_2-eq /ha]	9.60		10.56		22.05	

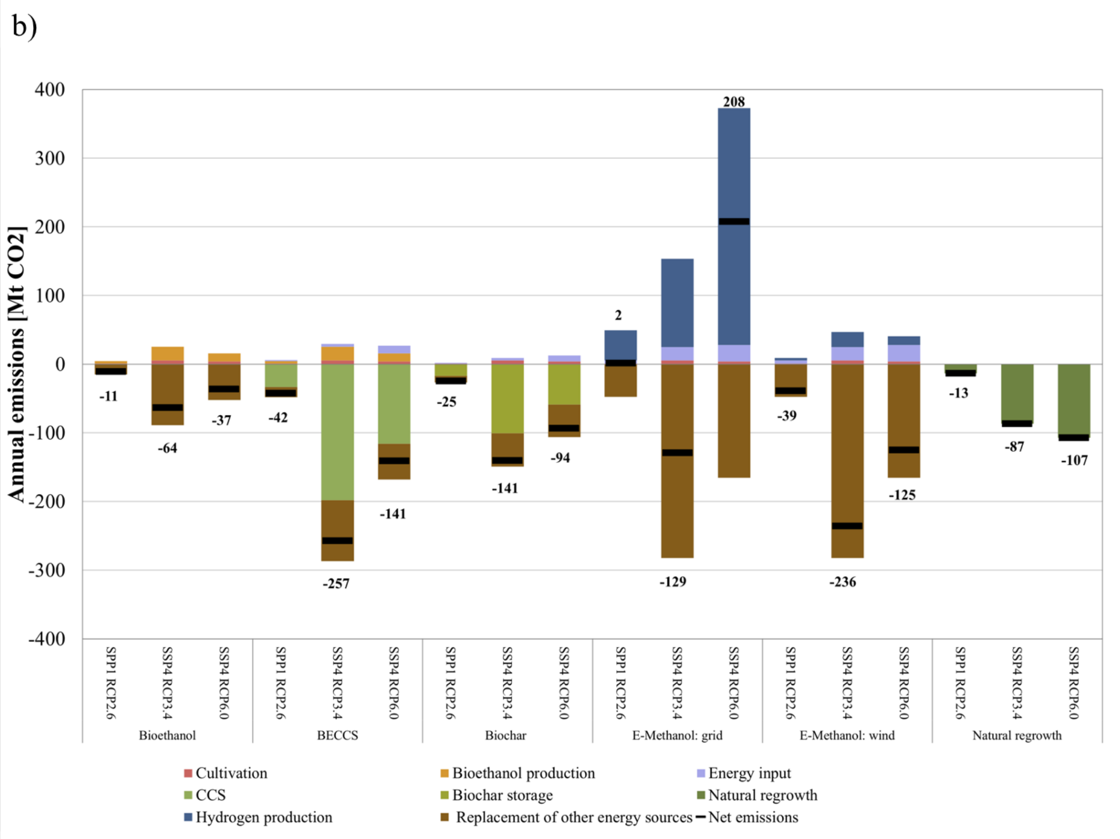
What first stands out from Table 2 is that Eucalyptus and Miscanthus are the crop species that generate the most DM and cover most land in all scenarios. Switchgrass is not used in any relevant location in SSP1-RCP2.6 and is barely used in the other two when the best crop species in chosen at each location. When the results of all crop types are summarized, the DM available ranges from 30.10 to 178 Mt DM, and the areas used for second-generation bioenergy crops range from 1.95 to 13.8 Mha in 2050. The biggest amount of DM is available in SSP4-RCP3.4, the scenario with largest dedicated cropland area. The density is highest in SSP1-RCP2.6, again indicating that the cropland in this scenario is, generally better suited for these crop species. NR has the largest mitigation potential (-107.34 Mt CO_2-eq) and the highest density in sequestration per hectare (22.05 ton CO_2-eq per hectare), in SSP4-RCP6.0. At the same time the NR covers only half of what it does in SSP4-RCP3.4, which might indicate that a larger share of the land in SSP4-RCP6.0 is better suited for NR than the land in SSP4-RCP3.4.

3.2 Climate change mitigation potential

From the identified land, amount of DM available and the NR potential, Figure 2 presents the net emissions of CO_2-eq in all LC activities in all strategies.



(a) Climate change mitigation potential from each activity per hectare of land used [Mt CO_2-eq /ha yr].



(b) Contribution to climate change mitigation potential from all LC activities [Mt CO_2-eq / yr].

Figure 2: Contribution from the different LC activities. (a) per hectare [Mt CO_2-eq /ha yr] and (b) total [Mt CO_2-eq / yr].

Figure 2a shows that the largest climate change mitigation potential from one hectare of cropland is -22 t CO_2-eq from BECCS in SSP1-RCP2.6. The least mitigation potential per hectare is given from e-methanol powered from the grid, which only reaches net negative emissions in scenario SSP4-RCP3.4 because of emissions from the electrolysis energy demand. In BE, BECCS, and biochar, where crop density determines much of the area performance, SSP1-RCP2.6 has the largest potential per hectare because of the high yield in the scenario. SSP4-RCP6.0 has least efficient cropland and, therefore least mitigation potential per hectare in all strategies except biochar because of the replacement of the grid electricity and NR. The performance of e-methanol is mainly dependent on the emissions from the energy source for electrolysis. While the possible replacement of gasoline is dependent on the amount of feedstock and is relatively similar per hectare in each scenario, the emissions from the energy demand vary with the grid emissions.

Figure 2b shows that BE and NR have approximately the same potential in SSP1-RCP2.6 (-11 and -13 Mt CO_2, respectively) (Fig. 2b). The difference is more significant in SSP4-RCP3.4 (-64 and -87 Mt CO_2-eq, respectively) and even larger in SSP4-RCP6.0, where the NR mitigation potential is almost three times as big as BE (-37 and -107 Mt CO_2-eq for BE and NR, respectively), indicating that the areas used for cultivation of second-generation bioenergy crops on average are better for NR in SSP4-RCP6.0. The chart shows that NR is the only strategy that does not have the largest potential in SSP4-RCP3.4. Detailed calculations of cultivation, BE, and NR performance are presented in Supplementary Tables S.9, S.8 and S.9.

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). The carbon captured by the CCS contributes to the largest share of the mitigation potential (up to -198 Mt CO_2-eq in SSP4-RCP3.4), while the potential for replacement of fossil fuel is the same in BE and BECCS strategies. This is because approximately 30% of the carbon is used for bioethanol while CCS captures the rest. The mitigation potential of BECCS is close to linearly dependent on the DM available but varies because of the grid electricity demand for capturing carbon. Detailed quantification of the LC emissions from BECCS is presented in Supplementary Table S.8.

Biochar storage contributes to the largest share of the mitigation potential in the biochar strategy. Because energy from the CHP covers the energy demand for the pyrolysis, the only positive emissions related to biochar are from the cultivation processes. The impact of replacing grid electricity with the CHP process will vary depending on the emissions from the grid. Biochar has the largest potential in SSP4-RCP3.4 (-141 Mt CO_2-eq). Detailed quantification of LC emissions for biochar is presented in Supplementary in Table S.10.

E-methanol powered from wind is the second best solution in all scenarios (-39, -236, and -125 Mt CO_2-eq, in SSP1-RCP2.6, SSP4-RCP3.4, and SSP4-RCP6.0, respectively). Figure 2b shows that the choice of electricity source is of great importance, especially in energy-intensive processes such as hydrogen electrolysis. First, there is a big difference between e-methanol with hydrogen produced with grid- and wind-generated electricity. Second, the mitigation potential of grid-powered processes varies significantly with the scenario because of the difference in the LC emissions from the electricity mix. Table 2 also shows that the negative emissions from BECCS and e-methanol correspond to each other because almost all carbon is captured, but that the energy demand affects the net potential. Detailed quantification of LC emissions for e-methanol is presented in the Supplementary in Table S.11.

In general, emissions from cultivation, BE production, and energy required for CCS make a small share of the total emissions in all strategies. Detailed quantification of LC emissions from cultivation is presented in the Supplementary in Table S.9.

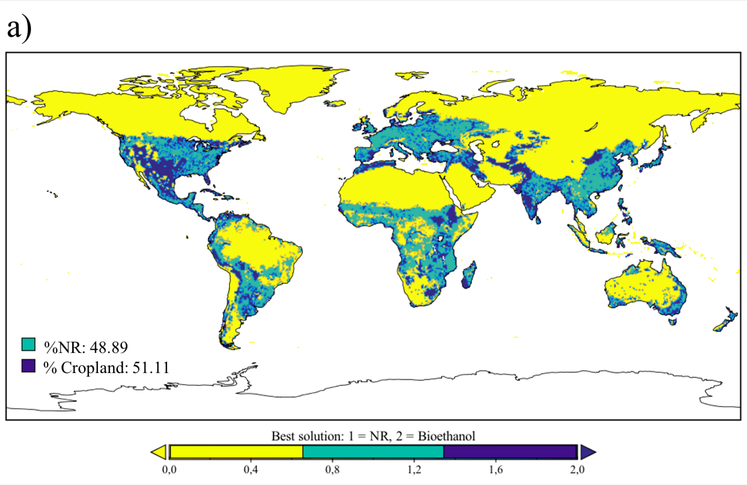
3.3 Optimal distribution of solutions

Figure 1 shows geographical differences in crop yield and natural regrowth potential. Therefore, it is reasonable to assume that the optimal climate change mitigation potential is reached by combining bioenergy cropland and NR. Each grid in all scenarios is therefore analyzed to identify if cropland or natural regrowth is the best management option at a location. The optimal distribution is thereby reached by choosing the most promising solution at each location. The average climate change mitigation potential for each technology in each scenario is presented in Table 3.

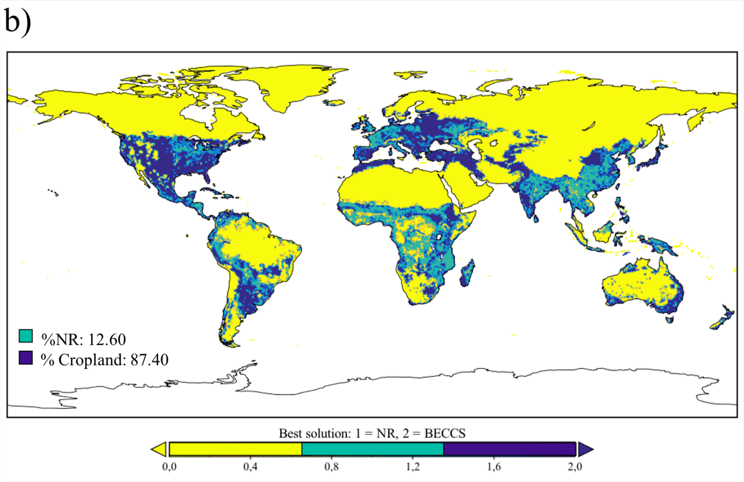
Table 3: Average climate change mitigation potential per DM available for chosen technologies in each scenario given in [t CO_2-eq/t DM].

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	-1.29	-1.33	-1.20

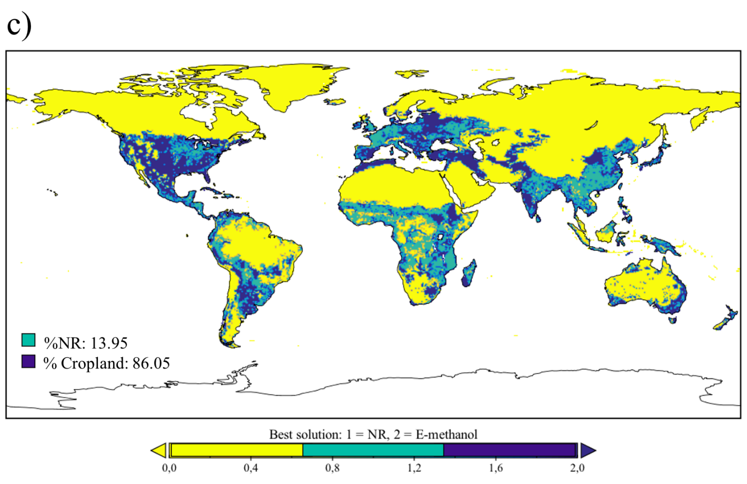
The values presented in Table 3 are used to evaluate whether cropland or NR is the optimal management in an area. This is done by comparing the average mitigation potential from the DM available in an area to the local NR potential. The result is the optimal geographical distribution illustrated in Figure 3. The figure illustrates the optimal distribution between NR and BE, BECCS and E-methanol in SSP4-RCP3.4 in 2050.



(a) SSP4-RCP3.4: Optimal distribution with Bioethanol and NR.



(b) SSP4-RCP3.4: Optimal distribution with BECCS and NR.



(c) SSP4-RCP3.4: Optimal distribution with E-methanol (wind) and NR.

Figure 3: Optimal geographical distribution between NR and technologies in SSP4-RCP3.4 in 2050. The technologies are: (a)BE, (b) BECCS and (c) E-methanol (wind). The yellow fields show where NR is the best solution, and the red fields are the places suited better for cropland growing biomass used for the selected technology. Figures S.6 and S.7 in Supplementary present the geographical distribution in the other scenarios.

What stands out from Figure 3 is that less NR is needed when combined with a technology of great potential, which accords with the information in Table 3. Further, NR is generally the best solution near the equator, while technology is better in areas closer to the poles; this could be because of climatic preferences for the crops. The distribution of NR together with BECCS and e-methanol is very similar because of the climate change mitigation potential per ton of DM of the technologies in this scenario. Table 4 presents the optimal distribution between NR and the technologies in terms of the percentage of land cover in all scenarios.

Table 4: Optimal Distribution of area for NR and cropland for each solution in all scenarios.

	SSP1-RCP2.6		SSP4-RCP3.4		SSP4-RCP6.0	
	% area NR	% area Cropland	% area NR	% area Cropland	% area NR	% area Cropland
Bioethanol	65.99	34.01	48.89	51.11	53.66	46.34
BECCS	8.48	91.52	12.60	87.40	21.31	78.69
Biochar	38.25	61.75	25.32	74.68	30.53	69.47
E-methanol (wind)	10.45	89.55	13.95	86.05	23.71	76.29

Table 4 shows that NR should cover most land only when combined with BE in SSP1-RCP2.6 and SSP4-RCP6.0. Cropland covers the largest share in SSP1-RCP2.6 when used for BECCS, with 91.52% cover. With this area distribution, Figure 4 illustrates the possible climate change mitigation potential when combining the solutions in each scenario.

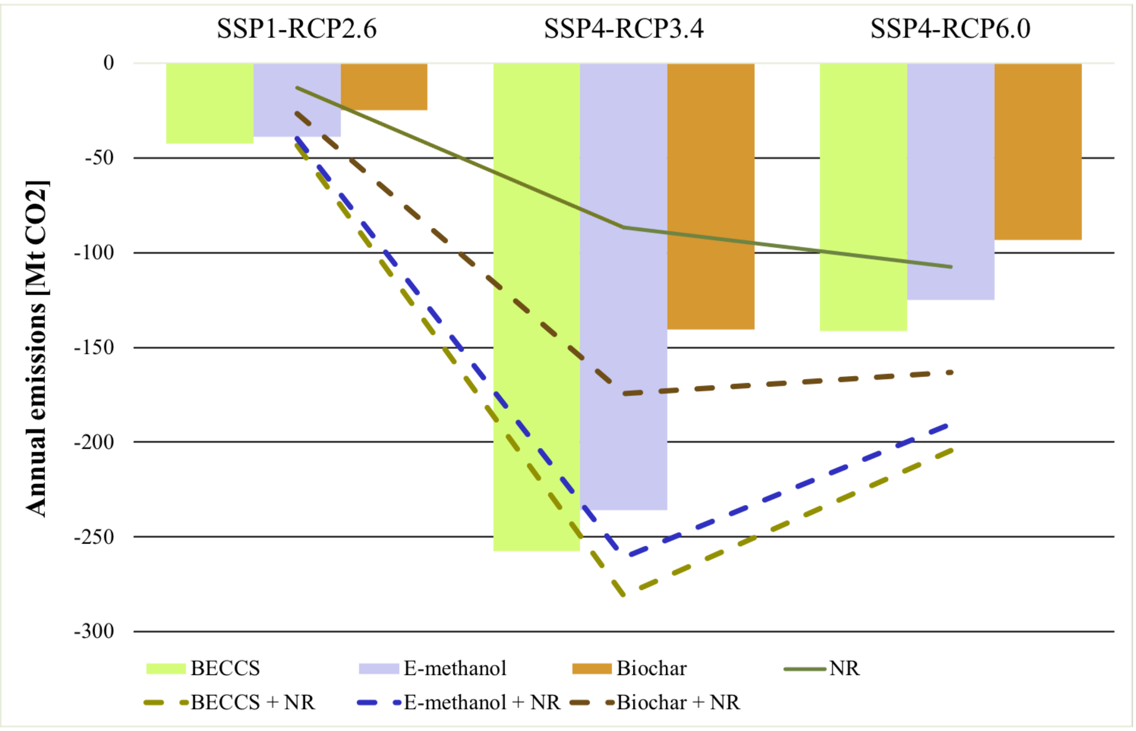


Figure 4: Climate change mitigation potential given in [Mt CO_2-eq yr^{-1}] from the optimal distribution between technologies: BECCS, biochar and e-methanol and NR in all scenarios, The bars illustrate the climate change mitigation potential of the technologies alone, the green the full line illustrate the NR potential, these elements represent the net value previously illustrated in Figure 2a. The dotted lines illustrate the climate change mitigation potential of the optimal combinations of the technologies and NR in each scenario.

Figure 4 shows that BECCS combined with NR is the most favorable solution in all scenarios (-43.30, -280.72, and -204.40 Mt CO_2-eq yr^{-1} in SSP1-RCP2.6, SSP4-RCP3.4, and SSP4-RCP6.0, respectively). E-methanol and NR is the second best solution in all scenarios (-39.89, -261.05, and -190.42 Mt CO_2-eq yr^{-1}, in SSP1-RCP2.6, SSP4-RCP3.4, and SSP4-RCP6.0 respectively). Biochar combined with NR reaches almost the same level of mitigation potential in SSP4-RCP6.0 as in SSP4-RCP3.4 because of the large potential from NR in SSP4-RCP6.0. SSP4-RCP6.0 is the scenario that benefits the most from combining technological solutions with NR, which increases the global climate mitigation potential by 44% from using BECCS only to combining it with NR. 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 in 2050 SSP1-RCP2.6, SSP4-RCP3.4 and SSP4-RCP6.0, respectively when compared to the SSP Database estimations in the respective IAMs (Table S.2). All climate change mitigation potentials of the optimal distributions are presented in the Supplementary in Table S.12.

4 Discussion

4.1 Evaluation of results

It is challenging to compare the potential of technologies when they are based on fundamentally different estimations and premises. This study attempts to remove barriers existing in the literature, consisting of different predictions and goals when estimating global potentials. It allows the technologies to be compared on the same grounds, and to identify the impacts the foundations laid on forehand have on the result. This study has reached its goal by identifying land areas used for second-generation cropland in three 2050 scenarios and quantified the climate change mitigation potential of the different technologies. However, the potentials of the different solutions are strongly dependent on the characteristics of these scenarios, which shows the importance of underlying assumptions such as land area and .

The area of cropland predicted in this study, ranging from 1.95 to 13.80 Mha, is relatively small compared to other studies. The identified cropland area is smallest in SSP1-RCP2.6, which is confirmed by the description from framework from Chini et al. 2020, the indication of more wisely selected areas in SSP1-RCP2.6 is also supported by the same framework. Næss et al. 2021 and Roe et al. 2019 estimate 83 Mha and 34 - 180 Mha, respectively, which results in estimates for the global potential of bioethanol and BECCS in larger magnitudes than this study. This difference is, among others, a result of different premises of how the land is identified due to different goals and scopes for the studies. Where Roe et al. 2019 estimate the demand for reaching the 1.5 °C goal, Næss et al. 2021 investigate the use of abandoned areas. Like in most literature, this further lay the foundation of the size of the global potential for the technologies, resulting in significantly different measures to climate change.

Although the global potential of this study differs from others because of premises for land identification, it confirms a couple of other aspects. For instance, the contribution of emissions from cultivation is small compared to the total LC emissions in all solutions (Figure 2b). The cultivation processes emit from 31.5 to 37.95 kg CO_2-eq per ton DM, which is close to the results of other studies estimating perennial cultivation emissions: 30.18, 33.83, and 40 kg CO_2-eq per ton DM without fertilizer use (Krzyzaniak et al. 2020; Sanscartier et al. 2014; Morales et al. 2015) respectively. It also shows that the pyrolysis into biochar contributes to little emissions compared to the negative emissions related to the strategy. This is the same conclusion as Tisserant et al. 2021 have. The mitigation potential per hectare in the two studies (here: -10 to -12 t CO_2-eq ha^{-1}, Tisserant et al. 2021: -4.59 t CO_2-eq ha^{-1}) is, on the other hand, challenging to compare due to different feedstock and geographical differences.

Currently, there is little data about the climate change mitigation potential of e-methanol. The current literature focuses primarily on the potential cost, efficiency, and uncertainties connected to e-methanol rather than the global potential (IRENA et al. 2021; Helgason et al. 2020; Ueckerdt et al. 2021). However, both aspects are important to consider if the realistic climate change mitigation potential should be estimated, not only the theoretical.

4.2 Limitations and uncertainties

The numerical results are heavily limited by the three datasets that lay the foundation of this study. The first database uses the LUH2 methodology and scenarios provided by REMIND-MAgPIE Integrated Assessment Model and four climate models (GFDL, HADGEM, IPSL, and MIROC) (Chini et al. 2020; Hurtt et al. 2020). 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 (Hurtt et al. 2020). 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 (Hurtt et al. 2020). The impact of comparing scenarios developed from different models can, in some cases, be more significant than the impact on the result from the choice of SSP (Carbon Brief 2018). This unknown impact leads to uncertainty in which underlying factors affect the climate change mitigation in the scenarios. However, it does not affect the numerical results within the scenarios chosen in this study.

The second database, BCY 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; the actual yield might therefore be more extensive than modeled (Li et al. 2020). Further, the parameters **Yields for Best Crop** and **Best Crop Type** are based on the current climate and CO_2 levels. The atmospheric CO_2 concentration is assumed to increase until then, and the results might therefore deviate from realistic 2050 values. Another limitation of using the BCY Database is that it contains only five crop species, which might leave out species with higher yields than the five. The average tons of annually harvested DM can be uncertain in some locations because of variations in soil properties. **Best Crop Type** also has some uncertainties because it mixes the climate information of each crop into one parameter when predicting which crop suits best in an area (Li et al. 2020).

The quality of the Natural Regrowth data set is dependent on the quality of the 11 360 publications it is based upon. It is also based on historical data, it might therefore not be representative of 2050 conditions (Cook-Patton et al. 2020). Another implication related to this data set is the high resolution of grids, which do not match the other two; this is solved by scaling the resolution down, which might have removed some details.

The optimal geographical distribution is based on the global average of CO_2 emissions per ton DM and does not consider crop species and spatial locations. Using the global average will slightly affect the spatial result because of the carbon content, which ranges from 0.46 to 0.497 percent, affecting how much carbon the biochar and CCS for e-methanol and BECCS can capture per ton DM and the ethanol conversion rate. Neither the spatial differences in the electricity mix are considered; this will affect where the different management options are best suited and possibly further improve the global climate change mitigation potential.

This study has calculated the theoretical climate change mitigation potential of the strategies. It has, therefore, not included the demand for bioenergy products and the spatial availability of, for instance, electricity in 2050, which would only be speculation. Whether the BE is actually replacing gasoline and if the produced electricity will be substituting grid electricity will affect the actual climate change mitigation potential of the technologies. Related to this is the possible rebound effect from an increased supply of BE or additional electricity affecting the prices of fossil energy sources (Smeets et al. 2014). This rebound effect might offset the climate change mitigation potential of all technologies. Further, NR includes risks related to wild fires, resulting in emissions and considerable drawbacks from the obtained mitigation. The technologies are analyzed using mostly state-of-the-art inventory data and might therefore be conservative because of future efficiency improvements.

5 Conclusion

Most future scenarios for climate change mitigation include land-based negative emission technologies. The aim of this study was to identify the cropland dedicated to second-generation bioenergy crops in 2050 in the scenarios SSP1-RCP2.6, SSP4-RCP3.4, and SSP4-RCP6.0 and to estimate the global climate change mitigation potential reachable by different NETs using this feedstock as well as the NR potential at the same locations. The areas were identified, and it is shown that the yield is best in the croplands in SSP1-RCP2.6, which is the scenario where cropland covers least land. NR has largest potential in SSP4-RCP6.0 and least in SSP1-RCP2.6, this strengthens the impression that the cropland is more wisely chosen in the sustainable scenario. From the area and dry mass available, bioethanol, BECCS, biochar, and e-methanol, are analyzed. All strategies have net negative emission potential in at least one scenario. The performances of BE, BECCS, and biochar mostly depend on the amount of DM available, using little energy compared to the amount of carbon they are avoiding. The performance of e-methanol is, on the other hand, more dependent on the emissions from the energy supply.

Because of spatial differences in yield and natural regrowth potential, the optimal strategy is to combine different solutions. This study investigates the opportunity to combine natural regrowth with bioenergy cropland. A combination of BECCS and natural regrowth is the best option in all scenarios. Combining different strategies has the largest impact on the mitigation potential in SSP4-RCP6.0, where the performance is significantly lifted by the high NR potential. Combining the solutions show that land-based negative emission management can mitigate up to 1.30 percent of global annual emissions in 2050 from these areas in the chosen scenarios. However, the performance of the technologies per amount of DM varies depending on the life cycle emissions of the energy supply. The study shows the importance of strategy choice for land-based negative emission technologies, as they vary in efficient use of available dry mass and the limited areas dedicated to bioenergy crops.

Prior to this study, it was challenging to compare the technologies due to an absence of common ground for comparison. Despite of its limitations, this study provides a common ground for comparison of the land-based solutions, using the same estimations of land use and energy supply. It also adds to the understanding of which LC activities leave the largest impact on the performance of different technologies. A natural progression of this work is to analyze other sources of CO_2 emissions, such as land use changes and below-ground carbon sequestration. This would be valuable to include in further research because this could affect whether cropland or NR would be the best management in an area. Also, additional impact categories such as biophysical consequences, social impacts, water use, and agricultural occupation should be considered to evaluate each technology's potential and trade-offs.

Bibliography

Bauer, Nico, Katherine Calvin, Johannes Emmerling, Oliver Fricko, Shinichiro Fujimori, Jérôme Hilaire, Jiyong Eom, Volker Krey, Elmar Kriegler, Ioanna Mouratiadou et al. (2017). 'Shared socio-economic pathways of the energy sector–quantifying the narratives'. In: *Global Environmental Change* 42, pp. 316–330. DOI: http://dx.doi.org/10.1016/j.gloenvcha.2016.07.006.

Borisut, Prapatsorn and Aroonsri Nuchitprasittichai (2019). 'Methanol production via CO2 hydrogenation: sensitivity analysis and simulation—based optimization'. In: *Frontiers in Energy Research*, p. 81.

Carbon Brief (2018). *Q&A: How 'integrated assessment models' are used to study climate change*. DOI: https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change.

Chini, Louise, George C Hurtt, R Sahajpal, S Frolking, K Frieler, A Popp, B BBodirsky, F Humpenoeder, M Stevanovic, K Calvin et al. (2020). 'LUH2-ISIMIP2b Harmonized Global Land Use for the Years 2015-2100'. In: *ORNL DAAC*. DOI: https://doi.org/10.3334/ORNLDAAC/1721.

Chum, Helena, Andre Faaij, José Moreira, Göran Berndes, Parveen Dhamija, Hongmin Dong, Benoît Gabrielle, Alison Goss Eng, Wolfgang Lucht, Maxwell Mapako et al. (2011). 'Bioenergy'. In: *Renewable energy sources and climate change mitigation: Special report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, pp. 209–332.

Cook-Patton, Susan C, Sara M Leavitt, David Gibbs, Nancy L Harris, Kristine Lister, Kristina J Anderson-Teixeira, Russell D Briggs, Robin L Chazdon, Thomas W Crowther, Peter W Ellis et al. (2020). 'Mapping carbon accumulation potential from global natural forest regrowth'. In: *Nature* 585.7826, pp. 545–550.

Deng, Yvonne Y, Michèle Koper, Martin Haigh and Veronika Dornburg (2015). 'Country-level assessment of long-term global bioenergy potential'. In: *Biomass and Bioenergy* 74, pp. 253–267.

Djomo, S Njakou, O El Kasmioui, T De Groote, LS Broeckx, MS Verlinden, G Berhongaray, R Fichot, D Zona, SY Dillen, JS King et al. (2013). 'Energy and climate benefits of bioelectricity from low-input short rotation woody crops on agricultural land over a two-year rotation'. In: *Applied Energy* 111, pp. 862–870.

Dooley, Kate and Sivan Kartha (2018). 'Land-based negative emissions: risks for climate mitigation and impacts on sustainable development'. In: *International Environmental Agreements: Politics, Law and Economics* 18.1, pp. 79–98.

Eisentraut, Anselm (2010). 'Sustainable production of second-generation biofuels: potential and perspectives in major economies and developing countries'. In: *IEA Energy Papers*.

Eitelberg, David A, Jasper van Vliet and Peter H Verburg (2015). ‘A review of global potentially available cropland estimates and their consequences for model-based assessments’. In: *Global Change Biology* 21.3, pp. 1236–1248.

Fazio, Simone and Andrea Monti (2011). ‘Life cycle assessment of different bioenergy production systems including perennial and annual crops’. In: *Biomass and Bioenergy* 35.12, pp. 4868–4878.

Field, John L, Tom L Richard, Erica AH Smithwick, Hao Cai, Mark S Laser, David S LeBauer, Stephen P Long, Keith Paustian, Zhangcai Qin, John J Sheehan et al. (2020). ‘Robust paths to net greenhouse gas mitigation and negative emissions via advanced biofuels’. In: *Proceedings of the National Academy of Sciences* 117.36, pp. 21968–21977. DOI: 10.1073/pnas.1920877117.

Gustafsson, Kåre, Ramiar Sadegh-Vaziri, Stefan Grönkvist, Fabian Levihn and Cecilia Sundberg (2021). ‘BECCS with combined heat and power: Assessing the energy penalty’. In: *International Journal of Greenhouse Gas Control* 108, p. 103248.

Helgason, Rafn, David Cook and Brynhildur Davìdsdóttir (2020). ‘An evaluation of the cost-competitiveness of maritime fuels–a comparison of heavy fuel oil and methanol (renewable and natural gas) in Iceland’. In: *Sustainable Production and Consumption* 23, pp. 236–248.

Hurtt, George C, Louise Chini, Ritvik Sahajpal, Steve Frolking, Benjamin L Bodirsky, Katherine Calvin, Jonathan C Doelman, Justin Fisk, Shinichiro Fujimori, Kees Klein Goldewijk et al. (2020). ‘Harmonization of global land use change and management for the period 850–2100 (LUH2) for CMIP6’. In: *Geoscientific Model Development* 13.11, pp. 5425–5464. DOI: https://doi.org/10.5194/gmd-2019-360.

IRENA and Methanol Institute (2021). *Innovation Outlook, Renewable Methanol.* URL: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf.

Jackson, Steven and Eivind Brodal (2019). ‘Optimization of the energy consumption of a carbon capture and sequestration related carbon dioxide compression processes’. In: *Energies* 12.9, p. 1603.

Krzyzaniak, Michàl, Mariusz J Stolarski and Kazimierz Warmiński (2020). ‘Life cycle assessment of giant miscanthus: production on marginal soil with various fertilisation treatments’. In: *Energies* 13.8, p. 1931.

Lanzerstorfer, Christof (2019). ‘Combustion of miscanthus: Composition of the ash by particle size’. In: *Energies* 12.1, p. 178.

Lask, Jan, Moritz Wagner, Luisa M Trindade and Iris Lewandowski (2019). ‘Life cycle assessment of ethanol production from miscanthus: A comparison of production pathways at two European sites’. In: *Gcb Bioenergy* 11.1, pp. 269–288. DOI: https://doi.org/10.1111/gcbb.12551.

Lewandowski, Iris and U Schmidt (2006). ‘Nitrogen, energy and land use efficiencies of miscanthus, reed canary grass and triticale as determined by the boundary line approach’. In: *Agriculture, Ecosystems & Environment* 112.4, pp. 335–346.

Li, Wei (2019). *Mapping the yields of lignocellulosic bioenergy crops from observations at the global scale [Data set].* URL: https://doi.org/10.5281/zenodo.3274254.

Li, Wei, P Ciais, Elke Stehfest, Detlef van Vuuren, Alexander Popp, Almut Arneth, Fulvio Di Fulvio, Jonathan Doelman, Florian Humpenöder, Anna B Harper et al. (2020). ‘Mapping the yields of lignocellulosic bioenergy crops from observations at the global scale’. In: *Earth System Science Data* 12.2, pp. 789–804. DOI: https://doi.org/10.5194/essd-12-789-2020.

Løvenskiold, Anne Cecilie (n.d.). ‘Estimates of global negative emission potentials in 2050 from dedicated bioenergy crops’. unpublished.

Manouchehrinejad, Maryam and Sudhagar Mani (2019). ‘Process simulation of an integrated biomass torrefaction and pelletization (iBTP) plant to produce solid biofuels’. In: *Energy Conversion and Management: X* 1, p. 100008.

Masson-Delmotte, V, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.Huang M.I. Gomis, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (2021). ‘IPCC, 2021: Summary for Policymakers’. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.*

Matuštík, Jan, Tereza Hnátková and Vladimír Kočí (2020). ‘Life cycle assessment of biochar-to-soil systems: A review’. In: *Journal of Cleaner Production* 259, p. 120998.

Meyer, Matthias, Filipa Tavares Wahren, Norbert Weber, Ronald S Zalesny and Martin Weih (2021). ‘Sustainable Biomass Value Chains Based on Poplar Plantations in European Rural Areas’. In: *BioEnergy Research* 14.2, pp. 355–356. DOI: https://doi.org/10.1007/s12155-021-10275-3.

Monti, Andrea, Simone Fazio and Gianpietro Venturi (2009). ‘Cradle-to-farm gate life cycle assessment in perennial energy crops’. In: *European Journal of Agronomy* 31.2, pp. 77–84.

Morales, M, A. Arvesen and Francesco Cherubini (2021). ‘Integrated process simulation for bioethanol production: Effects of varying lignocellulosic feedstocks on technical performance’. In: *Bioresource Technology* 328, p. 124833. DOI: https://doi.org/10.1016/j.biortech.2021.124833.

Morales, Marjorie, G Aroca, Rafael Rubilar, Eduardo Acuna, Blas Mola-Yudego and Sara González-García (2015). ‘Cradle-to-gate life cycle assessment of Eucalyptus globulus short rotation plantations in Chile’. In: *Journal of Cleaner Production* 99, pp. 239–249.

Næss, Jan Sandstad, Otavio Cavalett and Francesco Cherubini (2021). 'The land-energy-water nexus of global bioenergy potentials from abandoned cropland'. In: *Nature Sustainability* 4.6, pp. 525–536. DOI: https://doi.org/10.1038/s41893-020-00680-5.

Olsson, Lennart, Humberto Barbosa, Suruchi Bhadwal, Annete Cowie, Kenel Delusca, Dulce Flores-Renteria, Kathleen Hermans, Esteban Jobbagy, Werner Kurz, Diqiang Li et al. (2019). 'Land degradation'. In: *In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.* Intergovernmental Panel on Climate Change (IPCC).

Riahi, Keywan, Detlef P Van Vuuren, Elmar Kriegler, Jae Edmonds, Brian C O'neill, Shinichiro Fujimori, Nico Bauer, Katherine Calvin, Rob Dellink, Oliver Fricko et al. (2017). 'The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview'. In: *Global environmental change* 42, pp. 153–168. DOI: https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Roberts, Kelli G, Brent A Gloy, Stephen Joseph, Norman R Scott and Johannes Lehmann (2010). 'Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential'. In: *Environmental science & technology* 44.2, pp. 827–833.

Rockstrøm, Johan, Will Steffen, Kevin Noone, Åsa Persson, F Stuart Chapin, Eric F Lambin, Timothy M Lenton, Marten Scheffer, Carl Folke, Hans Joachim Schellnhuber et al. (2009). 'A safe operating space for humanity'. In: *Nature* 461.7263, pp. 472–475.

Roe, Stephanie, Charlotte Streck, Michael Obersteiner, Stefan Frank, Bronson Griscom, Laurent Drouet, Oliver Fricko, Mykola Gusti, Nancy Harris, Tomoko Hasegawa et al. (2019). 'Contribution of the land sector to a 1.5°C world'. In: *Nature Climate Change* 9.11, pp. 817–828. DOI: https://doi.org/10.1038/s41558-019-0591-9.

Sanscartier, David, Bill Deen, Goretty Dias, Heather L MacLean, Humaira Dadfar, Ian McDonald and Hilla Kludze (2014). 'Implications of land class and environmental factors on life cycle GHG emissions of Miscanthus as a bioenergy feedstock'. In: *Gcb Bioenergy* 6.4, pp. 401–413.

Shukla, PR, J Skea, E Calvo Buendia, V Masson-Delmotte, HO Pörtner, DC Roberts, P Zhai, Raphael Slade, Sarah Connors, Renée Van Diemen et al. (2019). *IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.*

Sims, Ralph EH, Warren Mabee, Jack N Saddler and Michael Taylor (2010). 'An overview of second generation biofuel technologies'. In: *Bioresource technology* 101.6, pp. 1570–1580. DOI: 10.1016/j.biortech.2009.11.046.

Sipilä, Kari (2016). 'Cogeneration, biomass, waste to energy and industrial waste heat for district heating'. In: *Advanced District Heating and Cooling (DHC) Systems*. Elsevier, pp. 45–73.

Smeets, Edward, Andrzej Tabeau, Siemen van Berkum, Jamil Moorad, Hans van Meijl and Geert Woltjer (2014). 'The impact of the rebound effect of the use of first generation biofuels in the EU on greenhouse gas emissions: A critical review'. In: *Renewable and Sustainable Energy Reviews* 38, pp. 393–403. DOI: https://doi.org/10.1016/j.rser.2014.05.035.

Sørmo, Erlend, Ludovica Silvani, Gorm Thune, Helmut Gerber, Hans Peter Schmidt, Andreas Botnen Smebye and Gerard Cornelissen (2020). 'Waste timber pyrolysis in a medium-scale unit: Emission budgets and biochar quality'. In: *Science of the Total Environment* 718, p. 137335.

Su, Ting, Deyang Zhao, Mohamad Khodadadi and Christophe Len (2020). 'Lignocellulosic biomass for bioethanol: Recent advances, technology trends, and barriers to industrial development'. In: *Current Opinion in Green and Sustainable Chemistry* 24, pp. 56–60.

Teir, Sebastian, Jens Hetland, Erik Lindeberg, Asbjørn Torvanger, Katarina Buhr, Tiina Koljonen, Jenny Gode, Kristin Onarheim, Andreas Tjernshaugen, Antti Arasto et al. (2010). 'Potential for carbon capture and storage (CCS) in the Nordic region'. In: *VTT research notes* 2556.

Tisserant, Alexandre and Francesco Cherubini (2019). 'Potentials, limitations, co-benefits, and trade-offs of biochar applications to soils for climate change mitigation'. In: *Land* 8.12, p. 179.

Tisserant, Alexandre, Marjorie Morales and Francesco Cherubini (2021). 'Life-cycle assessment to unravel co-benefits and trade-offs of large-scale biochar deployment in Norwegian agriculture'. In: *Resources, Conservation and Recycling*, p. 106030.

Ueckerdt, Falko, Christian Bauer, Alois Dirnaichner, Jordan Everall, Romain Sacchi and Gunnar Luderer (2021). 'Potential and risks of hydrogen-based e-fuels in climate change mitigation'. In: *Nature Climate Change* 11.5, pp. 384–393.

Valente, Antonio, Diego Iribarren and Javier Dufour (2020). 'Prospective carbon footprint comparison of hydrogen options'. In: *Science of The Total Environment* 728, p. 138212.

Supplementary

Results from project work

Table S.1: Kilo tonnes of DM and corresponding kilo hectares in 2050 in each scenario.

	SSP1-RCP2.6		SSP2-RCP4.5		SSP3-RCP7.0		SSP4-RCP3.4		SSP4-RCP6.0		SSP5-RCP8.5	
	kt	kha	kt	kha	kt	kha	kt	kha	kt	kha	kt	kha
Eucalyptus	16900.00	1020.00	0.00	0.00	12.40	0.73	65400.00	4260.00	37100.007	2400.00	637.00	42.00
Miscanthus	12700.00	867.00	0.00	0.00	22.20	1.46	89100.00	6450.00	50700.00	3630.00	687.00	50.50
Poplar	95.80	14.20	0.00	0.00	0.17	0.02	901.00	129.00	797.00	109.00	102.00	13.30
Switchgrass	0.00	0.00	0.00	0.00	0.00	0.00	80.50	11.10	25.00	2.91	8.40	1.02
Willow	389.00	51.3	0.00	0.00	2.97	0.04	22200.00	2970.00	15400.00	2020.00	562.00	69.70
Total	30100.00	1950.00	0.00	0.00	34.80	2.21	178000.00	13800.00	104000.00	8170.00	2000.00	177.00
Density [tonnes /ha]	15.40		0.00		15.80		12.90		12.70		11.30	

Table S.2: Scenario characteristics for SSP1-RCP2.6, SSP4-RCP3.4 and SSP4-RCP6.0. Data is collected from the SSP-Database (Bauer et al. 2017).

	SSP1-RCP2.6	SSP4-RCP3.4	SSP4-RCP6.0
IAM	IMAGE	GCAM	GCAM
Temperature 2050 (compared to 1850 levels)	+1.76	+1.89	+2.05
Temperature 2100 (compared to 1850 levels)	+1.76	+2.19	+3.16
Life cycle emission el mix [g CO2 /kWh]	173.93	85.65	392.72
Total annual GHG emissions 2050 [Mt CO2]	17 963.50	19 838.70	48 377.80

Inventory data

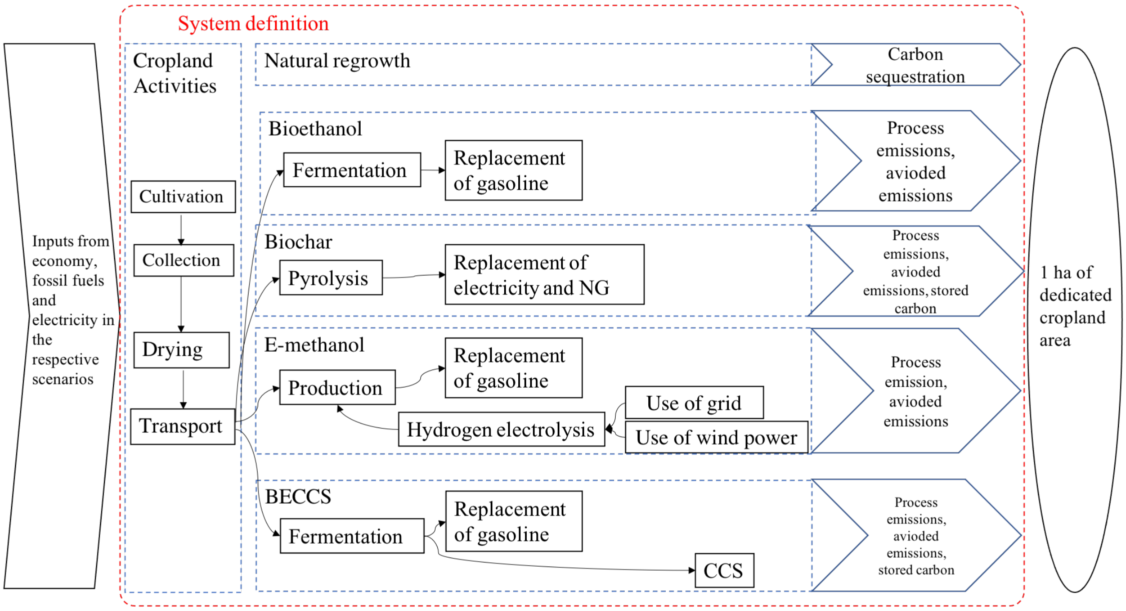


Figure S.1: System definition of the land-based solutions.

Table S.3: Inventory data. Plantation data from Monti et al. 2009, Morales et al. 2015, Manouchehrinejad et al. 2019 and Fazio et al. 2011. Bioethanol data is taken from Chum et al. 2011, Lask et al. 2019 and Morales et al. 2021.Pyrolysis data from (K. G. Roberts et al. 2010) and Tisserant et al. 2021. BECCS data from Morales et al. 2021. Electrolysis data from Valente et al. 2020 and Ecoinvent.

Technology	Inventory data	Value	Unit
Plantation	Cultivation: diesel input for M and S	35	L ha^{-1}
	Cultivation: diesel input for E, P and W	50	L ha^{-1}
	Drying energy input	50.4	MJ (t wet $BM)^{-1}$
Transport	Distance	200 x 2	km
	Carbon intensity diesel 18 tonne HGV	876	g CO_2 km^{-1}
Bioethanol	Substituted emissions	70	Mt CO_2 EJ^{-1}
	Bioethanol production	0.15	g CO_2 MJ^{-1}
Biochar	Input energy	893	MJ t DM
	Biochar output	0.457	t (t C $input)^{-1}$
	Bio-oil output	0.426	t (t C $input)^{-1}$
	Syngas output	0.117	t (t C $input)^{-1}$
	Energy output	2.1	kWh kg^{-1} BC
	Energy output	15.9	MJ kg^{-1} BC
BECCS	Carbon captured	0.68	C (C in $DM)^{-1}$
	Capture efficiency	0.92	-
	Conversion to CO_2	3.70	t CO_2 (t $C)^{-1}$
E-methanol	Carbon from DM to air	0.95	-
	Combustion energy demand	1.2	MJ kWh^{-1}
	Electricity from combustion	1.25	kWh (kg $DM)^{-1}$
	CCS capture efficiency	0.92	-
	Electricity input electrolysis	45	kWh (kg $H_2)^{-1}$
	Carbon intensity wind	0.0145	kg CO_2 kWh^{-1}

Life cycle emissions of the grid

Table S.4: Energy supply from different energy sources to electricity. From Bauer et al. 2017.

	SSP1-RCP2.6		SSP4-RCP3.4		SSP4-RCP6.0	
	EJ/yr	share	EJ/yr	share	EJ/yr	share
oil	0.091	0.06 %	1.30	1.01 %	1.26	0.68 %
hydro	22.43	14.24 %	15.85	7.03 %	15.85	8.50 %
nuclear	3.90	2.48 %	76.68	36.4 %	38.61	20.69 %
solar	49.42	31.37 %	19.78	9.07 %	12.64	6.77 %
wind	24.78	15.73 %	30.55	14.05 %	16.32	8.75 %
BM w/ccs	4.26	2.71 %	6.54	3.23 %	0.33	0.18 %
BM w/o ccs	0.44	0.28 %	1.08	1.01 %	3.38	1.81 %
coal w/ ccs	8.23	5.22 %	20.58	10.09 %	1.85	0.99 %
coal w/o ccs	9.01	5.72 %	4.96	2.12 %	52.90	28.35 %
gas w/ ccs	5.09	3.23 %	15.58	7.13 %	3.37	1.81 %
gas w/o ccs	29.86	18.96 %	17.53	8.10 %	36.29	19.45 %
geothermal	0.00	0.00 %	5.24	2.10 %	3.81	2.04 %
sum [EJ yr^{-1}]	157.52		215.69		186.61	

Table S.5: Life cycle emissions for energy supply by energy source. All data collected from ecoinvent3.6.

Energy source for electricity	kg CO_2 kWh^{-1}.
oil	0.9139
hydro	0.051
nuclear	0.0127
solar	0.07776
wind	0.0145
BM w/ccs	-0.115
BM w/o ccs	0.0618
coal w/ ccs	0.022
coal w/o ccs	1.0087
gas w/ ccs	0.055
gas w/o ccs	0.4297
geothermal	0.0693

Table S.6: Annual Life cycle emissions from electricity in each scenario. PWh = 10^{12} kWh.

	SSP1-RCP2.6		SSP4-RCP3.4		SSP4-RCP6.0	
	PWh	Gt CO_2	PWh	Gt CO_2	PWh	Gt CO_2
Oil	0.25	0.02	0.35	0.322	0.340	0.311
Hydro	6.21	0.31	4.28	0.221	4.28	0.22
Nuclear	1.05	0.01	20.70	0.263	10.40	0.13
Solar	13.3	1.04	5.34	0.42	3.41	0.26
Wind	6.69	0.09	8.25	0.12	4.41	0.06
BM w/ccs	1.15	-0.13	1.77	-0.20	0.08	-0.01
BM w/o ccs	0.12	0.01	0.29	0.02	0.91	0.06
Coal w/ ccs	2.22	0.05	5.56	0.12	0.49	0.01
Coal w/o ccs	2.43	2.45	1.34	1.35	14.30	14.4
Gas w/ ccs	1.38	0.08	4.21	0.23	0.91	0.05
Gas w/o ccs	8.06	3.46	4.73	2.03	9.80	4.21
Geothermal	0.00	0.00	1.42	0.10	1.03	0.07
Sum	43.60	7.39	59.74	5.12	51.69	20.30
g CO_2 kWh^{-1}	**173.93**		**85.66**		**392.72**	

Table S.7: Feedstock characteristics.

Crop Type	Carbon share [%wt]	Conversion factor [MJ ethanol (kg DM)$^{-1}$]
Eucalyptus	0.49	7.10
Miscanthus	0.48	7.20
Poplar	0.50	7.10
Switchgrass	0.46	7.70
Willow	0.498	7.10

Results

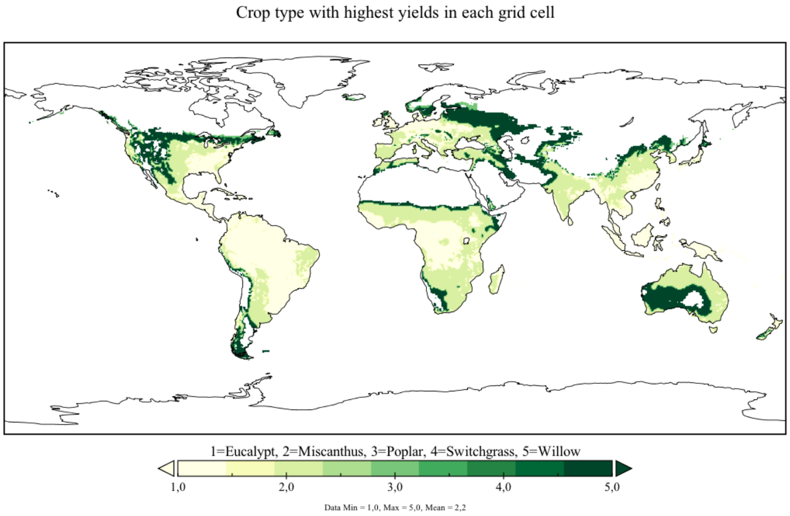


Figure S.2: Best Crop Type in bioenergy Crop Yields.

Table S.8: Best crop type grid cells and area.

Crop Type	Grid cells [-]	Area [Mha]	Area Share [%]
Eucalyptus	10 684	30.50	38.30
Miscanthus	12 292	33.30	41.70
Poplar	477	0.93	1.20
Switchgrass	13	0.29	0.30
Willow	6 330	14.80	18.50

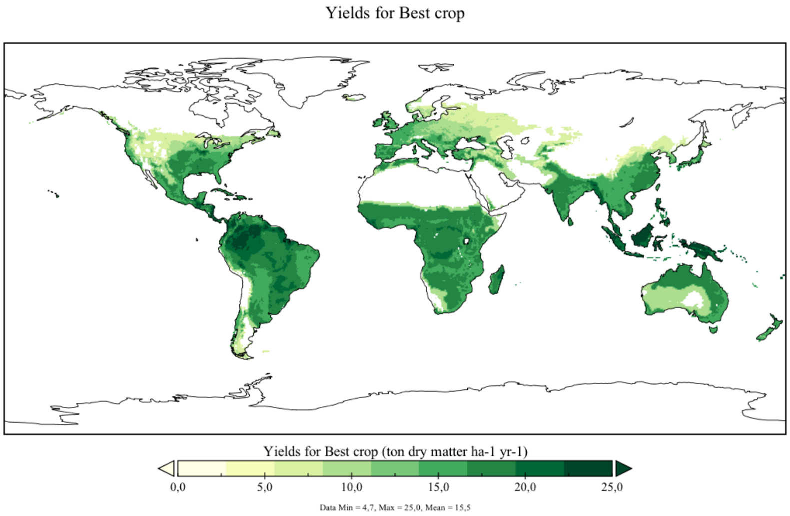
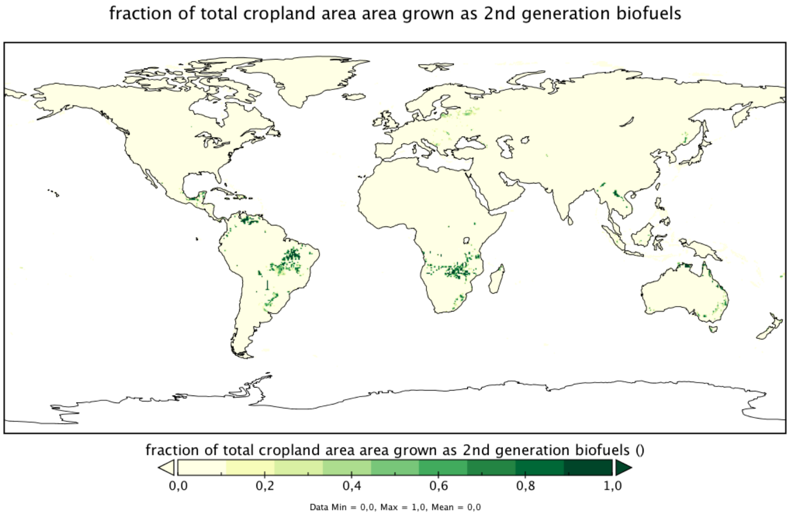
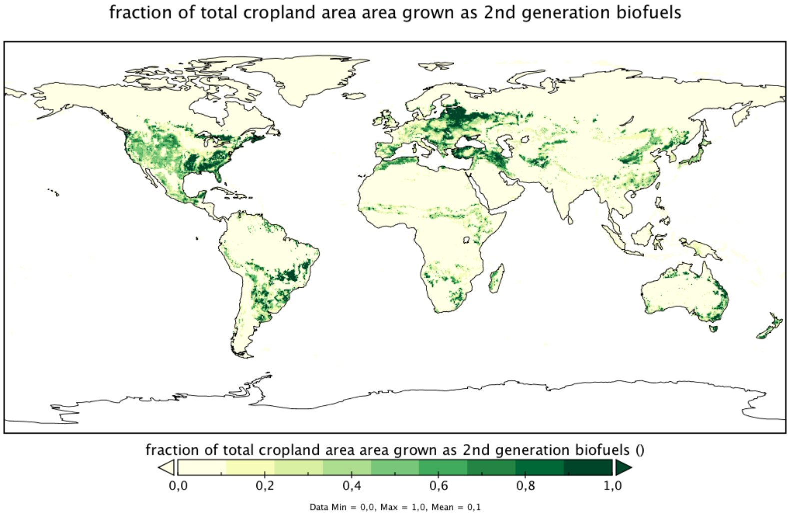


Figure S.3: Yields for best crop.

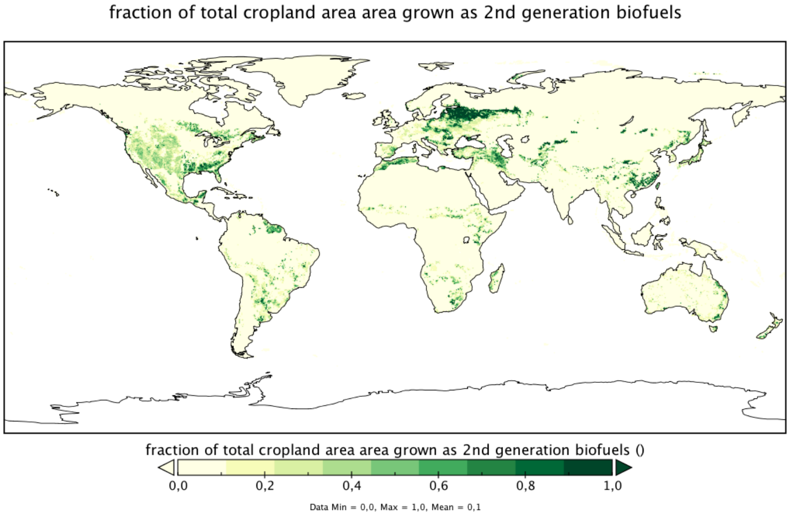
Figure S.4: Graphics of the fraction of grid cells used for second-generation bioenergy crops in 2050 in the scenarios.



(a) SSP1-RCP2.6



(b) SSP4-RCP3.4



(c) SSP4-RCP6.0

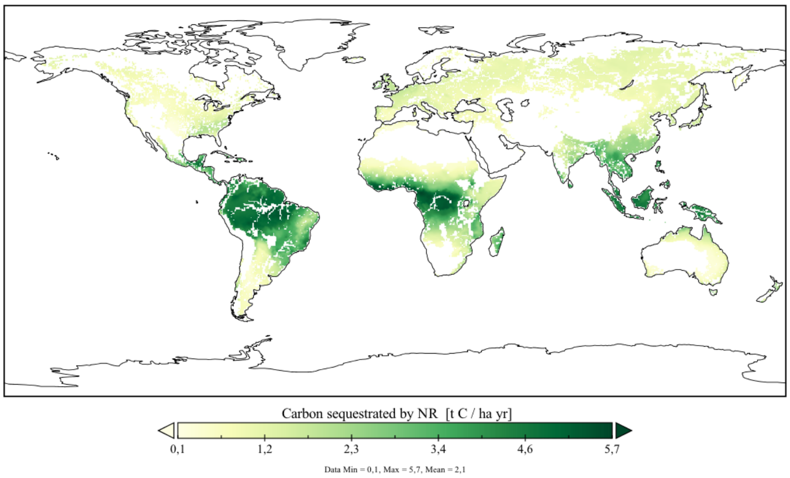


Figure S.5: Natural regrowth potential from Cook-Patton et al. 2020.

Table S.9: Crop treatment.

Plantation activity	SSP1 RCP2.6	SSP4 RCP3.4	SSP4 RCP4.6
Cultivation [Mt CO_2]	0.255	1.82	1.06
Drying [Mt CO_2]	0.11	0.32	0.86
Transport farm-production[Mt CO_2]	0.29	1.73	1.01
Further transport [Mt CO_2]	0.29	1.73	1.01
Total emissions [Mt CO_2 yr^{-1}]	0.95	5.60	3.95
[t CO_2 ha^{-1}]	0.49	0.40	0.48
kg CO_2 t DM^{-1}	31.58	31.49	37.95

Table S.9: Natural regrowth mitigation potential.

Reforestation data	SSP1 RCP2.6	SSP4 RCP3.4	SSP4 RCP4.6
Sequetration [Mt C]	3.61	23.67	29.25
Sequestration [Mt CO_2]	**13.26**	**86.88**	107.34
Area [Mha]	1.38	8.22	4.87
Concentration [t CO_2/ha]	9.60	10.56	22.05

Table S.8: Bioethanol and BECCS.

	SSP1 RCP2.6	SSP4 RCP3.4	SSP4 RCP6.0
Bioethanol potential [EJ]	0.22	1.27	0.74
Bioethanol production emissions [Mt CO_2]	3.35	19.80	11.60
Emissions avoided: bioethanol [Mt CO_2]	**15.00**	**88.90**	**52.10**
Carbon input to CCS [Mt C]	14.50	86.00	50.40
Carbon output to CCS [Mt]	9.05	53.50	31.30
Electricity demand [TWh]	8.28	49.5	29.00
Electricity emissions [Mt CO_2]	1.44	4.24	11.4
Saved by CCS [Mt CO_2]	**33.10**	**198.00**	**116.00**
BECCS including Crop treatment			
Total negative emission [Mt CO_2]	48.17	287.07	168.13
Total positive emissions [Mt CO_2]	5.08	29.66	26.94
Net emissions [Mt CO_2]	**-42.43**	**-257.41**	**-141.19**
Net emissions [t CO_2 ha^{-1}]	-21.73	-18.62	-17.28

Table S.10: Biochar.

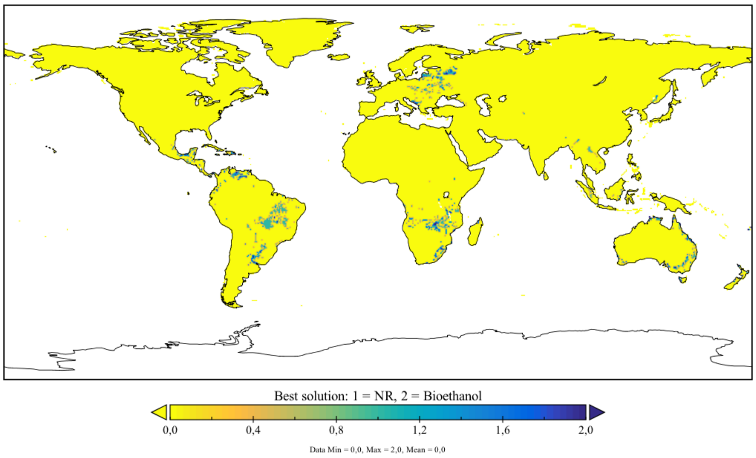
	SSP1 RCP2.6	SSP4 RCP3.4	SSP4 RCP4.6
Biochar [Mt C]	6.65	39.30	23.00
Bio-oil [Mt C]	6.20	36.60	21.50
Syngas [Mt C]	1.70	10.10	5.90
Energy req for pyrolysis [EJ]	0.027	0.16	0.09
Biochar content [Mt CO_2]	**-17.04**	**-100.79**	**-59.05**
Energy emissions for CCS [Mt]	**1.12**	**3.26**	**8.75**
Biochar output [Mt]	8.43	49.80	29.10
Electricity output [TWh]	17.70	105.0	61.20
Energy output[EJ]	0.13	0.79	0.463
Energy remaining after pyrolysis [EJ]	0.11	0.63	0.37
Emissions avoided: electricity [Mt CO_2]	**-3.08**	**-8.97**	**-24.02**
Emissions avoided: natural gas [Mt CO_2]	-6.70	-39.60	-23.15
Net emissions w/ Crop treatment [Mt CO_2]	**-24.76**	**-140.53**	**-93.52**
t CO_2/ t DM	-0.82	-0.79	-0.89
t CO_2 / ha	-12.69	-10.18	-11.44

Table S.11: E-methanol.

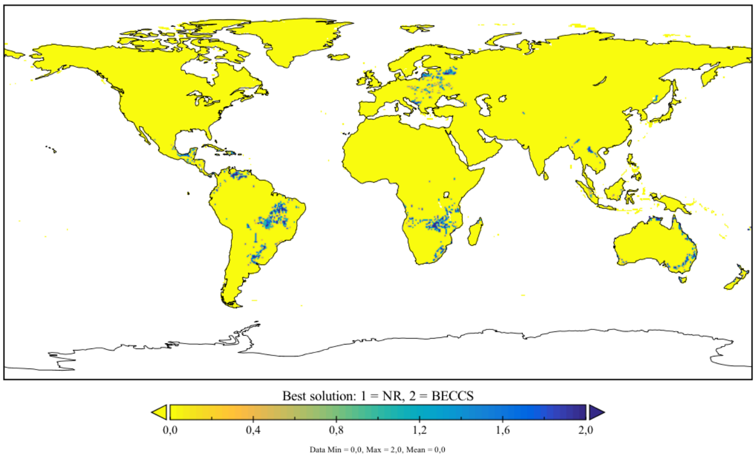
	SSP1-RCP2.6	SSP4-RCP3.4	SSP4-RCP6.0
Carbon to combustion [Mt C]	12.70	75.20	44.00
Combustion energy emissions from NG [Mt CO_2]	2.25	13.30	7.80
Electricity generated from combustion TWh	37.60	222.00	130.00
Saved by CCS [Mt CO_2]	47.1	278.00	163.00
Energy emissions CCS [Mt CO_2]	2.05	5.96	16.02
Electrolysis			
Input [Giga mole CO_2]	1.07	6.33	3.71
Input [Giga mole H_2]	3.21	19.03	11.13
Input [Mt H_2]	6.47	38.30	22.40
Electrolysis electricity [TWh]	254.00	1500.00	879.00
Emissions grid electrolysis [Mt CO_2]	**44.12**	**128.51**	**345.23**
Emissions wind electrolysis [Mt CO_2]	**3.68**	**21.75**	**12.75**
E-Methanol energy [EJ]	0.68	4.04	2.36
Emissions avoided: gasoline [Mt CO_2]	**47.77**	**282.46**	**165.49**
Total emissions w/ Crop treatment			
E-methanol (grid) [Mt CO_2]	**1.61**	**-129.07**	**207.50**
E-methanol (wind) [Mt CO_2]	**-38.84**	**-235.82**	**-124.98**

Optimal climate change mitigation potential

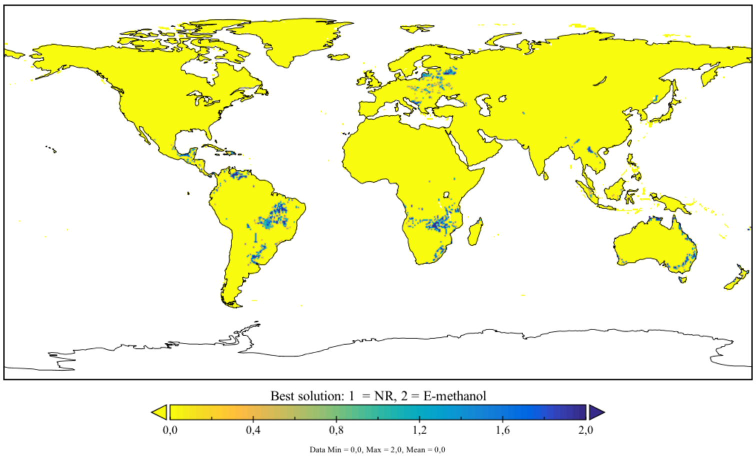
Figure S.6: Optimal distribution between Natural Regrowth and technologies in SSP1-RCP2.6.



(a) SSP1-RCP2.6: Optimal distribution with Bioethanol and NR.

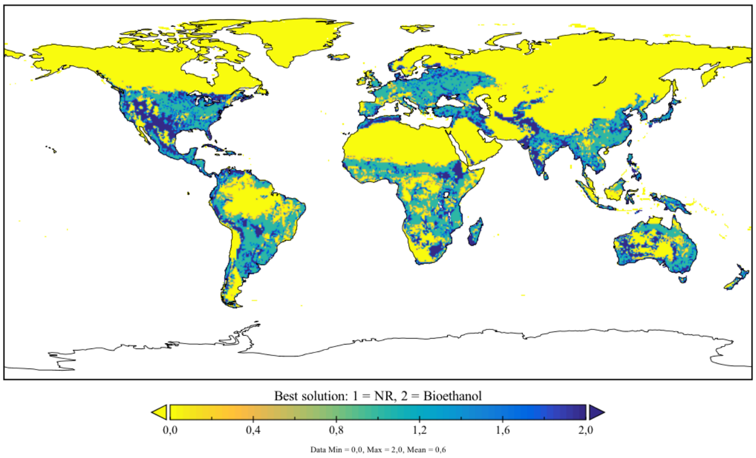


(b) SSP1-RCP2.6: Optimal distribution with BECCS and NR.

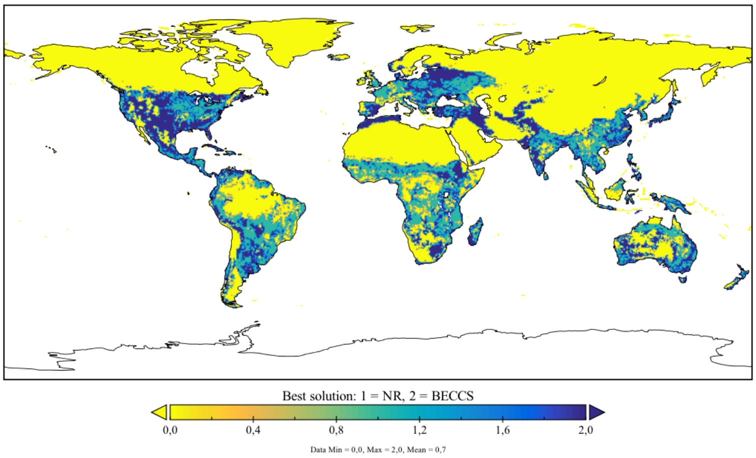


(c) SSP1-RCP2.6: Optimal distribution with E-methanol (wind) and NR.

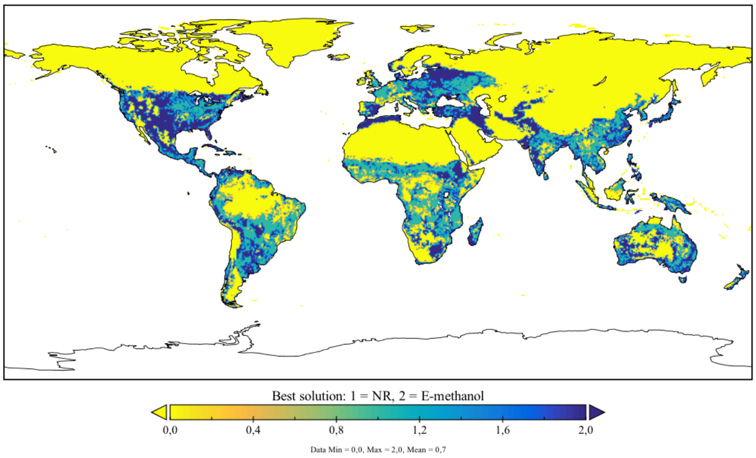
Figure S.7: Optimal distribution between Natural Regrowth and technologies in SSP4-RCP6.0.



(a) SSP4-RCP6.0: Optimal distribution with Bioethanol and NR.



(b) SSP4-RCP6.0: Optimal distribution with BECCS and NR.



(c) SSP4-RCP6.0: Optimal distribution with biochar and NR.

Table S.12: Optimal distribution CCM potential.

	SSP1-RCP2.6	SSP4-RCP3.4	SSP4-RCP6.0
NR [t DM/ha]	-13.25	-86.88	-107.34
Biochar alone [t DM/ha]	-24.75	-140.52	-93.00
Biochar + NR [t DM/ha]	-26.64	-174.43	-163.2
BECCS alone [t DM/ha]	-42.42	-257.41	-141.18
BECCS + NR [t DM/ha]	-43.30	-280.72	-204.4
E-methanol alone [t DM/ha]	-38.84	-235.82	-124.98
E-methanol + NR [t DM/ha]	-39.89	-261.05	-190.42

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