Master's thesis

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

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Climate change mitigation potentials of bioenergy production, natural regrowth and afforestation on abandoned croplands

Master's thesis in Energy and Environmental Engineering
Supervisor: Francesco Cherubini
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Abstract

Carbon sequestration and capture and storage from land use activities are considered promising and essential contributions in future climate change mitigation. As pressure on land areas and competition between land use sectors still are significant challenges, this study investigates the potentials of exploiting global abandoned croplands for land based climate change initiatives. Assessed here is the comparison of fossil fuel substitution and carbon capture and storage (CCS) from bioenergy production (scenarios called BE and BECCS), natural regrowth (NR) and afforestation (AF). The optimal distribution of these land use strategies is evaluated emphasizing the highest mitigation potential, in addition to scarce land areas in biodiversity hotspots. A total area of 97.6 Mha of croplands were identified as abandoned between 1992 and 2018, where approximately 37.6 Mha are located inside biodiversity hotspots and 60 Mha outside. The optimal distribution of the land use strategies dedicated 77.91 % of the abandoned croplands to BECCS, 25.48 % to AF and 3.50 % to NR. This distribution contributes with a mitigation potential of 2.56 GtCO$_2$eq.yr^{-1}. Abandoned croplands are identified using high-resolution satellite land cover data from ESA CCI and furthermore integrated with Global Agro-ecological Zones (GAEZ) drymass yield, the Global Forest Model (G4M) and natural regrowth data from Cook-Patton et al. 2020. All calculations are conducted for a period of 30 years in 5 arc minutes spatial resolution.

Norwegian Summary

Karbonopptak og -lagring som følge av landbruksendringer har fått økende oppmerksomhet som viktige bidrag i fremtidig klimaarbeid. Ettersom økende press på landarealer og konkurranse mellom ulike sektorer fortsatt er betydelige utfordringer, undersøker denne studien potensialene knyttet til å utnytte globale forlatte jordbruksområder til klimatiltak i form av endringer i landområder. Studien fokuserer på substituering av fossilt drivstoff og karbonfangst- og lagring (CCS) fra produksjon av bioenergi (scenarier kalt BE og BECCS), naturlig gjenvekst (NR) og påskogning (AF). Optimal distribusjon av disse strategiene er evaluert med hensyn til høyeste potensial for karbonopptak og reduksjon i klimagassutslipp, i tillegg til sårbare områder med høyt biomangfold (eng: biodiversity hotspots). Et totalt jordbruksareal på 97.6 Mha ble identifisert som forlatt i perioden 1992-2018, hvor omtrent 37.6 Mha befinner seg innenfor sårbare områder og 60 Mha utenfor. Optimal distribusjon tildeler 77.91 % av områdene til BECCS, 25.48 % til AF og 3.50 % til NR. Denne distribusjonen bidrar til totalt 2.56 $GtCO_2eq.yr^{-1}$ fra karbonopptak og reduksjoner i klimagassutslipp. Forlatte jordbruksområder er identifisert ved å bruke satelittdata distribuert av European Space Agency Climate Change Initiative (ESA CCI), som videre er integrert med data for biomasse fra Global Agro-ecological Zones (GAEZ), data for påskogning fra Global Forest Model (G4M) og data for naturlig gjenvekst fra Cook-Patton et al. 2020. Alle beregninger er gjort for en periode på 30 år.

Preface

This master project has been carried out the spring of 2021 at the Department of Energy and Process Engineering, at the Norwegian University of Science and Technology. The aim of the project is to investigate the potential climate change mitigation and carbon sequestration from bioenergy production with and without CCS, natural regrowth and afforestation on global abandoned croplands.

I would like to thank my supervisor Francesco Cherubini for his guidance during this project. A special thanks to my co-supervisor Jan Sandstad Næss for his patience, contributions, good advice and discussions during my work. I would also like to thank Georg Kindermann for running the G4M data, Bo Huang for his work with the climatic data for G4M and Martin Dorber for the gridded version of the terrestrial biomes.

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Nomenclature

Units and abbreviations used in this report:

Units

$GtCO_2eq.$	Giga tons of carbon dioxide equivalents
Mha	Million hectares

Abbreviations

AC	Abandoned Cropland
AF	Afforestation
AR	Assessment Report
BE	Bioenergy
BECCS	Bioenergy with Carbon Capture and Storage
BH	Biodiversity Hotspot
BM	Biomass
CS	Carbon Sequestration
DM	Drymass
ESA CCI	European Space Agency Climate Change Initiative
FAO	Food and Agriculture Organization
GHG	Greenhouse Gas
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
LC	Land Cover
M	Miscanthus
NR	Natural Regrowth
RC	Reed Canary Grass
RCP	Representative Concentration Pathway
S	Switchgrass
SSP	Shared Socio-economic Pathway

Chapter 1

Introduction

1.1 Background

Carbon capture through land-based biomass sequestration and is vital in scenarios limiting global temperature increase well below 2 °C relative to pre-industrial times (Shukla et al. 2019a). Nature based solutions and related land use activities are promising options for mitigating climate change (Roe et al. 2019), such as revegetation of degraded lands, reforestation and afforestation. Another promising and emerging option is bioenergy production with carbon capture and storage (BECCS). Large land cover changes are predicted in the future socioeconomic pathways (SSPs) and representative concentration pathways (RCPs). For SSP1-RCP1.9, the most sustainable scenario according to implementation of mitigation measures (Rogelj et al. 2018), change in bioenergy cropland, cropland and forest from 2010 to 2050 is estimated to +210 Mha, -120 Mha and +340 Mha, respectively (mean values). Furthermore for SSP2-RCP1.9, estimated changes are +450 Mha, -120 Mha and +340 Mha, respectively (Arneth et al. 2019). SSP2 is characterized by a growth in energy use and fossil fuels (Riahi et al. 2011). Lastly, for SSP5-RCP1.9, predicted changes are +670 Mha, -190 Mha and +310 Mha, respectively (Arneth et al. 2019). This scenario is characterized as resource-intensive, with economical, social and technological development, as well as increased human and social capital (Riahi et al. 2011). Climate change mitigation through land use changes for RCP1.9 by 2100 is furthermore estimated to be -2.4 $GtCO_2yr^{-1}$ from afforestation and -14.9 $GtCO_2yr^{-1}$ from BECCS (Shukla et al. 2019b). Across all SSPs in the 1.5 °C scenario, the land use changes are characterized by decreasing food crops and increasing forest and energy crops in 2050 compared to that of 2020 (Roe et al. 2019).

Food security and pressure on global land areas have been, and still are, increasing challenges. The development of cropland areas has resulted in large greenhouse gas (GHG) emissions, the original vegetation being reduced from activities such as land degradation, use of fertilizers and beef production. While croplands continue to increase in area (Winkler et al. 2021), cropland abandonment is also happening at increasing rate all over the world, due to a variety of reasons. The most prominent are ecological, socio-economic and political factors (Benayas et al. 2007). An example of this is the privatization of the public land ownership that resulted in a large share of rural labourers in Eastern Europe abandoning their land and moving to the cities after the collapse of the Soviet Union in 1991 (S. Li and X. Li 2017). Furthermore, there are both positive and negative consequences associated with land abandonment. These are highly dependent on climate and location. Consequences considered positive are for example passive revegetation, soil recovery, water retention and increase of biodiversity. Land abandonment leads to an increase in carbon accumulation, and actively or passively exploiting these land areas is a promising near-term climate change mitigation option. Another opportunity for climate change mitigation is dietary shifts and the release of several crop areas for natural regrowth. This could enhance the carbon sequestered through revegetation and natural regrowth (Cook-Patton et al. 2020). Regeneration measures, such as natural regrowth and afforestation, have the potential of sequestering large amounts of carbon, as well as positively affecting biodiversity and soil quality (Shukla et al. 2019a).

Strong bioenergy growth is one of the requirements presented by the International Institute for Applied Systems Analysis (IIASA) in their Global Energy Assessment of 2012 for an almost fully decarbonized energy sector (Johansson et al. 2012). A primary bioenergy supply of 80-190 EJyr^{-1} by 2050 is reported in the Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) provided by the IPCC (P. Smith et al. 2014). Bonsch et al. 2016 gives an estimate of a potential total bioenergy area in the year of 2095 of up to 1002 Mha. This scenario furthermore corresponds to an increase in forest loss of 20 % between 1995 and 2095. BECCS is considered a mitigation strategy that has the advantage of both being a substitute for fossil fuels, sequestering carbon through biogeochemical processes and of storing carbon in geological pools (Creutzig et al. 2015). Opportunities and limitations are associated with this technology. CCS is considered a costly technology and the process of removing carbon from the atmosphere is difficult to implement in the 'cap and trade' system (Creutzig et al. 2015; Torvanger 2019). However, the technology is considered one of the most promising climate change mitigation measures, with a carbon removal potential of up to 11.3 GtCO$_2$yr^{-1} in 2050 (Shukla et al. 2019a).

Biofuel is traditionally categorized as either first or second generation. First generation biofuel is produced from crops in competition with food production, such as sugar or starch. The advantage of this kind of biofuel is the high content of carbohydrates, but it is normally seen as unethical due to the competition with food crops (Lotze-Campen et al. 2010). Second generation biofuel on the other hand, is characterized by being produced from non-food crops, and will thus not affect food security. These biomasses can be residues from agriculture, forestry and industry (Cherubini 2010). Lignocellulosic biomass is a type of biomass used for production of second generation biofuel and is constructed by cellulose, hemicellulose and lignin, and goes through the processes of hydrolysis and fermentation to become bioethanol (Su et al. 2020). Examples of perennial grasses of lignocellulosic composition are miscanthus, reed canary grass and switchgrass. Choice of bioenergy feedstock and biorefinery technology is significant, and the right combination will vary depending on location and especially climatic factors (Cherubini 2010).

Nature based solutions are of increasing importance and interest as they are considered cost effective and associated with several social and environmental co-benefits. In the period of 2000-2007, the carbon sequestration potential of tropical forest regrowth (i.e. tropical forest areas recovering from deforestation) was estimated to 1.72 ± 0.54 GtCyr^{-1} (Pan et al. 2011). 30 years of natural regrowth (2020-2050) on 349 Mha and 678 Mha (globally distributed forest and savanna biomes) could capture 1.08 GtCyr^{-1} and 1.60 GtCyr^{-1} in aboveground biomass and 0.37 GtCyr^{-1} and 0.54 GtCyr^{-1} in belowground biomass, respectively (Cook-Patton et al. 2020). Active recovery of abandoned croplands on the other hand, such as afforestation, could speed up the recovery process and the carbon sequestration (Yang et al. 2020), but can result in a larger change in biogeophysical conditions (Cao et al. 2019).

New land cover data gives the opportunity of higher accuracy when identifying land use changes. The areas of abandoned croplands are globally distributed and under different climatic conditions. Some areas will consequently have a higher carbon sequestration potential, depending on climatic factors, previous land-use and location. Most previously conducted studies addresses region specific conditions (Field et al. 2020) and large climatic zones (Evans et al. 2015), or do an analysis of one land use strategy only. There is little or no research containing a global spatially explicit analysis and comparison of the mitigation potentials of bioenergy production, natural regrowth and afforestation.

The aim of this study is to present promising options to exploit the advantages associated with cropland abandonment. By integrating data for biodiversity hotspots (Hoffman et al. 2016) and 16 terrestrial biomes (Olson et al. 2001), this study explores the optimal land use strategy for different locations by considering both climate change mitigation potential and land scarcity. Biodiversity hotspots are defined as areas containing at least 1500 endemic species, and that have lost 70 % of the primary vegetation (Myers et al. 2000), and are consequently considered vulnerable. Thus, land use changes in these areas should be conducted with extra consideration. Biomass production is evaluated for three types of perennial grasses, miscanthus, reed canary grass and switchgrass, with high agricultural management intensity and rainfed irrigation. Abandoned croplands are identified by using high-resolution satellite land-cover data distributed yearly by the European Space Agency Climate Change Initiative (ESA-CCI). Simulations on bioenergy crops are conducted using the Global Agro-ecological Zones version 3.0 (GAEZ v3.0). Furthermore, data distributed by Cook-Patton et al. 2020 and the Nature Conservancy is used to evaluate the estimated carbon sequestration following a period of natural regrowth, that is, passive revegetation of degraded land areas. This strategy is compared with simulations conducted with the Global Forest Model (G4M), assessing potential carbon stocks and carbon sequestration rates from afforestation. All data is evaluated for a 30 year period at 5 arc minutes spatial resolution.

1.2 Problem formulation and objectives

The main objectives of this study are listed below:

1. What is the global extent and spatial pattern of cropland abandonment between 1992 and 2018 according to the ESA CCI-LC and C3S-CDS land cover products?
2. What are the annual aboveground carbon sequestration rates of natural vegetation regrowth and active afforestation on abandoned cropland?
3. What are carbon yields, liquid biofuel final energy potentials, BECCS potentials and fossil fuel substitution potentials from producing dedicated bioenergy crops on abandoned cropland?
4. What is the best use of abandoned cropland for climate change mitigation, and how does this vary with spatial location, vegetation management, natural restoration policies and technological constraints?

Chapter 2

Methodology

This section gives an overview of utilized methods. Table 2.1 presents a summary of the model framework and Figure 1 (Appendix A) a complete overview of the models, as well as the conducted data integration and generated results. A 30 year average is made for all data. As demonstrated in Table 2.1, utilized data sets are initially of different spatial resolution. For high visibility and consistency, all data is gridded to 5 arc minutes spatial resolution. Panoply Version 4.11.6. is used for the map constructions.

Table 2.1: Model framework and data foundation.

Model/data	**Developer/ source**	**Resolution**	**Time frame/scenario**	**Relevant content**
ESA CCI-LC	ESA CCI, C3S-CDS	300 m/10 arc seconds	Yearly from 1992 to 2018	Global land cover data
Biodiversity Hotspots (version 2016.1)	Hoffman et al. 2016	-	-	Biodiversity hotspot maps
Terrestrial biomes	Olson et al. 2001	-	-	Map of 16 terrestrial eco-regions/biomes
GAEZ	FAO, IIASA	5 arc minutes, 30 arc seconds	Average of RCP4.5 from 2010 to 2040	Drymass yield
Biorefinery Data	Morales et al. 2021	-	-	CCS and bioethanol efficiency
Phyllis2	ECN/TNO	-	-	Biomass and waste data
Natural Regrowth	Cook-Patton et al. 2020	1 km/30 arc seconds	Historical data from 1990 to 2020	Aboveground carbon accumulation
Global Forest Model	IIASA	50 km	Average of SSP1-RCP1.9 from 2020 to 2050	Biomass, carbon stock and forest area data

2.1 Model framework and data analysis

2.1.1 Land availability

Identification of abandoned croplands

High-resolution satellite land-cover (LC) data distributed by the European Space Agency Climate Change Initiative (ESA-CCI) was used to map global areas of abandoned croplands (ref. *ESA Land Cover CCI: PRODUCT USER GUIDE VERSION 1.1* 2017). 22 land cover types are classified after the Land Cover Classification System (LCCS) developed by the United Nations Food and Agriculture Organization. ESA-CCI LC identifies global land cover types with 300 m (approximately 10 arc seconds) horizontal resolution. Land cover maps are distributed with a yearly temporal resolution for the period of 1992-2015 and are here extended to 2018. The land cover data for 2016-2018 is distributed by Copernicus Climate Change Service (C3S) and made consistent with those of ESA CCI (Defourny 2020). Identification of abandoned croplands is conducted by mapping the abandonment that have occurred in a period of 26 years, identifying areas of cropland in 1992 that are transformed to non-croplands by 2018 (Leirpoll et al. 2021; Næss et al. 2021). The data is further up-scaled to 5 arc minutes resolution for the calculations in this study. As biodiversity hotspots (Hoffman et al. 2016) are considered vulnerable, calculations are conducted for areas inside and outside of biodiversity hotspots separately (See Appendix A Figure 2). The same accounts for the 16 terrestrial biomes (Olson et al. 2001) presented in the end of this chapter.

Scenario description

The following scenarios (summarized in Table 2.2) are defined to evaluate the mitigation potentials related to land use changes on abandoned croplands. Scenario 1-7 assesses areas inside and outside of biodiversity hotspots. The optimal distributions (that does not address biodiversity hotspots) in scenario 3, 4, 6 and 8 are obtained by identifying the highest mitigation potential in each grid cell between the land use strategies. For NR and AF the mitigation potential covers the carbon sequestration potential in each grid cell. For BE it is the emission reduction from fossil fuel substitution and for BECCS the emission reduction from fossil fuel substitution and the CCS potential.

1. **Bioenergy production (BE).** Bioenergy production on all abandoned croplands. The mitigation in this scenario is a result of fossil fuel substitution only. Potentials are calculated with drymass potential and lower heating value, as well as biorefinery data.
2. **Bioenergy production with CCS (BECCS).** Bioenergy production with CCS on all abandoned croplands. The mitigation in this scenario is a result of both fossil fuel substitution and CCS. Potentials are calculated as for BE for fossil fuel substitution and drymass potential and carbon content of drymass for the CCS potential.
3. **Combination of natural regrowth and bioenergy production (NR-BE).** Natural regrowth on abandoned croplands in biodiversity hotspots and bioenergy production on abandoned croplands outside of biodiversity hotspots.
4. **Combination of natural regrowth and bioenergy production with CCS (NR-BECCS).** Natural regrowth on abandoned croplands in biodiversity hotspots and bioenergy production with CCS on abandoned croplands outside of biodiversity hotspots.
5. **Natural regrowth (NR).** Natural regrowth on all abandoned croplands.
6. **Combination of natural regrowth and afforestation (NR-AF).** Natural regrowth on abandoned croplands in biodiversity hotspots and afforestation on abandoned croplands outside of biodiversity hotspots.
7. **Afforestation (AF).** Afforestation on all abandoned croplands.
8. **Optimal (Opt).** The optimal combination of BECCS, NR and AF.

Table 2.2: Scenario description. Acronyms refer to: BH - biodiversity hotspots, BE - bioenergy, BECCS - bioenergy with carbon capture and storage, NR - natural regrowth, AF - afforestation, Opt - Optimal scenario.

BH	non-BH	Scenario name	Description
BE	BE	BE	Bioenergy production on all abandoned croplands.
BE	BE	BECCS	Bioenergy production with CCS on all abandoned croplands.
NR	BE	NR-BE	Natural regrowth on abandoned croplands in biodiversity hotspots and bioenergy production on abandoned croplands outside biodiversity hotspots.
NR	BE	NR-BECCS	Natural regrowth on abandoned croplands in biodiversity hotspots and bioenergy production with CCS on abandoned croplands outside biodiversity hotspots.
NR	NR	NR	Natural regrowth on all abandoned croplands.
NR	AF	NR-AF	Natural regrowth on abandoned croplands in biodiversity hotspots and afforestation on abandoned croplands outside biodiversity hotspots.
AF	AF	AF	Afforestation on all abandoned croplands.
Optimal	Optimal	Opt	The optimal combination of BECCS, NR and AF.

2.1.2 Biomass potentials, carbon capture and storage and biorefinery

Miscanthus *(Miscanthus ssp)* is a perennial grass with C_4 photosynthesis. This type of grass is adaptable to temperature and growing native in both tropic and sub-arctic regions (Lewandowski, JC Clifton-Brown et al. 2000). Several field studies have shown high efficiency and yields for combustion of miscanthus. Reed canary grass *(Phalaris arundinacea)* on the other hand, is a C_3 grass growing native in Northern Europe, mainly Sweden and Finland. It can be harvested once a year and has a low water, ash, potassium and chloride content which is considered an advantage (Lewandowski and Schmidt 2006). Switchgrass *(Panicum airgatum)* is also a C_4 grass originated from North America. Usually seen for switchgrass is a higher yield for lower latitudes (Parrish and Fike 2005). C_4 photosynthetic pathway is characterized by having higher radiation use efficiency and water and nitrogen efficiency than C_3 grasses. Therefore, C_4 grasses are usually better suited for bioenergy production and conditions with limited water and nitrogen sources (Lewandowski and Schmidt 2006; Parrish and Fike 2005).

The Global Agro-ecological Zones version 3.0 (GAEZ v3.0) (ref. Fischer et al. 2012) is used for identification of global aboveground drymass yield. GAEZ is developed by FAO and IIASA and assesses climatic, soil and terrain data. It is a spatially explicit model constructed at 5 arc minutes and 30 arc seconds resolutions. To assess suitability and potential yield, GAEZ distinguishes between 49 crop categories and 92 crop types. Intensity of agricultural management is also significant, and three different levels of intensity are defined in the model, that is, low, medium and high. Potentials are in addition evaluated for 'irrigated' and 'rainfed' water management. Miscanthus, reed canary grass and switchgrass are the three lignocellulosic bioenergy feedstocks identified in GAEZ. These perennial grasses are in this study evaluated at high agricultural management intensity and rainfed water supply. High-intensity agricultural management is characterized by a commercial farming system, being mechanized with low labor intensity (Fischer et al. 2012). Fertilizers and other controlling mechanisms are used against pests, diseases and weed. Furthermore, the calculations are conducted for the most representative conditions of today, which is Representative Concentration Pathway with increase in radiative forcing of maximum 4.5 Wm^{-2} (RCP4.5). This scenario is evaluated for the year of 2020, that is an average of the period 2010-2040.

Table 2.3: Biomass data collected from the Phyllis2 database. Carbon (C) content is given as fraction of drymass. Lower heating value (used for calculations on bioenergy potential) is vectorized after crop part and given in MJkg^{-1}.

Feedstock	**C content of drymass ***	**Lower heating value** [MJkg^{-1}]
Miscanthus	0.4777	18.55
Reed Canary Grass	0.4526	18.06
Switchgrass	0.4632	17.82

Source: Phyllis2

**Ash content of drymass is not included.*

Table 2.4: Biorefinery data for the future BECCS scenario. Data distributed by Morales et al. 2021. The same data is assumed for reed canary grass, as for switchgrass.

Property	**Miscanthus**	**Switchgrass**
Energy efficiency [Share of feedstock LHV]		
MJ/MJ feedstock	0.400	0.460
Carbon inputs [C kmol(C kmol feedstock)$^{-1}$]		
Feedstock	1.000	1.000
Other *	0.010	0.010
Carbon outputs [C kmol(C kmol feedstock)$^{-1}$]		
Ethanol	0.280	0.310
Combustion exhaust	0.510	0.510
Scrubber vent	0.140	0.160
Aerobic gases	0.026	0.007
*Total ***	*0.956*	*0.987*

Source: Morales et al. 2021

** "Other" includes yeast, enzyme and CSL.*
*** The remaining 1.3-4.4 % is here referred to as as 'other carbon outputs' and includes ash, molecular sieves vent and other emissions not identified.*

Drymass of miscanthus, reed canary grass and switchgrass is given in the GAEZ dataset as $tdmha^{-1}yr^{-1}$. This dataset represents the rate of net drymass production per year, given by the respiration and the rate of gross photosynthesis for the respective feedstock. The optimal distribution of the three perennial grasses is based on drymass efficiency in each grid cell. This distribution is further used when calculating the potentials related to bioenergy production. Carbon content as fraction of drymass and lower heating value is given in the Phyllis2 database (Bergman et al. 2002; Rabou et al. 2004) for the three feedstocks (Table 2.3). Yearly carbon yield is used to calculate the CCS potential, and the yearly energy potential is used to estimate the possible emission reduction from fossil fuel substitution. Phyllis2 is a biomass and waste database developed by the Energy Research Centre of the Netherlands (ECN) and the Netherlands Organisation for applied scientific research (TNO). It is assumed an evenly distributed carbon content in aboveground biomass.

Biofuels can act as a substitute for fossil fuels, and thus contribute to reducing the fossil fuel related GHG emissions to the atmosphere (i.e. the BE scenario). Bioenergy production can also be a negative emission technology, as GHGs can be removed from the atmosphere through CCS. Carbon will be sequestered in the growing process, and instead of being emitted in the refinery process it will be captured and stored. Thus, production of bioenergy can contribute to both decarbonize fossil fuel dependent sectors and as a negative emission (i.e. the BECCS scenario). Biorefinery data distributed by Morales et al. 2021 (Table 2.4) is used to calculate bioethanol efficiency and CCS potential. Data is given for miscanthus and switchgrass. Reed Canary Grass is a feedstock less investigated, and energy efficiency, as well as carbon inputs and outputs, are assumed the same as for Switchgrass. Combustion exhaust, scrubber vent and aerobic gases constitutes the proportion of carbon output that could be captured through CCS. The amount of carbon possible to sequester according to Morales et al. 2021 is in total 0.676 of carbon input for Miscanthus and 0.677 for Switchgrass. Due to some expected leak from combustion exhaust during CCS, an efficiency of 85 % is assumed (Muri 2018). This results in a total CCS potential of 0.600 for Miscanthus and 0.601 for Switchgrass.

Associated with the combustion of fuel from regular petroleum is an emission of 70 $MtCO_2eqEJ^{-1}$ (Burnham et al. 2012; Chum et al. 2011). Calculated here is a direct substitution between biofuels and fossil fuels and it is thus assumed that 70 $MtCO_2eq$ is the possible emission reduction per EJ of bioethanol (final energy). Yearly drymass yield and lower heating value of the respective feedstocks is used to calculate yearly bioenergy yield. The reduction in energy from fossil fuels due to the biofuel substitution is considered a reduction in GHG emissions from fossil fuels. Potential of GHG emission reduction and CCS is furthermore added together to evaluate the total BECCS potential.

2.1.3 Natural regrowth

Natural regrowth is estimated by utilizing a dataset developed by a group of researchers from the Nature Conservancy (ref. Cook-Patton et al. 2020). The dataset provides global aboveground carbon accumulation rates and thus makes it possible to estimate the climate change mitigation potentials related to natural regrowth. The dataset is available at 30 arc seconds resolution and is here aggregated to 5 arc minutes spatial resolution. Natural regrowth is defined by Cook-Patton et al. 2020 as the spontaneous recover of forest and savanna biomes, without any silvicultural measures, but with the removal of potential disturbances. Aboveground biomass included here is stem and branch biomass, not foliage (Cook-Patton et al. 2020 Supplementary Information).

Considered in this dataset and report (Cook-Patton et al. 2020) is primarily aboveground carbon, as global soil carbon (belowground) data is little investigated in previous studies. Thus, an increased representation was possible for the aboveground carbon accumulation modelling. Simulations conducted with this dataset is therefore only carbon sequestration in aboveground forest regrowth, consistent with the GAEZ and G4M data.

2.1.4 Afforestation

Afforestation simulations are conducted with the spatially explicit Global Forest Model (G4M). This is a model of 0.5°x 0.5°resolution that simulates land use changes. It is based on decisions on forest management from 229 units (countries and territories) and calculates the corresponding CO_2 emissions (Mykola Gusti and Georg Kindermann 2011). The model is presented by Gusti (2015) as composed of four categories, each with their respective parameters:

- Environment: Based on natural conditions and forest parameters
- Economy: Land prices and net present value of forestry and agriculture, as well as costs of harvesting and planting
- Decision making: Based on forest management and land use
- Emission estimation: Emissions based on previous categories

The currently available information on forest biomass is limited. The G4M uses the Global Forest Resources Assessment (FRA) produced by the Food and Agriculture Organization (FAO). FRA contains country level maps on growing stock, carbon stock and forest biomass, and is the main source of G4M (Kindermann et al. 2008). The simulations are furthermore conducted for SSP1-RCP1.9. This scenario is chosen to reach the highest possible compliance between G4M, GAEZ and the natural regrowth data (Cook-Patton et al. 2020). The parameters are averaged in the time period 2020-2050. Mean annual increment (MAI) is given in $tCha^{-1}yr^{-1}$, and both carbon stock and MAI are functions of maximum average increment and year and are dependent on forest age.

G4M emphasizes stem biomass (G. E. Kindermann et al. 2013) and a share of the biomass and aboveground carbon will therefore be left out. This is corrected by adding +20 % to the G4M data, representing branches, leaves, needles and other parts of the aboveground biomass not covered by the stemwood. This estimate is age dependent and will decrease with forest age. Furthermore, the calculations are conducted for coniferous and non-coniferous forests independently and combined. This gives the opportunity of evaluating the efficiency of different types of forests. The optimal distribution of these two types of forests is used to calculate the potential in the scenarios including AF, estimated from highest carbon sequestration potential.

2.1.5 Terrestrial biomes

To evaluate how location and climate affects the growth rate and carbon accumulation of biomass, afforestation and natural regrowth the data is integrated with a map of 16 terrestrial biomes, developed by Olson et al. 2001. Land use strategy is highly dependent on location and climate. This data integration explores the differences between habitats and how vegetation and habitats affect the carbon sequestration potential of the respective lands. The 16 biomes are major habitat types and defined with the following IDs: (1) Tropical and subtropical moist broadleaf forests, (2) Tropical and subtropical dry broadleaf forests, (3) Tropical and subtropical coniferous forests, (4) Temperate broadleaf and mixed forests, (5) Temperate conifer forests, (6) Boreal forests/taiga, (7) Tropical and subtropical grasslands, savannas and shrublands, (8) Temperate grasslands, savannas and shrublands, (9) Flooded grasslands and savannas, (10) Montane grasslands and shrublands, (11) Tundra, (12) Mediterranean forests, woodlands and shrub, (13) Deserts and xeric shrublands, (14) Mangroves, (98) Lakes, (99) Rock and ice. See Appendix A Figure 3 for a visualization of the biomes.

Chapter 3

Results and Discussion

This section presents the main findings of this study and the related uncertainties. Abandoned croplands are first presented, followed by the potentials of the three land use climate change mitigation strategies for the areas of abandoned croplands. Each strategy is evaluated independently, followed by a comparison of the eight scenarios presented in Section 2.1.1. All potentials are calculated for biodiversity hotspots and non-biodiversity hotspots. The potentials in the 16 terrestrial biomes are presented and discussed throughout the chapter.

3.1 Identification of abandoned croplands

A total cropland abandonment of 97.6 Mha was identified between 1992 and 2018 (Figure 3.1 (a)). Out of these 97.6 Mha, approximately 37.6 Mha (Figure 3.1 (b)) is located inside biodiversity hotspots and 60 Mha outside of biodiversity hotspots (Figure 3.1 (c)). Compared to the 83.3 Mha of previously mapped abandoned croplands (Leirpoll et al. 2021; Næss et al. 2021) in the period 1992-2015, the new C3S dataset indicates that the rate of land abandonment is increasing, demonstrated with an abandonment of 3.6 Mha yr^{-1} between 1992 and 2015 from ESA CCI-LC and 4.8 Mha yr^{-1} between 2015 and 2018.

The highest shares of abandoned croplands are found in four prominent terrestrial biomes: 27.81 %, 18.57 %, 19.09 % and 7.25 % in tropical and subtropical moist broadleaf forests (id 1), temperate broadleaf and mixed forests (id 4), tropical and subtropical grasslands, savannas and shrublands (id 7) and temperate grasslands, savannas and shrublands (id 8), respectively (Table 3.1). The abandoned croplands are presented individually for each terrestrial biome in Figure 4 (biome 1-8) and Figure 5 (biome 9-16) in Appendix A. In terrestrial biome 1, approximately 70 % of the abandoned croplands are located inside biodiversity hotspots. These are primarily identified in the Malay Archipelago (and some areas on the mainland Southeast Asia), South East Asia and Central America, as well as Brazil, Colombia, the West and East African coast and eastern Indian coast. Tropical and subtropical moist broadleaf forests are characterized with high levels of rainfall and stable temperatures, containing a high amount of endemic species (FAO and UNEP 2020). In terrestrial biome 4, 7 and 8 on the other hand, less than 20 % of the areas are located in biodiversity hotspots and could possibly be better suited for large-scale bioenergy production. Cautions should be made regarding native species of the chosen area, as large spreading of for example a biomass feedstock can be unfortunate in some regions (Lewandowski, John Clifton-Brown et al. 2016). The largest part of the abandoned croplands in Europe is located in terrestrial biome 4 (temperate broadleaf and mixed forests) (Figure 4 (d) Appendix A). All of the European areas seen here are identified outside of biodiversity hotspots and can thus be well suited for e.g. larger scale bioenergy crops or afforestation.

It is assumable that some of the abandoned croplands are unfavorable for anything other than natural regrowth. That is, biome 10 (montane grasslands and shrublands), 11 (tundra), 13 (deserts and xeric shrublands), 98 (lakes) and 99 (rock and ice). These areas make up a total of 8.40 Mha

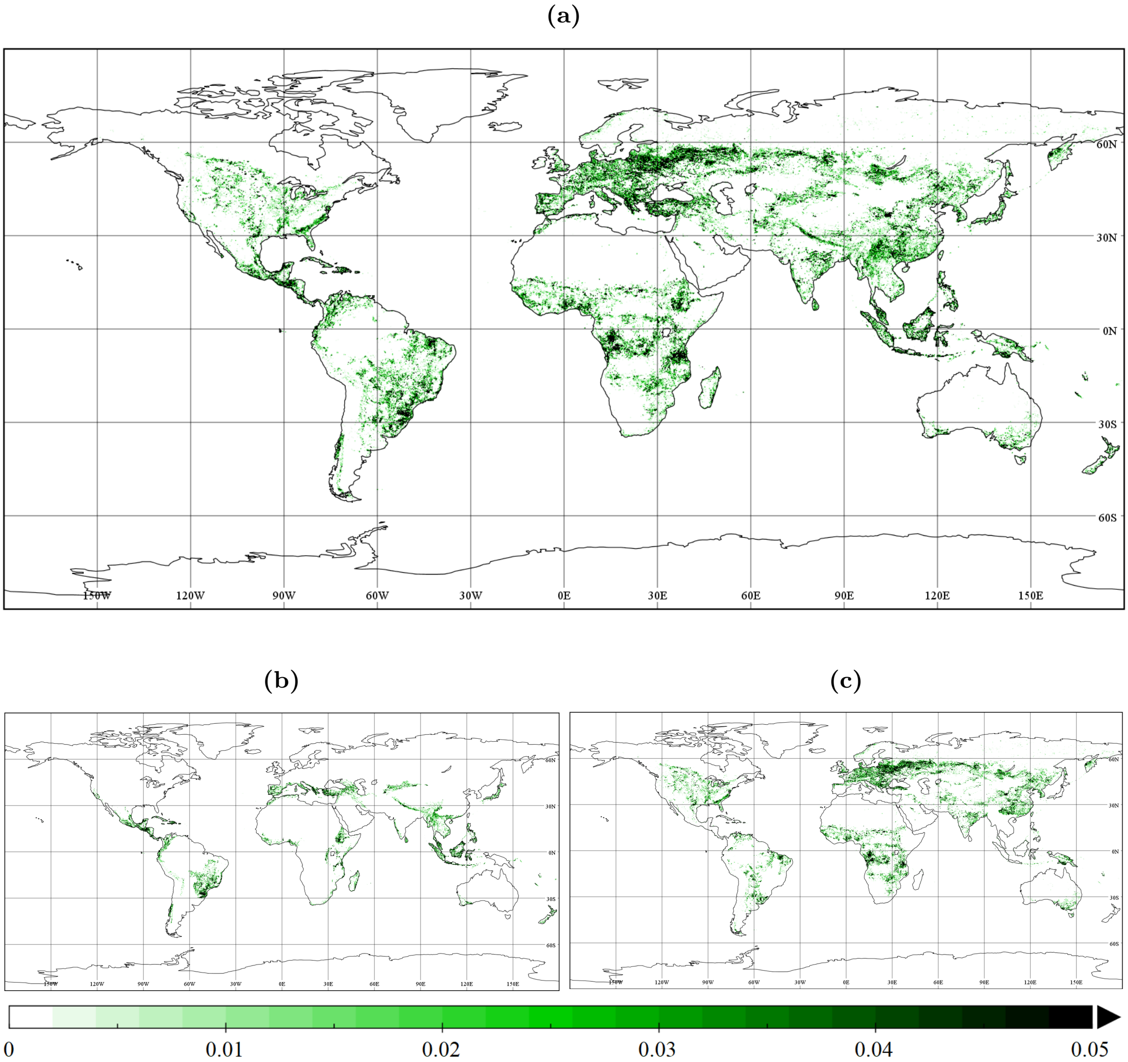


Figure 3.1: Global cropland abandonment between 1992 and 2018. Cropland abandonment demonstrated as total (**a**), inside (**b**) and outside (**c**) of biodiversity hotspots as fraction of grid cell area.

and is a significant share of the total area of abandoned croplands. Furthermore, the areas with a relatively low share of biodiversity hotspots (maximum 22 %) are biome 4-9 with a total area of 49.91 Mha. Areas that contain a large part of the biodiversity hotspots (minimum 65.16 %) are biome 1, 2, 3, 12 and 14, which makes up a total area of 38.74 Mha. These are rough divisions of the abandoned croplands, but an indication of which land use strategy that is appropriate in the respective areas.

The previous land use of the respective land areas will have a large impact on current and future productivity (Cramer et al. 2008). For example, recent abandoned croplands in previous eucalypt woodland areas in south-western Australia is recovering slowly. Due to intensive use of fertilizers, the conditions for the native species to grow are weak. Thus, these land areas are mainly revegetated with invasive exotic species, and the native species can gain a foothold only after several decades. This will affect the efficiency of the different land use strategies, especially those that are passive. Active revegetation, such as afforestation or biomass production, could potentially have more prominent results. Land abandonment is in addition predicted to increase in the future, due to agricultural intensification and climate change (Cramer et al. 2008). An increasing rate of land abandonment can contribute to an increasing rate of carbon accumulation in land and can have positive effects on both soil quality and local biodiversity. However, increasing land abandonment is a result of a decreasing global cropland area and can potentially affect food security.

Table 3.1: Abandoned croplands in terrestrial biomes. Amounts and shares of abandoned croplands in the 16 terrestrial biomes. Acronyms refer to: AC - abandoned cropland, BH - biodiversity hotspots. Biome IDs: (1) Tropical and subtropical moist broadleaf forests, (2) Tropical and subtropical dry broadleaf forests, (3) Tropical and subtropical coniferous forests, (4) Temperate broadleaf and mixed forests, (5) Temperate conifer forests, (6) Boreal forests/taiga, (7) Tropical and subtropical grasslands, savannas and shrublands, (8) Temperate grasslands, savannas and shrublands, (9) Flooded grasslands and savannas, (10) Montane grasslands and shrublands, (11) Tundra, (12) Mediterranean forests, woodlands and shrub, (13) Deserts and xeric shrublands, (14) Mangroves, (98) Lakes, (99) Rock and ice.

Biome ID	**AC in biome** [Mha]	**Share of all AC in biome** [%]	**Share of all AC in BH in biome** [%]	**Share of all AC in non-BH in biome**[%]
1	27.142	27.814	70.040	29.960
2	4.298	4.404	65.359	34.641
3	1.532	1.570	98.383	1.617
4	18.117	18.566	11.475	88.525
5	3.200	3.279	22.286	77.714
6	2.150	2.204	0.000	100.000
7	18.619	19.081	16.464	83.536
8	7.073	7.248	14.449	85.551
9	0.750	0.768	11.337	88.663
10	4.147	4.249	42.180	57.820
11	0.500	0.096	0.000	100.000
12	4.951	5.073	92.130	7.870
13	3.709	3.801	5.976	94.024
14	0.813	0.833	65.162	34.838
98	0.036	0.037	29.623	70.377
99	0.007	0.007	33.596	66.404

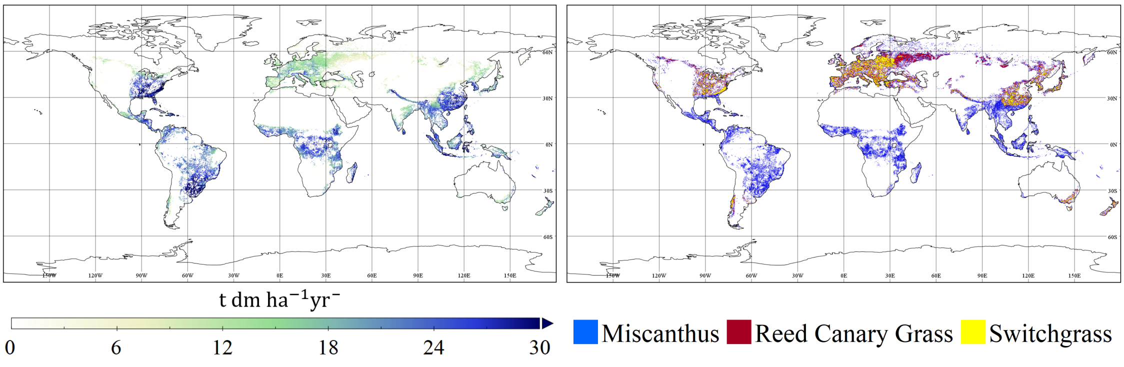
3.2 Climate change mitigation potential of bioenergy production, afforestation and natural regrowth

The following sections first presents the mitigation potentials of the four scenarios BE, BECCS, NR and AF. Then presented is the combination of these four scenarios, as well as the optimal scenario, i.e. NR-BE, NR-BECCS, NR-AF and Opt.

3.2.1 Bioenergy production and CCS

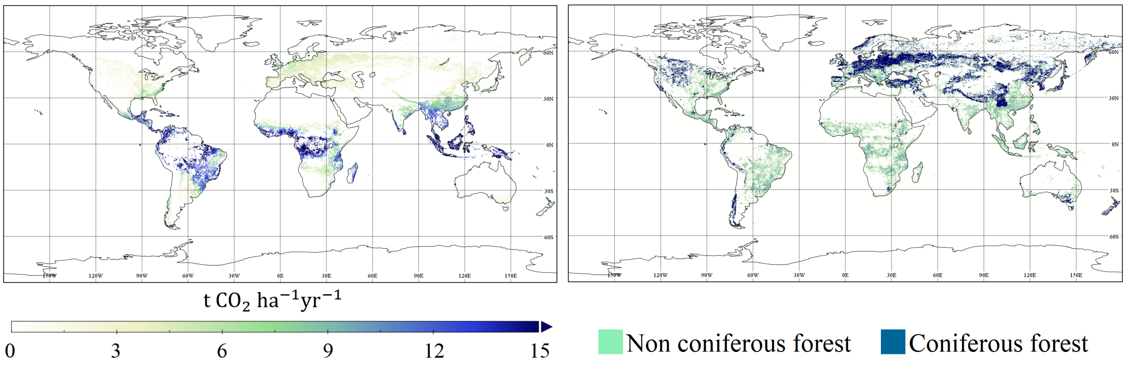
This section presents the results for the scenarios only assessing bioenergy production, i.e. BE (scenario 1) and BECCS (scenario 2). Global distribution of drymass yield in abandoned croplands is demonstrated in Figure 3.2 (a) and the optimal distribution of miscanthus, reed canary grass and switchgrass can be seen in Figure 3.2 (b). When considering all abandoned croplands (97.6 Mha), the results gives that miscanthus is best suited, covering 53.5 % of the abandoned croplands, followed by 30.1 % for switchgrass and 16.5 % for reed canary grass. Miscanthus has the highest drymass efficiency primarily in the abandoned croplands around the equator (tropical regions), switchgrass in Europe, Eastern United States and Eastern Asia (China, Korea and Japan) and reed canary grass primarily in Russia and Scandinavia. Highest drymass yield in the optimal feedstock combination is seen primarily in the areas where miscanthus is dominating, but also in some of the areas where switchgrass has the highest efficiency.

Table 3.2 shows drymass and bioenergy potential within and outside of biodiversity hotspots, as well as the CCS potential. Drymass yield is estimated to 12.00 t dm ha^{-1}yr^{-1}, 0.74 t dm ha^{-1}yr^{-1} and 3.46 t dm ha^{-1}yr^{-1} for miscanthus, reed canary grass and switchgrass in all abandoned crop-



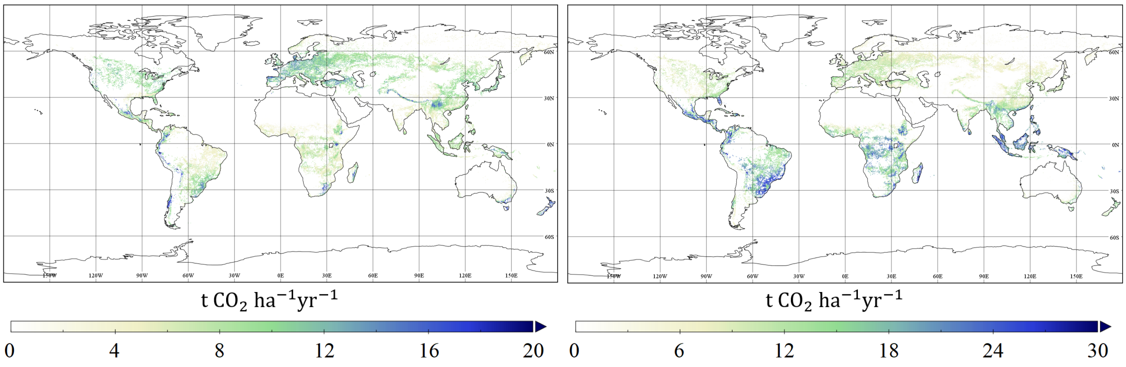
(a) Bioenergy drymass yield

(b) Optimal bioenergy feedstock distribution



(c) Natural regrowth yield

(d) Optimal forest distribution



(e) Afforestation yield for coniferous forests

(f) Afforestation yield for non-coniferous forests

Figure 3.2: Optimal yields. Forest and feedstock distribution. Global drymass yield of the optimal combination of miscanthus, reed canary grass and switchgrass in all abandoned croplands **(a)**, optimal feedstock distribution based on drymass potential in all abandoned croplands **(b)**, natural regrowth yield **(c)**, optimal distribution of coniferous and non-coniferous forests **(d)** and carbon sequestration yield for coniferous forests **(e)** and non-coniferous forests **(f)** in all abandoned croplands. Note the scale differences between the maps.

lands, respectively. A range of possible carbon sequestration through CCS of 0.78-1.62 GtCO$_2$yr^{-1} is obtained by assuming that all areas are available for bioenergy crop production. Ethanol potential (Table 3.2) is estimated to 5.43-11.16 EJyr^{-1}. These ranges correspond to bioenergy crops in biodiversity hotspots (minimum) and in all abandoned croplands (maximum). By assuming a direct substitution between fossil fuels and biofuels, these potentials results in a possible emission reduction of 0.38-0.78 GtCO$_2$eq.yr^{-1} (Table 3.3) from the implementation of biofuels. Total mitigation for the two scenarios (Table 3.3) is estimated to 0.78 GtCO$_2$eq.yr^{-1} and 2.41 GtCO$_2$eq.yr^{-1} for BE and BECCS, respectively. Hence, CCS can contribute to more than tripling the mitigation potential from bioenergy.

Table 3.2: Bioenergy mitigation potentials. Optimal distribution of the three bioenergy feedstocks, drymass yield and potential, as well as mitigation potentials from bioenergy production: fossil fuel substitution (ethanol potential) and CCS.

Potential	Optimal distribution	Miscanthus	Reed Canary Grass	Switchgrass	Total
% of each feedstock in optimal distribution	In BH	78.11	4.95	16.94	100.00
	Outside BH	38.67	23.38	37.95	100.00
	All	53.50	16.45	30.05	100.00
Drymass yield [t dm ha^{-1}yr^{-1}]	In BH	17.72	0.22	2.00	19.94
	Outside BH	8.42	1.07	4.38	13.87
	All	12.00	0.74	3.46	16.02
Drymass potential [Mt dm yr^{-1}]	In BH	666.57	8.21	74.85	749.62
	Outside BH	504.83	64.37	262.91	832.11
	All	1171.40	72.57	337.76	1581.74
Primary bioenergy potential [EJyr^{-1}]	In BH	12.36	0.15	1.33	13.85
	Outside BH	9.36	1.16	4.69	15.21
	All	21.73	1.31	6.02	29.06
Ethanol potential [EJyr^{-1}]	In BH	4.95	0.07	0.41	5.43
	Outside BH	3.75	0.53	1.45	5.73
	All	8.69	0.60	1.87	11.16
CCS potential [MtCO$_2$yr^{-1}]	In BH	700.06	8.18	70.93	779.17
	Outside BH	530.19	64.15	249.17	843.51
	All	1230.26	72.33	320.10	1622.69

Table 3.3: Total mitigation for the BE and BECCS scenario. Bioenergy potential with and without CCS presented for areas inside and outside biodiversity hotspots and all abandoned croplands. The two scenarios both assesses bioenergy production on all abandoned croplands and the total amount on all abandoned croplands (bold) gives the total mitigation potential for these two scenarios.

Mitigation	Area	BE	BECCS
Emission reduction (fossil fuel substitution) [MtCO$_2$eq.yr^{-1}]	in bh	379.93	379.93
	outside bh	401.31	401.31
	all	781.24	781.24
Emission removal (CCS) [MtCO$_2$yr^{-1}]	in bh	-	779.17
	outside bh	-	843.51
	all	-	1622.69
Total	in bh	379.93	1159.10
	outside bh	401.31	1244.82
	all	**781.24**	**2403.92**

For both BE and BECCS, highest yields are seen in terrestrial biome 1, 3 and 14 (Table 3.4). For BE, estimated ethanol yields are 171.06 GJha^{-1}yr^{-1} (biome 1), 157.11 GJha^{-1}yr^{-1} (biome 3) and 159.89 GJha^{-1}yr^{-1} (biome 14), with the corresponding CCS yields 24.38 MtCO$_2$yr^{-1} (biome 1), 22.46 MtCO$_2$yr^{-1} (biome 3) and 22.63 MtCO$_2$yr^{-1} (biome 14). As biomass production might have negative consequences for biodiversity and native species in the chosen region, cautions should be made regarding the alternative locations considered suited for this kind of industry. According to the divisions made in Section 3.1 neither biome 1, 3 nor 14 might be the areas best suited for biomass production, based on land scarcity and productivity. Biome 4-9 could be better options, with total potentials of 0.72 GtCO$_2$yr^{-1} for CCS and 4.82 EJyr^{-1} for fossil fuel substitution. Terrestrial biome 7, i.e. tropical and subtropical grasslands, savannas and shrublands (see Figure 4 (g) Appendix A), has a relatively high yield (19.76 MtCO$_2$yr^{-1} from CCS and 139.59 GJha^{-1}yr^{-1} from fossil fuel substitution). The areas of this biome are primarily located in South America and Africa south of Sahara. This also applies for biome 4 (temperate broadleaf and mixed forests) that is the third

Table 3.4: Bioenergy potential in terrestrial biomes. Bioenergy yields and potentials in the 16 terrestrial biomes. Biome IDs: (1) Tropical and subtropical moist broadleaf forests, (2) Tropical and subtropical dry broadleaf forests, (3) Tropical and subtropical coniferous forests, (4) Temperate broadleaf and mixed forests, (5) Temperate conifer forests, (6) Boreal forests/taiga, (7) Tropical and subtropical grasslands, savannas and shrublands, (8) Temperate grasslands, savannas and shrublands, (9) Flooded grasslands and savannas, (10) Montane grasslands and shrublands, (11) Tundra, (12) Mediterranean forests, woodlands and shrub, (13) Deserts and xeric shrublands, (14) Mangroves, (98) Lakes, (99) Rock and ice.

Biome ID	**Dm yield [t dm ha^{-1}yr^{-1}]**	**Dm potential [Mt dm yr^{-1}]**	**CCS yield [tCO$_2$ ha^{-1}yr^{-1}]**	**CCS potential [MtCO$_2$ yr^{-1}]**	**Ethanol yield [GJha^{-1}yr^{-1}]**	**Ethanol potential [EJyr^{-1}]**
1	23.314	632.787	24.381	661.750	171.060	4.643
2	16.793	72.168	17.636	75.794	124.602	0.535
3	21.523	32.974	22.464	34.416	157.110	0.241
4	14.572	264.000	13.948	252.696	87.015	1.576
5	13.232	42.341	13.003	41.608	84.942	0.272
6	6.854	14.738	6.827	14.679	56.698	0.122
7	18.816	350.335	19.760	367.917	139.592	2.599
8	3.357	23.740	3.286	23.242	22.666	0.160
9	16.583	12.435	17.049	12.785	117.068	0.088
10	6.996	29.011	7.303	30.285	51.976	0.216
11	0.094	0.018	0.603	0.116	5.030	0.001
12	11.705	57.951	11.350	56.191	70.569	0.349
13	3.464	12.847	3.600	13.351	25.175	0.093
14	21.549	17.525	22.632	18.406	159.894	0.130
98	11.406	0.409	11.544	0.414	77.229	0.003
99	0.634	0.004	0.621	0.004	4.516	0.000

largest area of abandoned croplands. In this case, only 11.48 % is located in biodiversity hotspots. Biome 4 located outside of biodiversity hotspots is primarily found in Europe. Biome 5, 6 and 8 are also of significant size (3.20 Mha, 2.15 Mha and 7.07 Mha respectively) and are located completely outside of, or with a small share within biodiversity hotspots. All of these areas are primarily found in North America, Europe and Central Asia. Yields of these areas are significantly lower than that of biome 1, 3 and 14, but still with a certain impact.

Previous studies generally show a higher drymass productivity for miscanthus than for switchgrass. This is especially the case in central Africa and South America (Ai et al. 2020; Evans et al. 2015; W. Li et al. 2020). The high yields in tropical and subtropical regions might be due to the high rainfall and humidity in these regions (FAO and UNEP 2020). This study evaluates only yields from rainfed bioenergy production and the yields would be different for irrigated scenarios, for instance in temperate regions (Ai et al. 2020). High agricultural management intensity also leads to higher biomass yield (Næss et al. 2021), but might have negative consequences for local climatic conditions and biodiversity.

3.2.2 Natural regrowth

This section presents the results for the NR scenario. Highest NR yield (Figure 3.2 (c)) is seen in Central and South America, Central Africa and Southeast Asia. These yields are significantly higher than for the rest of the abandoned croplands. Table 3.5 shows the predicted carbon sequestration from NR in forest and savanna biomes in abandoned croplands globally. These are estimates for the next 30 years (2020-2050) based on historical data. NR yields are estimated to 10.08 tCO$_2$ha^{-1}yr^{-1}, 6.69 tCO$_2$ha^{-1}yr^{-1} and 7.99 tCO$_2$ha^{-1}yr^{-1} in biodiversity hotspots, outside of biodiversity hotspots and in all abandoned croplands, respectively. The total potential range is calculated to 379.11-780.14 MtCO$_2$yr^{-1}.

Table 3.5: Carbon sequestration potential of natural regrowth in forest and savanna biomes.

Area	NR yield **[tCO_2 $ha^{-1}yr^{-1}$]**	NR potential **[$MtCO_2yr^{-1}$]**
In BH	10.08	379.11
Non-BH	6.69	401.03
All	7.99	780.14

Table 3.6: Natural regrowth and afforestation in terrestrial biomes, as well as emission reduction from fossil fuel substitution. Yields and potentials of natural regrowth and afforestation in the 16 terrestrial biomes, as well as emission reduction from fossil fuel substitution. Biome IDs: (1) Tropical and subtropical moist broadleaf forests, (2) Tropical and subtropical dry broadleaf forests, (3) Tropical and subtropical coniferous forests, (4) Temperate broadleaf and mixed forests, (5) Temperate conifer forests, (6) Boreal forests/taiga, (7) Tropical and subtropical grasslands, savannas and shrublands, (8) Temperate grasslands, savannas and shrublands, (9) Flooded grasslands and savannas, (10) Montane grasslands and shrublands, (11) Tundra, (12) Mediterranean forests, woodlands and shrub, (13) Deserts and xeric shrublands, (14) Mangroves, (98) Lakes, (99) Rock and ice.

Biome ID	**NR yield [tCO_2 $ha^{-1}yr^{-1}$]**	**NR potential [$MtCO_2$ yr^{-1}]**	**AF yield [tCO_2 $ha^{-1}yr^{-1}$]**	**AF potential [$MtCO_2$ yr^{-1}]**	**Fossil fuel reduction yield [tCO_2-eq $ha^{-1}yr^{-1}$]**	**Fossil fuel reduction potential [$MtCO_2$ yr^{-1}]**
1	13.492	366.201	17.779	482.559	11.974	325.010
2	9.450	40.614	13.145	56.491	8.722	37.450
3	9.195	14.087	18.439	28.250	10.998	16.870
4	4.349	78.792	10.594	191.930	6.091	110.320
5	4.092	13.095	10.706	34.258	5.946	19.040
6	3.670	7.892	7.981	17.162	3.969	8.540
7	10.400	193.651	15.282	284.549	9.771	181.930
8	2.682	18.967	8.541	60.409	1.587	11.200
9	1.290	0.968	11.819	8.863	8.195	6.160
10	2.921	12.112	11.123	46.123	3.638	15.120
11	0.094	0.018	4.621	0.885	0.352	0.070
12	3.546	17.553	8.725	43.196	4.940	24.430
13	1.977	7.333	7.968	29.552	1.762	6.510
14	3.495	2.843	13.877	11.286	11.193	9.100
98	3.833	0.137	7.885	0.283	5.406	0.210
99	0.360	0.002	2.328	0.015	0.316	0.000

Table 3.6 shows the natural regrowth potentials in the 16 terrestrial biomes. Highest yields are seen in biome 1 and 7, in addition to relatively high yields in biome 2 and 3. Natural regrowth will most likely have positive effects on local climates and biodiversity, but can result in lower biomass production compared to active recovery (e.g. afforestation) (Valkó et al. 2016). By assuming that all areas inside biodiversity hotspots are suited for natural regrowth, a carbon sequestration potential of 0.38 $GtCO_2$-eq.yr^{-1} is obtainable. This can be considered the minimum mitigation potential of this study. By considering terrestrial biomes containing a large amount of biodiversity hotspots (i.e. 1, 2, 3, 12 and 14) and the areas where bioenergy and afforestation might be difficult to implement (10, 11, 13, 98 and 99) the total potential for NR is 0.46 $GtCO_2yr^{-1}$.

A large potential is associated with the NR scenario. However, there are uncertainties related to these potentials and to the variables affecting the NR related carbon sequestration. The climate gain might be affected by social and political factors, as well as the management of the respective land areas left for NR (B. W. Griscom et al. 2017).

Table 3.7: Carbon sequestration potential and yield of afforestation. Potentials and yields for the AF scenario, given for coniferous and non-coniferous forests independently and for the optimal combination of them.

	AF potential [$MtCO_2yr^{-1}$]		AF yield and potential in optimal forest distribution	
Area	**Coniferous forests**	**Non-coniferous forests**	**Yield** [$tCO_2ha^{-1}yr^{-1}$]	**Potential** [$MtCO_2yr^{-1}$]
In BH	288.96	595.34	16.14	607.05
Non-BH	438.33	674.35	11.69	701.13
All	727.29	1269.69	13.41	1308.18

3.2.3 Afforestation

Highest carbon sequestration from afforestation is obtained with 38 % of coniferous and 62 % of non-coniferous forests (Figure 3.2 (d)). Figure 3.2 (e) and (f) shows independent yields for coniferous and non-coniferous forests, respectively. Highest yields for coniferous forests is found in Europe and for non-coniferous forests in Central and South America, Africa south of Sahara and Southeast Asia. Optimal forest distribution results in a potential carbon sequestration of 0.61-1.31 $GtCO_2yr^{-1}$ (Table 3.7). For this optimal forest distribution, the spatial carbon sequestration is estimated to 13.4 $tCO_2ha^{-1}yr^{-1}$, 16.14 $tCO_2ha^{-1}yr^{-1}$ and 11.69 $tCO_2ha^{-1}yr^{-1}$ in all abandoned croplands, only biodiversity hotspots and outside biodiversity hotspots, respectively. These results are consistent with those of previous studies, such as the mitigation potential presented for secondary forests in the Amazon, of maximum 3.2 ± 0.6 $tCha^{-1}yr^{-1}$ (Heinrich et al. 2021), that corresponds to 11.7 ± 2.2 $tCO_2ha^{-1}yr^{-1}$. Afforestation yield is also affected by rainfall and drought, and rate of fires affect the emissions related to forest disturbances.

Table 3.6 shows the afforestation potentials in the 16 terrestrial biomes. Highest yield is seen in biome 3, followed by biome 1, 7 and 14. As for the BE and BECCS scenarios, cautions should be made regarding the choice of location for afforestation. However, afforestation might be less aggressive than bioenergy production and a positive contribution for local climate and communities. For example, mangroves (biome 14) are primarily located on abandoned croplands inside biodiversity hotspots (65.16 %). Several large-scale mangrove afforestation initiatives have been implemented in Bangladesh and turned out to have several associated co-benefits (Islam and Rahman 2015; Saenger and Siddiqi 1993). Afforestation initiatives in scarce regions should still be conducted carefully, as some species might be better suited than others. The forest management (e.g. cutting and trimming) and water use routines are also important for positive outcomes (B. W. Griscom et al. 2017).

Several co-benefits are associated with afforestation and the planting of trees for climate change mitigation in general (e.g. agroforestry). Examples are improved conditions for biodiversity, water regulation and soil quality, as well as air quality (B. W. Griscom et al. 2017). Benefits are also observed in agroforestry systems, where trees can contribute with for example crop shading and increased soil fertility (Tschora and Cherubini 2020). Thus, combinations of the land use strategies assessed in this study are also promising options.

3.2.4 BE, NR and AF in terrestrial biomes

A comparison between NR and AF can be conducted regarding the discussion about active vs. passive revegetation. Active recovery measures does not guarantee a faster or more complete restoration (Meli et al. 2017), but can enhance the recovery process in a shorter time-horizon (Curran et al. 2014). For all 16 biomes, AF shows both a higher yield and potential than NR. The main difference is seen for the biome with the highest yield, which is biome 1 for NR and 3 for AF. Biome 1 has a high share of abandoned croplands and these areas are primarily located where the highest NR yields can be identified. The highest yields for AF in biome 3 is located in areas where coniferous forests are dominating. This is first and foremost abandoned croplands identified in Europe that contains a low share of scarce land areas. Furthermore, it is observe a larger potential for AF than for BE in all biomes, which suggests that AF might be a better solution in areas where CCS cannot be implemented. When comparing BE and NR, the areas best suited for large-scale land use industries (i.e. biome 4-9) such as biomass production, shows highest BE yield in biome 4-6 and 9, and highest NR yield in biome 7 and 8. Thus, NR could be conducted in the areas in these biomes that are considered scarce, and BE in the remaining areas.

3.3 Mitigation scenarios and optimal land use strategy

This section presents and compares all eight scenarios. The lowest mitigation is obtained with NR on all abandoned croplands (see Table 3.8 and Figure 3.3), i.e. NR in 97.6 Mha of abandoned croplands. The carbon sequestration potential of this scenario is 0.78 $\mathrm{GtCO_2yr^{-1}}$. The highest potential is 2.58 $\mathrm{GtCO_2yr^{-1}}$, obtainable with the optimal scenario. Apart from the optimal scenario, BECCS is the one with the highest potential, of 2.40 $\mathrm{GtCO_2eq.yr^{-1}}$. The calculations show that almost the same mitigation is possible to obtain with NR and BE both inside and outside biodiversity hotspots. As NR most likely is the cheapest option out of all four land use strategies, the benefits associated with bioenergy production should be evaluated before implementing this strategy over NR. The same accounts for AF, that again show a higher potential than the BE scenario. BECCS shows the highest potential in this study, but is still an emerging and costly technology (B. W. Griscom et al. 2017). Thus, NR and AF are promising alternatives where CCS is not applicable.

If not assessing biodiversity and non-biodiversity hotspots in the NR-BE, NR-BECCS and NR-AF scenarios, the optimal distribution of these land use strategies can be conducted as in Figure 3.4. Figure 3.4 (a) shows the optimal combination of AF and NR. AF is in most locations a more efficient climate change mitigation strategy than NR when considering yearly carbon accumulation potential. 88.76 % of the global abandoned croplands are best suited for AF and 11.24 % for NR. As seen in the map, NR is more efficient primarily in the areas just south of the Sahara. Some areas are also seen in northwestern Africa, South America (Venezuela and Brazil), Mexico and the Middle East. This distribution of AF vs. NR suggests that, according to the data distributed by Cook-Patton et al. 2020 and G4M, active restoration of abandoned croplands have a greater climate gain in form of carbon sequestration than passive restoration in most locations. Figure 3.4 also shows the optimization of BE and NR (b) that dedicates 53.42 % to BE and 46.58 % to NR, BECCS and NR (c) that dedicates 77.91 % to BECCS and 22.09 % to NR and all three land use strategies (d) that dedicates 71.02 % for BECCS, 25.48 % for AF and 3.50 % for NR. BE will be less effective than BECCS in all cases in this study, and is thus not shown in Figure 3.4 (d).

The carbon sequestration potentials for the NR scenario is generally high. This suggests that NR might be an efficient strategy for climate change mitigation that at the same time is least likely to have negative impacts on other variables of importance, that are not assessed in this study. By combining NR in biodiversity hotspots and the optimal scenario outside biodiversity hotspots, it is still possible to obtain a carbon sequestration of 1.76 $\mathrm{GtCO_2eq.yr^{-1}}$. This mitigation option will position itself after the optimal and the BECCS scenario.

The carbon sequestration potential of land use changes depends on a variety of factors. Climatic factors such as temperature and precipitation can affect the growth rate of the feedstock or forest. The same accounts for management practices. Previous land use and quality of the land will also affect productivity and soil quality. For example, carbon accumulation rate can be lower on lands that have been subject to repeatedly deforestation and fires the last decades (Heinrich et al. 2021). For secondary forests to reach the same level of aboveground carbon as primary forests, they need both time and high quality land. Some agricultural practices can have resulted in dramatic degradation of land, so that natural regrowth might be slow and inefficient the first period after abandonment (Török et al. 2011). Thus, some seeding might be necessary in extreme cases to enhance the recovery process. All land use strategies have the highest yield in terrestrial biome 1, except for AF with the highest yield in biome 3. Biome 1 is also the largest area of abandoned croplands (27.14 Mha) and the high productivity seen here might be due to the climate and high

Table 3.8: Mitigation potentials of the eight scenarios. Total carbon sequestration potential for the scenarios BE, BECCS, NR and AF and the combination of them.

	Total mitigation potential [$GtCO_2eq.yr^{-1}$]		
Scenario	**BH**	**Non-BH**	**All**
BE	0.380	0.401	0.781
BECCS	1.159	1.245	2.404
NR-BE	0.379	0.401	0.780
NR-BECCS	0.379	1.245	1.624
NR	0.379	0.401	0.780
NR-AF	0.379	0.701	1.080
AF	0.607	0.701	1.308
Opt	1.193	1.382	2.575

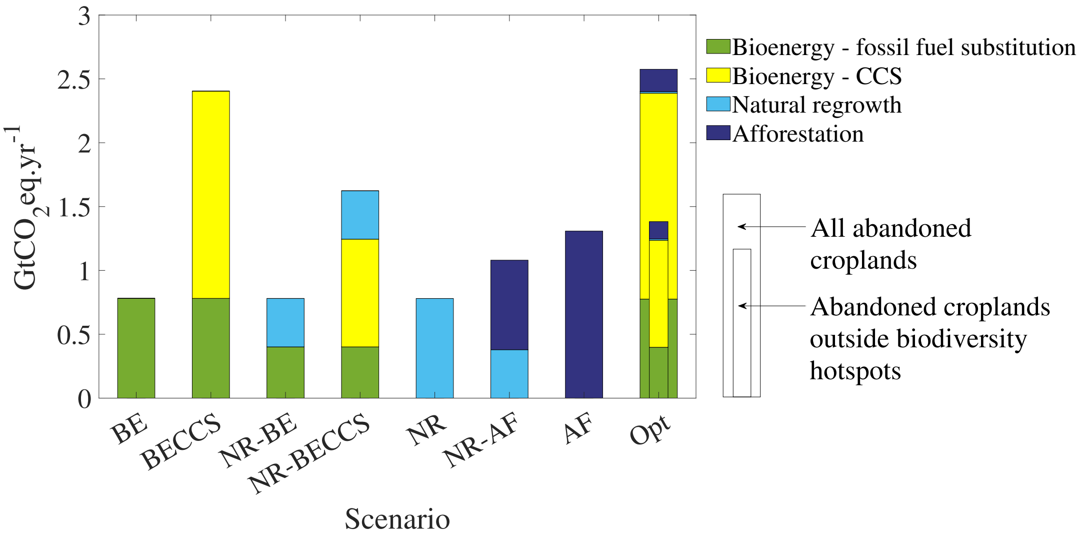
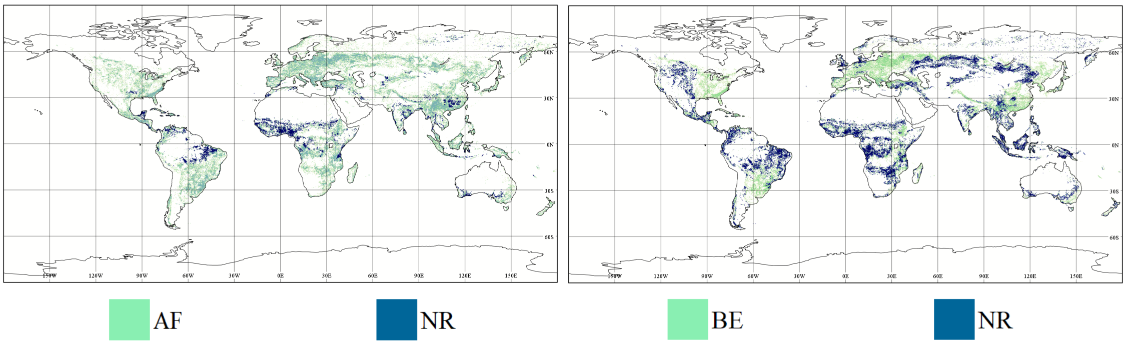


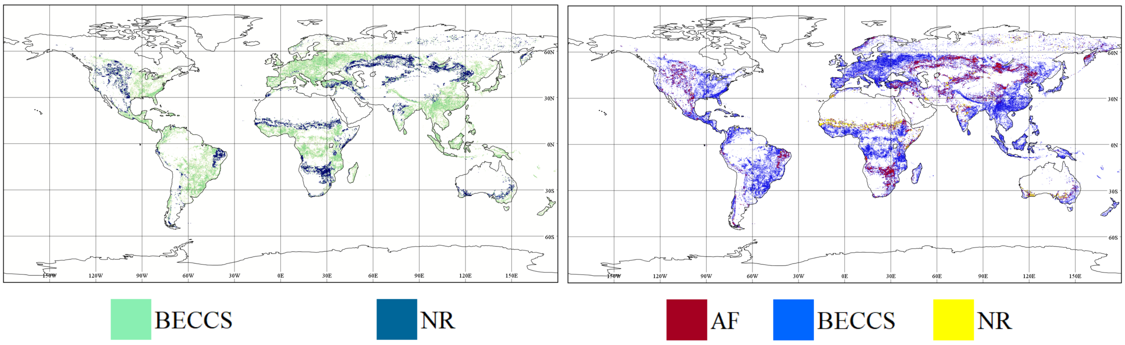
Figure 3.3: Mitigation potentials of the eight scenarios. Comparison of the carbon sequestration potentials of the eight land use strategy scenarios. For the optimal scenario, the large bar represents all abandoned croplands and the bar in overlay represents abandoned croplands outside biodiversity hotspots. Mitigation from fossil fuel substitution (green) and CCS (yellow) is presented independently.

humidity categorizing these regions. However, as about 70 % is located inside biodiversity hotspots, the rate of carbon sequestration obtainable in these areas should be evaluated against the risk of further affecting biodiversity and soil quality.

Climate solutions such as the NR and AF scenarios are considered the most promising options for near-term climate change mitigation, as the CCS technology is associated with uncertainty and high costs (B. W. Griscom et al. 2017). These measures are also associated with several co-benefits. However, for AF the tree management practices are significant (such as cutting and trimming), as well as choice of species. Secondary and 'new' forest might lead to reduced water yields (Yang et al. 2020) and the species should be suited for the respective area. A common denominator for all scenarios is the governmental enforcement and the collaboration between local communities and higher governmental levels (Agrawal et al. 2014). As a large share of the abandoned croplands are located in forest biomes (i.e. biome 1-6, in total 56.44 Mha), these regions could potentially benefit from active recovery measures and afforestation (Koch et al. 2021). It is furthermore observed that change in land cover will affect the biophysical conditions of the respective area, such as albedo and evapotranspiration (R. M. Bright et al. 2012). A transition from abandoned croplands to for example tree cover or bioenergy crop, might result in a lower land surface albedo, which in turn has a warming effect (Cao et al. 2019). The same accounts for evapotranspiration and precipitation, as level of humidity is highly affected by vegetation type.


(a) Optimal distribution of AF and NR

(b) Optimal distribution of BE and NR


(c) Optimal distribution of BECCS and NR

(d) Optimal distribution of AF, BECCS and NR

Figure 3.4: Optimal distribution of BE, BECCS, NR and AF. Optimal distribution of BE, BECCS, NR and AF based on highest carbon sequestration rate (not emphasizing biodiversity hotspots). Optimization conducted for AF and NR **(a)**, BE and NR **(b)**, BECCS and NR **(c)** and AF, BECCS and NR **(d)**.

Concerns are expressed related to the emerging attention to the broad specter of negative emission technologies, such as BECCS, NR and AF. Related to these mitigation measures are high uncertainties regarding e.g. potentials and trade-offs. For the AF scenario, fires can result in high emissions that can be a large step-back from the obtained mitigation. For BECCS there can be challenges related to the CCS implementation. This may apply especially to tropical countries around the equator. Here, the highest bioenergy potentials can be observed, but these regions might also be the areas with the biggest challenges related to the implementation of CCS (Fridahl and Lehtveer 2018). A too high dependency on negative emission technologies can be problematic, and these technologies should therefore be seen as supplementary in global climate change mitigation policies, not dominating (Anderson and G. Peters 2016). Another important concern is the significance of national and global policies, political and social support, as well as uncertainties related to carbon prices. Political issues are difficult to measure and will have a large impact on the outcome of the implementation of the respective mitigation strategies (G. P. Peters 2016). On the basis of this, the mitigation potentials related to several negative emissions technologies, especially that of BECCS, should be evaluated critically and conservative (Vaughan and Gough 2016)

3.4 Comparison with projected land requirements for bioenergy production and forest growth

Large land cover changes are projected up to 2050 (Table 3.9). With implementation of the optimal scenario, where 69.3 Mha (77.91 %), 24.9 Mha (25.48 %) and 3.4 Mha (3.50 %) are dedicated to BECCS, AF and NR, respectively, a significant share of predicted land requirements can be covered with abandoned croplands. For the most stringent scenario, SSP1-RCP1.9, as much as 33 % of the

Table 3.9: Comparison with projected land requirements for bioenergy production and forest growth. Projected land cover changes in relation to three SSP-RCPs (Arneth et al. 2019) from 2010 to 2050. All changes are positive and indicates increase in area. Comparisons conducted for potentials of BECCS and AF in the optimal scenario.

Shared socio-economic pathway	**SSP1-RCP1.9**	**SSP2-RCP1.9**	**SSP5-RCP1.9**
Median projected bioenergy cropland change [Mha]	210	450	670
AC as share of projected change	33 %	15 %	10 %
AC outside of BH as share of projected change	19 %	9 %	6 %
Median projected forest change [Mha]	340	340	310
AC as share of projected change	7 %	7 %	8 %
AC outside of BH as share of projected change	5 %	5 %	6 %

required area for bioenergy production can be covered by abandoned croplands. As the share of bioenergy crops in the optimal scenario is significantly larger than that of AF, a smaller share of the required forest area will be covered by abandoned croplands. Still, there are large potentials related to abandoned croplands, and the potentials of these are significant in the global picture. As mentioned in Section 1.1, cropland areas are predicted to decrease from 2010 to 2050 by 120 Mha in SSP1-RCP1.9 and SSP2-RCP1.9 and 190 Mha in SSP5-RCP1.9 (mean values) (Arneth et al. 2019). This indicates that a larger abandoned cropland area might be available for nature based climate solutions in the future. Natural regrowth and land recovery will begin when croplands are abandoned (Yang et al. 2020) so that abandonment alone can be seen as a climate change mitigation measure.

3.5 Limitations and uncertainties

With FAO statistics as reference, the ESA CCI-LC datasets tends to overestimate cropland areas of some regions in Africa and Asia. The maps of America is on the other hand quite accurate, compared to the FAO statistics. The improvements between the land cover maps (i.e. 2010 and 2015) are significant, but some errors are inherited and impairs the later versions. Another source of error is the presence of mosaic land use classes, as they tend to increase the rate of misclassification errors (Pérez-Hoyos et al. 2017). Furthermore, as estimates on global abandoned cropland areas are varying (e.g. Campbell et al. (2008) and Næss et al. (2021)) due to different spatial resolution, scope and time periods they can be difficult to compare.

Another weakness related to the calculations conducted with the land cover data is that the time of abandonment is unknown, and only based on that the cropland areas are abandoned some time between 1992 and 2018. After land abandonment and before implementation of new land use, the croplands will begin the process of revegetation into previous land use. Parts of the vegetation that have regrown during this period might have to be removed when using these land areas for biomass production or afforestation. These potential emissions before biomass feedstock or forest planting might be significant depending on previous land use and time period of revegetation, but is neglected in this study. Former croplands tend to recover more slowly that other land cover types, but variance is high and dependent on for example agricultural management intensity (Jones and Schmitz 2009; Meli et al. 2017). Recovery time and previous land use are two strong determinants of biogeochemical functions, such as above- and belowground carbon (Meli et al. 2017). As the previous land use, i.e. crop type and agricultural management intensity, is also unknown, these factors are not taken into account.

Due to increasing quality on remote-sensing satellite data, change in data can give an impression of land cover changes that in reality reflects an increase in data quality, not real land cover changes like increasing/decreasing forest cover (Ceccherini et al. 2020) or increasing rate of land abandonment (Wernick et al. 2021). Thus, cautions should be made when doing temporal analyses on global datasets derived from satellite data (Palahí et al. 2021) and one should be aware that change in data quality (e.g. between 1992 and 2018) could affect the simulations.

GAEZ is based on several databases and assumptions and is therefore dependent on the quality of this data. There are uncertainties related to yield calculations due to the large number of factors affecting the crop productivity. This is especially true for how major changes in climatic conditions affect the entire crop cycle. Lower yield is adjusted in the model with reduction factors in Module III for agro-climatic constraints (such as soil efficiency, pest and diseases) and in Module IV for soil and terrain limitations (such as nutrient availability, rooting conditions, oxygen availability, etc.) (Fischer et al. 2012). GAEZ is furthermore based on a large of data to make the model as reliable as possible.

A large part of previous conducted research refers to bioenergy production as carbon neutral process. This approach has been criticized for underestimating the emissions from the bioenergy production phase (Cherubini 2010; P. Smith et al. 2014). Ideally, when estimating the potentials of bioenergy and BECCS, the life cycle emissions related to biorefinery processes should be evaluated in addition to the substitution effect and the mitigation potential. This study does not emphasise potential emission from bioenergy production, and this should be taken into consideration when analysing the results.

Climatic calculations and estimations of future yields of land use strategies are generally challenging because of a variety of variables rapidly changing. To make estimations it is necessary to also predict variables of future climatic conditions, and using historical numbers will for many cases not be representative for the future. Furthermore, as this study only considers high agricultural management and rainfed irrigation, some areas of abandoned croplands might be unfavourable for biomass production. This can be areas in particularly dry areas dependent on some kind of irrigation in addition to rain. Still, the highest biomass yield is seen in the tropical areas of the world, i.e. within the range of [30 °N, 30 °S]. Additionally, an increase in amount of biofuels in the market will not necessarily lead to a corresponding decrease in fossil fuel consumption. This rebound effect is usually a result of economic factors due to the fuel market price being easily affected by an increasing amount of fuel in the market. The rebound effect can be both positive and negative, and is a consequence of a variety of market related factors. For example, if the mixed fuel price is higher than for fossil fuels, the rebound effect can be negative. This means that the consumption of the mixed fuel turns out to be lower than desired. Furthermore, a lower fuel price due to an increasing amount of fuel in the market may lead to an increase in consumption and consequently an increase in emissions (Smeets et al. 2014).

Natural regrowth data distributed by Cook-Patton et al. 2020 (The Nature Conservancy) is based on 11 360 publications, and is dependent on the scope and quality of this data. Availability and quality vary across locations and studies. These uncertainties could be limited by further expanding the data foundation. In addition, due to a global changing climate and temperature, the use of historical forest growth may not be representative to estimate future carbon stocks and accumulation rates. There are also many other factors that could potentially affect accumulation rates, that are not included as variables in this study (Cook-Patton et al. 2020). Research on how biodiversity is affected by active and passive revegetation is complex as undersampling is a challenge that can lead to somewhat imprecise results (Curran et al. 2014).

G4M defines aboveground biomass as stem biomass. Because of this, an additional 20 % of mass is added to the calculations to account for the remaining aboveground biomass. In the natural regrowth data, aboveground biomass is defined as stem and branch biomass. Here, no additional mass is added, as the foliage share is probably less significant than the branch share. Thus, there might be irregularities between the two data sets regarding the aboveground carbon content of this mass that should be taken into account when evaluating the results.

The division of coniferous and non-coniferous tree productivity calculated with the G4M data might be too coarse in some areas. By comparing to the Ecoregions app provided by Google and Nasa, the share of coniferous forests according to G4M appears to be larger. For example, in the mountain areas of Norway, it is identified a high amount of 'Scandinavian Montane Birch forest and grasslands' in the ecoregions map that is not identified by G4M. In the northern parts of North-America, a higher share of coniferous forests is identified in the ecoregions map than in G4M. Thus, there are some irregularities between the two maps, but the patterns are similar.

3.6 Further research

Inter-sectional studies are necessary for a comprehensive analysis of the optimal exploitation of abandoned croplands. Other factors should be considered in addition to carbon sequestration potential, such as social, economical and local biophysical effects. An analysis evaluating the opportunity of recovering biodiversity against the climate change mitigation potential of different land use strategies could contribute to the evaluation of how to implement the different land use measures. This study assesses only the positive mitigation effects possible to obtain and further inter-sectional research should be conducted for an overall picture. This includes studies on optimal management systems, that could contribute to knowledge on how to successfully implement and complete land use projects. Good governance is important for the outcome of bioenergy and afforestation implementation (P. Smith et al. 2014).

A thorough comparison of active and passive recovery of different land types would be an important contribution in the local decision-making processes. Active restoration might impair the opportunities for native species in the respective area to re-develop and passive restoration might therefore contribute to better conditions (Meli et al. 2017). Agricultural management intensity prior to cropland abandonment is also essential for the outcome of the biodiversity recovery (Plieninger et al. 2014). In addition, it is suggested that some species are more important than others, and that functionally oriented restoration (i.e. focus on functionally important species) initiatives could contribute to enhance the biodiversity recovery process (Montoya et al. 2012).

Belowground carbon constitutes a significant share of total carbon stock in forests and vegetation in general. Large carbon pools are stored in the soil is highly affected by land use changes. Unfortunately, belowground carbon data is difficult to obtain (Cook-Patton et al. 2020), but a thorough data foundation on both belowground and aboveground carbon stocks would make it possible to do a comprehensive analysis on changes in carbon stocks over the previous and next decades, as well as optimal future land use strategies for climate change mitigation.

Chapter 4

Conclusions

By using high-resolution satellite land cover data, this study has identified the global extent of cropland abandonment between 1992 and 2018. As pressure on food crops and other land areas is a significant challenge globally, the aim of this study has been to evaluate the climate change mitigation potentials of bioenergy production, natural regrowth and afforestation, without further contributing to pressure on land. Significant mitigation potentials are observed for all scenarios, lowest in the case of natural regrowth (NR scenario) and highest for bioenergy production with CCS (BECCS scenario). While BECCS has the highest potential, it is also the mitigation strategy and technology with highest related uncertainties and costs. Thus, both NR and afforestation are good alternative measures, contributing with a significant carbon sequestration, as well as a possible lower impact on local conditions, such as biodiversity. As the BE and NR scenarios have almost the same potential, and AF has a higher potential than BE, the NR and AF scenarios can be considered the most promising near-term options, at least until the CCS technology is more developed and established. Furthermore, an increasing rate of land abandonment is observed, which indicates that an increasing amount of abandoned croplands can be available for climate change mitigation measures such as BE, BECCS, NR and AF. This study supplements existing climate change mitigation research and can be indicative of how to utilize global abandoned cropland areas for climate change mitigation measures in form of land use changes. Each location is unique and the optimal strategy for the respective locations should be considered thoroughly based on local climate, biodiversity scarcity, water demand and local communities.

Additional Information

Code availability

Matlab code developed for this study is uploaded and available in Box, upon request.

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Appendix

A Figures

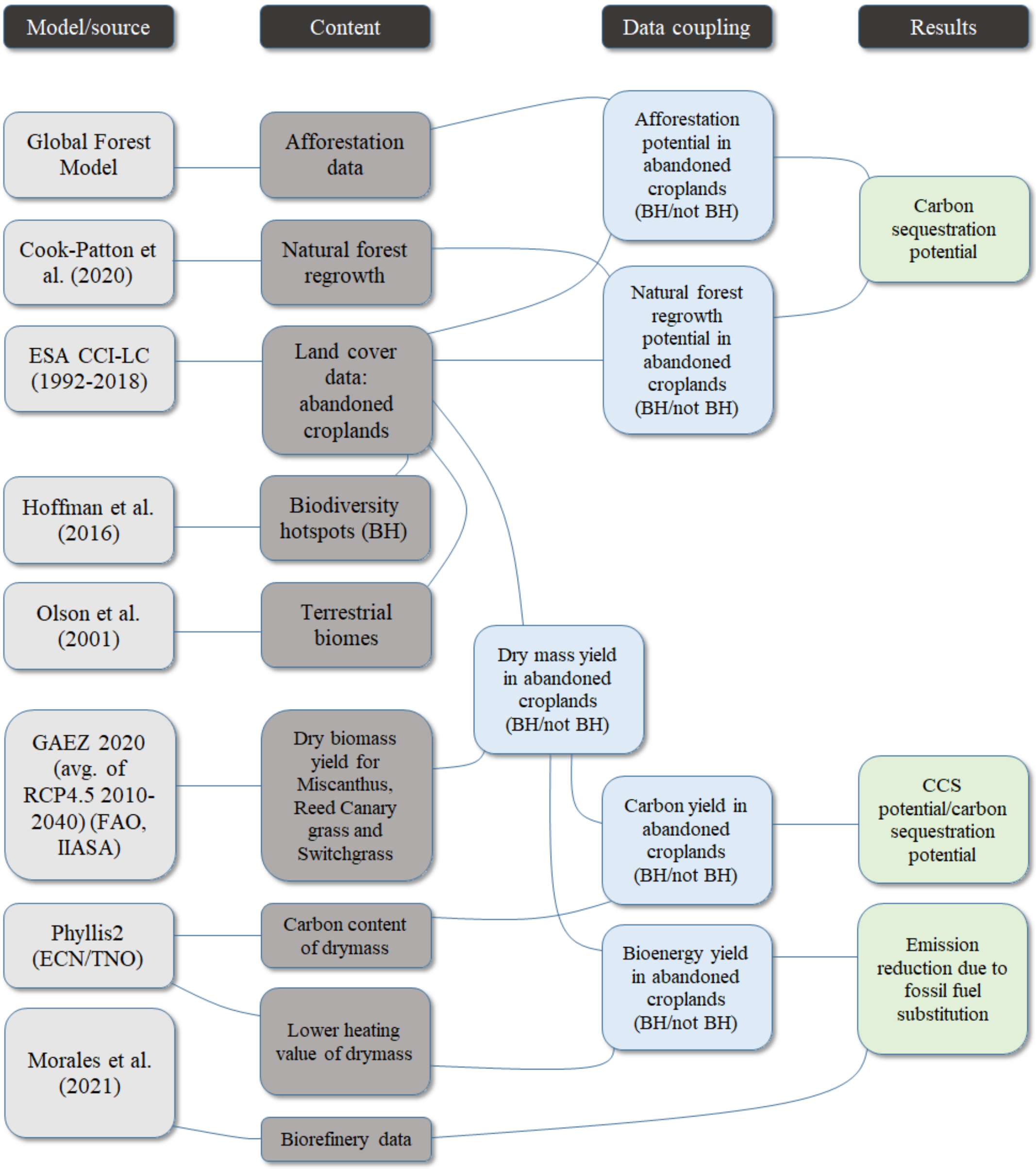

Figure 1: Model Flowchart. Overview of data foundation, utilized datasets and data integration.

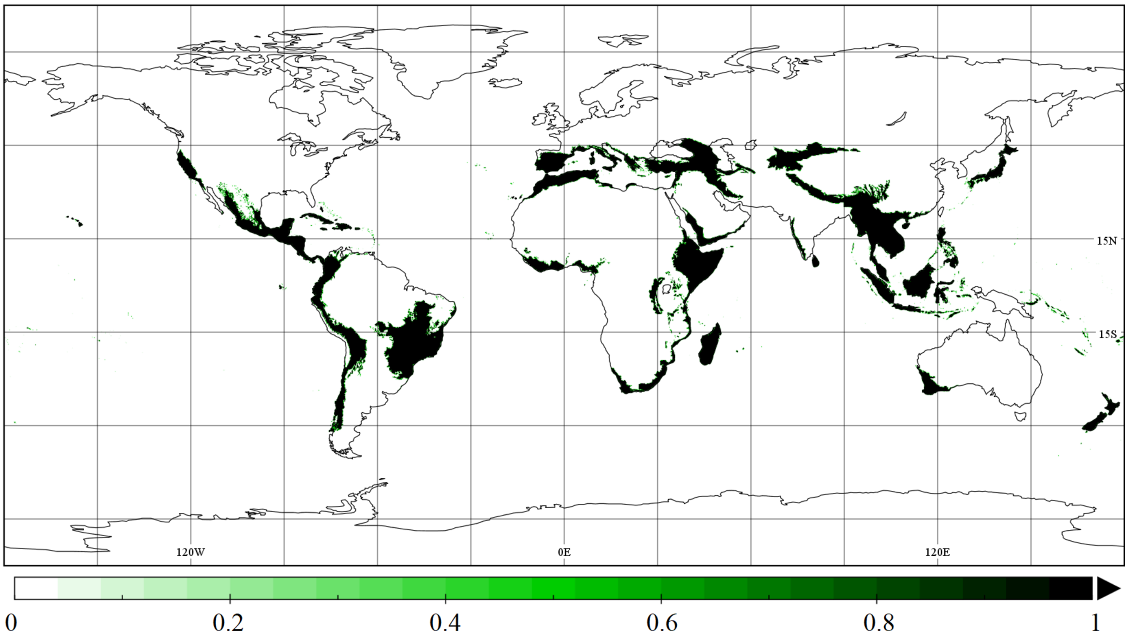

Figure 2: Global biodiversity hotspots as fraction of grid cell area.

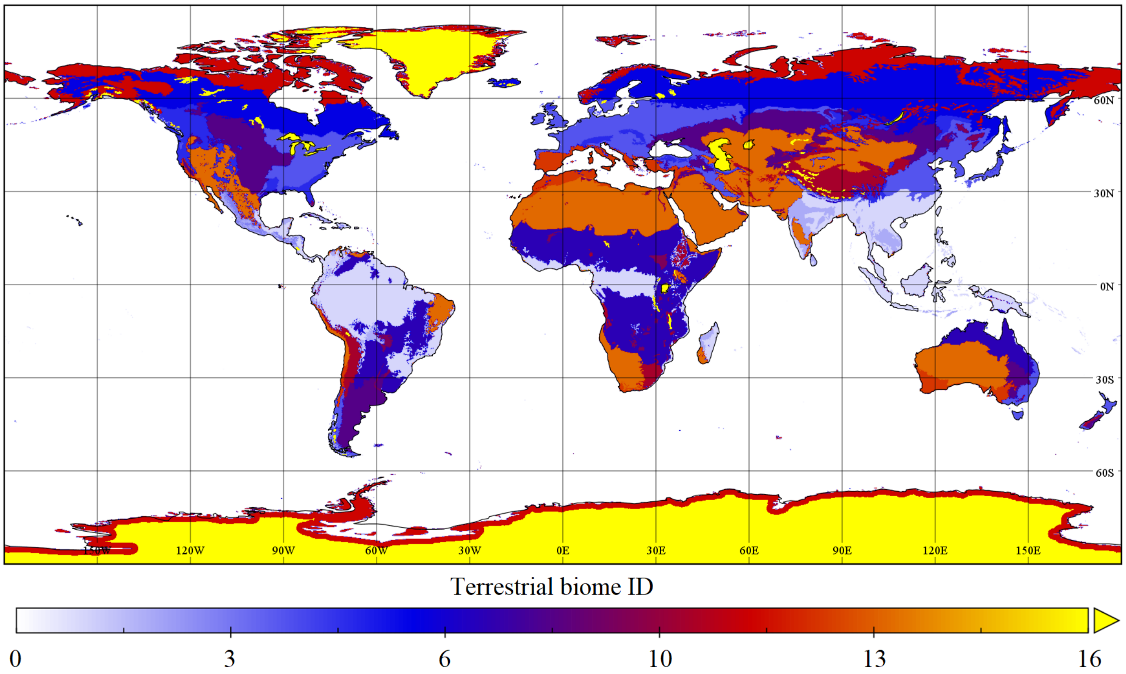

Figure 3: Definition of 16 terrestrial biomes. 16 terrestrial biomes defined by Olson et al. 2001. IDs: (1) Tropical and subtropical moist broadleaf forests, (2) Tropical and subtropical dry broadleaf forests, (3) Tropical and subtropical coniferous forests, (4) Temperate broadleaf and mixed forests, (5) Temperate conifer forests, (6) Boreal forests/taiga, (7) Tropical and subtropical grasslands, savannas and shrublands, (8) Temperate grasslands, savannas and shrublands, (9) Flooded grasslands and savannas, (10) Montane grasslands and shrublands, (11) Tundra, (12) Mediterranean forests, woodlands and shrub, (13) Deserts and xeric shrublands, (14) Mangroves, (98) Lakes, (99) Rock and ice.

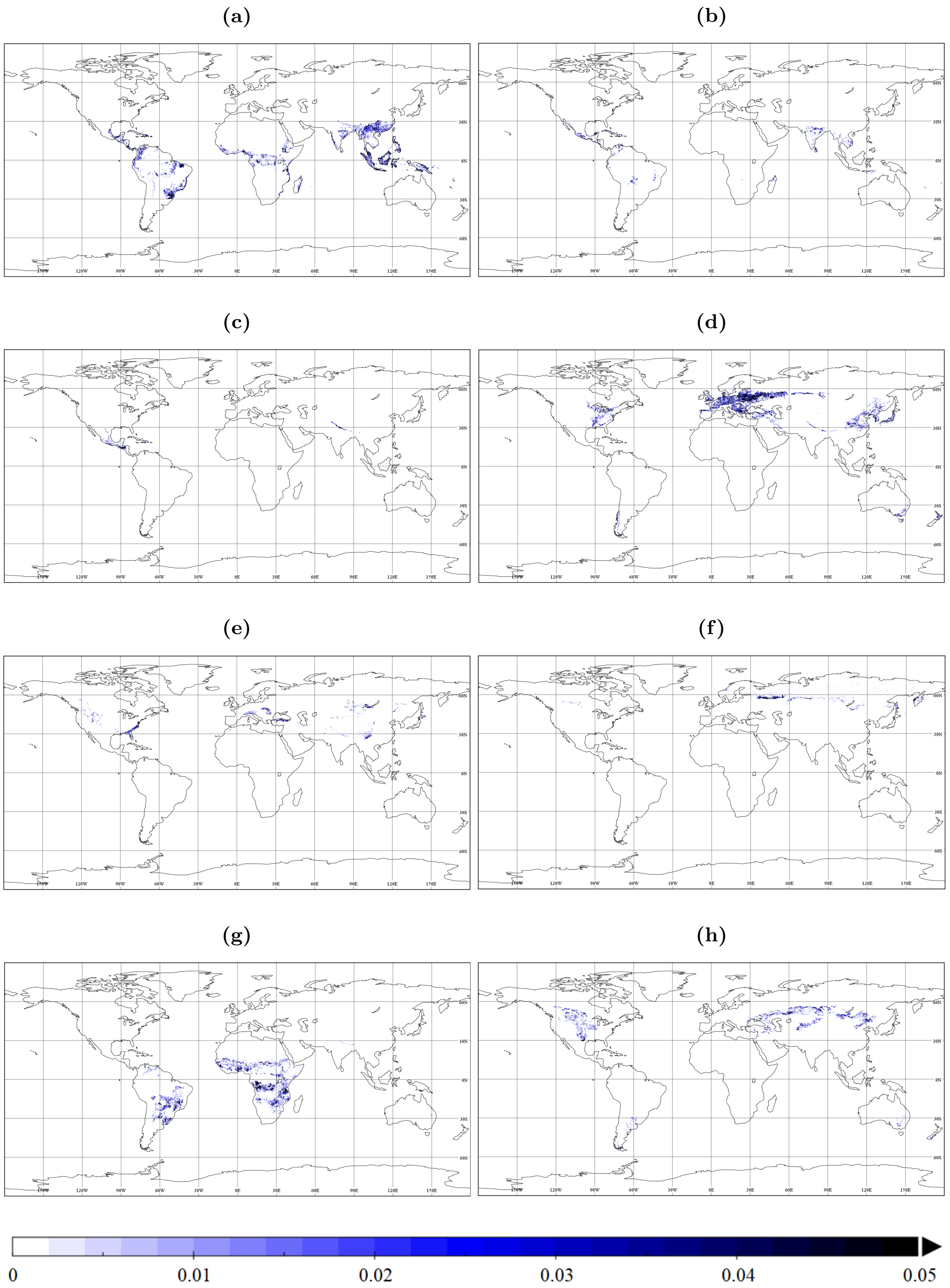

Figure 4: Abandoned croplands in each terrestrial biome. Abandoned croplands as fraction of grid cell area presented individually for tropical and subtropical moist broadleaf forest (id 1) **(a)**, tropical and subtropical dry broadleaf forests (id 2) **(b)**, tropical and subtropical coniferous forests (id 3) **(c)**, temperate broadleaf and mixed forests (id 4) **(d)**, temperate conifer forest (id 5) **(e)**, boreal forests/taiga (id 6) **(f)**, tropical and subtropical grasslands, savannas and shrublands (id 7) **(g)**, temperate grasslands, savannas and shrublands (id 8) **(h)**.

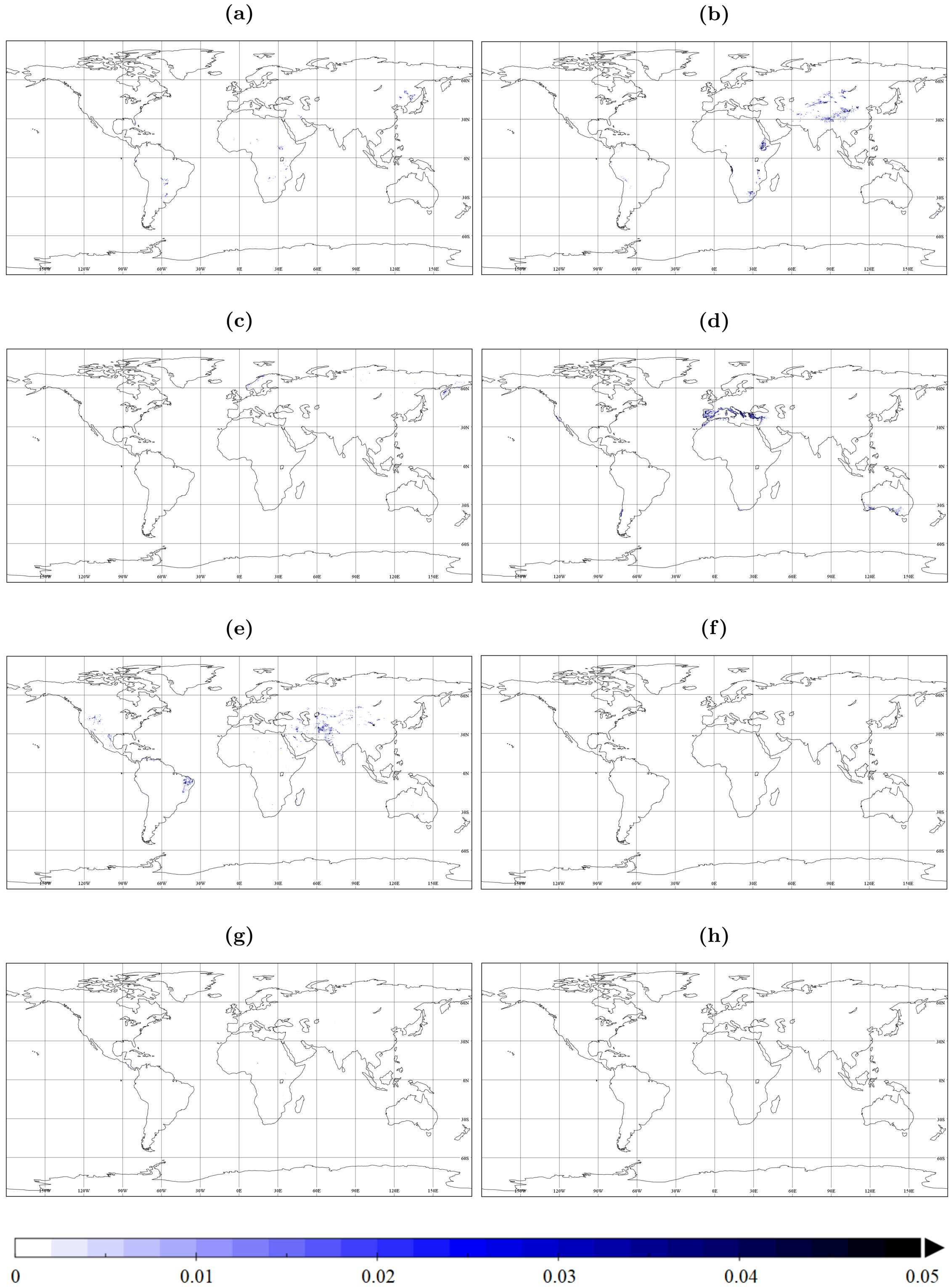

Figure 5: Abandoned croplands in each terrestrial biome (cont.). Abandoned croplands as fraction of grid cell area presented individually for flooded grasslands and savannas (id 9) **(a)**, montane grasslands and shrublands (id 10) **(b)**, tundra (id 11) **(c)**, mediterranean forests, woodlands and shrub (id 12) **(d)**, deserts and xeric shrublands (id 13) **(e)**, mangroves (id 14) **(f)**, lakes (id 98) **(g)**, Rock and ice (id 99) **(h)**.

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