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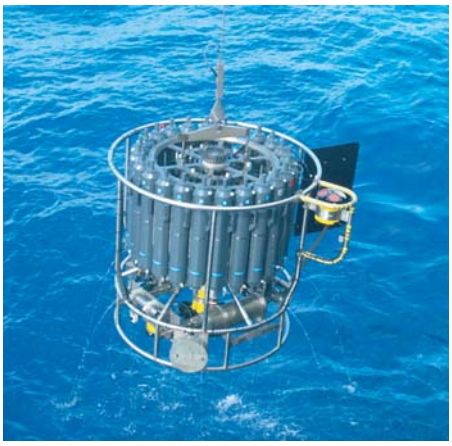
The role of bioenergy production in the terrestrial carbon cycle and energy balance

Pawlok Dass



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Anschrift / Address

Max-Planck-Institut für Meteorologie
Bundesstrasse 53
20146 Hamburg
Deutschland

Tel.: +49-(0)40-4 11 73-0
Fax: +49-(0)40-4 11 73-298
Web: www.mpimet.mpg.de

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Pawlok Dass
International Max Planck Research School (IMPRS-ESM), Hamburg
Bundesstrasse 53
20146 Hamburg

Potsdam Institute for Climate Impact Research (PIK)
Telegraphenberg A 31
14473 Potsdam

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Abstract

Land Use and Land Cover Change (LULCC) affects the climate not only by changing the carbon stock of different terrestrial carbon pools and thereby changing the atmospheric CO_2 concentration, but also through changes in biogeophysical parameters like albedo and evapotranspiration. While LULCC has been one of the major sources of anthropogenic carbon emissions, it also has the potential to reduce the atmospheric CO_2 concentration by increasing the terrestrial carbon pools or by de-carbonization of the energy system through utilizing energy from biomass plantations. This thesis focuses thus on the role of bioenergy production is the terrestrial carbon cycle and energy balance which is investigated using global vegetation and climate models.

Previous modeling studies have shown that the net effect of deforestation of the high latitudes is a cooling. However, a mismatch with a few observational studies indicates an underestimation of emissions estimated by these studies. I performed a purely hypothetical experiment of high latitude deforestation using terrestrial biosphere model, LPJmL and found the emissions due to deforestation accumulated over the 21st century to be higher than in previous modeling studies. This reflects the difference in how ‘deforestation’ is implemented and how the carbon cycle is represented in the different models. Moreover, it was found that even when bioenergy plantations were carried out only on suitable parts of the deforested areas, the emissions saved by the end of the 21st century, by avoided usage of fossil fuels, could not compensate for the total carbon emitted by deforestation. Therefore, considering only biogeochemical effects, even if extensive deforestation is followed by bioenergy cropping, it leads to an anthropogenic warming.

Some fraction of former agricultural land in the temperate and boreal region was abandoned in the near past due to different reasons. If such abandoned areas were to be managed by allowing natural reforestation or by bioenergy plantations, there would have been a sequestration of carbon or saving of carbon emissions by avoided usage of fossil fuels. In addition, there would have been no negative side effects like emissions from LULCC or competition for land with food crops. Using LPJmL to determine which of these two management methods are more effective, I found that the bioenergy plantations are more effective as the total carbon potentially saved by fossil fuel substitution is more than an order of magnitude higher than the total carbon sequestered by natural vegetation by the end of the 21st century.

Tropical forests are highly productive and some fraction of agricultural land has been abandoned in the near past mainly due to damage and degradation. Thus I used LPJmL to determine whether allowing tropical abandoned croplands to revert naturally to forests and increase the carbon storage, is a more effective mitigation measure than carrying out bioenergy plantations. As for the temperate and boreal regions, I found bioenergy plantations to be more effective.

I conclude that, (i) extensive deforestation even if followed by bioenergy cropping causes more climate change than it reduces, (ii) bioenergy plantations on abandoned croplands is a more effective mitigation measure compared to natural re-growth of forests, (iii) lignocellulosic bioenergy grass species, having the ability to grow on nutrient poor soils, can be considered to be the most effective, and (iv) the tropical region has the highest mitigation potential compared to the temperate region, mainly because of the higher terrestrial net primary productivity.

Zusammenfassung

Landnutzung und Landbedeckungsänderungen (LULCC) beeinflussen das Klima nicht nur durch ihren Einfluss auf den Gesamtkohlenstoffgehalt der unterschiedlichen terrestrischen Kohlenstoffbestände, wodurch die atmosphärische CO_2 Konzentration geändert wird, sondern auch durch Beeinflussung der biogeophysikalischen Parameter wie Albedo und Evapotranspiration. LULCC war nicht nur eine der Hauptquellen anthropogener Kohlenstoffemissionen, es hat auch das Potential, die atmosphärische CO_2 Konzentration zu reduzieren indem sie eine Vergrößerung des terrestrischen Kohlenstoffbestands bewirken oder indem die Nutzung von Energie, die aus pflanzlicher Biomasse gewonnen wurde, zu einer Dekarbonisierung der Energienutzungssysteme führt. In dieser Dissertation werde globale Vegetations- und Klimamodelle genutzt, um die Rolle der Produktion von Bioenergie im terrestrischen Kohlenstoffkreislauf und in der Energiebilanz zu untersuchen.

Vorhergehende Modellstudien zeigten, dass die Entwaldung in den höheren Breiten netto eine Abkühlung bewirkt. Allerdings suggerierte die Abweichung zu den wenigen verfügbaren Beobachtungsdaten, dass diese Studien die Emissionen unterschätzten. Mit Hilfe des terrestrischen Biosphärenmodells LPJmL habe ich in einem rein hypothetischen Experiment die Entwaldung der höheren Breiten untersucht und herausgefunden, dass die im Verlauf des 21. Jahrhunderts von der Entwaldung verursachten Emissionen sich auf höhere Werte akkumulien, als die bisherigen Modellergebnisse zeigten. Dieses Ergebnis spiegelt den Unterschied, in dem ‚Entwaldung' in die Modelle integriert wurde, und wie die verschiedenen Modelle den Kohlenstoffkreislauf repräsentieren. Die Einsparung von Emissionen aus fossilen Kraftstoff durch die Nutzung der auf den entsprechend geeigneten, vorher entwaldeten Arealen

produzierten Bioenergie kann bis zum Ende des 21. Jahrhunderts die Gesamtsumme des durch die Entwaldung freigesetzten Kohlenstoffs nicht ersetzen. Im Ergebnis führt die ausschließliche Berücksichtigung biogeochemischer Effekte zu einer anthropogenen Erwärmung, auch wenn nach extensiver Entwaldung Bioenergieanpflanzungen folgen.

In der nahen Vergangenheit wurden auf Grund verschiedener Ursachen Teile der ehedem landwirtschaftlich genutzten Areale in den temperierten und den borealen Regionen aufgelassen. Eine Nutzung dieser Areale durch natürlichen Wiederaufwuchs oder durch Bioenergieanpflanzungen würde zur Kohlenstoffsequestrierung oder zur Kohlenstoffeinsparung durch die Vermeidung der Nutzung fossiler Kraftstoffe führen. Zusätzlich würden keine negativen Nebeneffekte auftreten wie Kohlenstoffemissionen durch LULCC oder Konkurrenz um Land für den Anbau von Nahrungsmitteln. Ich habe das LPJmL Modell angewendet, um festzustellen, welche dieser beiden Nutzungsmethoden effektiver ist. Es stellte sich heraus, dass die Bioenergieanpflanzung effektiver ist, da die buis zum Ende des 21. Jahrhunderts potentiell durch den Ersatz fossiler Brennstoffe eingesparte Gesamtkohlenstoffmenge mehr als eine Größenordnung höher ist, als die berechnete Gesamtkohlenstoffsequestrierung durch die natürliche Vegetation im selben Zeitraum.

Tropische Wälder sind hochproduktiv. In den Tropen wurden in der nahen Vergangenheit Teile des landwirtschaftlich genutzten Flächen wegen Übernutzung und Degenerierung aufgelassen. Ich habe LPJmL eingesetzt um zu untersuchen ob die Wiederherstellung des natürlichen Waldes auf diesen ungenutzten Flächen den Kohlenstoffvorrat erhöht und somit eine effektive Maßnahme zur Vermeidung als Bioenergieanpflanzungen darstellt. Vergleichbar wie für temperierte und boreale Regionen konnte ich feststellen, dass Bioenergieanpflanzungen effektiver sind.

Zusammenfassend halte ich fest, dass (i) extensive Entwaldung mehr Klimawandel verursacht als folgende Bioenergieanpflanzungen reduzierend wirken, (ii) Bioenergieanpflanzungen auf aufgelassenen Agrarflächen eine effektivere Mitigationsmaßnahme darstellen, als natürlicher Wiederaufwuchs des Waldes, (iii) die Nutzung lignozellulosereicher Grasssorten, die auch auf nährstoffarmen Böden wachsen können, für die Bioenergieproduktion am effektivsten ist, und (iv) verglichen mit temperierten Regionen tropische Regionen das höchste Mitigationspotential haben, was hauptsächlich auf die hohe Nettoproduktivität tropischer Pflanzen zurückzuführen ist.

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Contents

List of Abbreviations

- [CO_2] – atmospheric carbon dioxide (CO_2) concentration
- AR4 – Assessment Report 4 (on IPCC)
- CMIP5 – Coupled Model Intercomparison Project 5
- DGVM – Dynamic Global Vegetation Model
- ESM – Earth System Model
- GCM – General Circulation Model
- GHG – Green House Gases
- GtC – Giga Tons of Carbon = Peta gram of Carbon = 10^{15} gC
- IPCC – Intergovernmental Panel on Climate Change
- LU – Land Use
- LUC – Land Use Change
- LULCC – Land Use Land Cover Change
- MJ – Mega Joule
- NPP – Net Primary Production
- PFT – Plant Functional Type
- ppm – parts per million
- SRES – Special Report on Emission Scenarios (of IPCC)
- TAR – Third Assessment Report (of IPCC)

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Chapter 1: Introduction

1.1 Increase in atmospheric CO2 concentration [CO_2] and global temperatures

In the recent years, the components of the global carbon balance have changed considerably with significant increases in anthropogenic emissions (Raupach et al., 2007) and changes in land and ocean sink fluxes due to climate variability and change (Buermann et al., 2007). The global average [CO_2] rose from 280 ppm at the beginning of the industrial revolution to 379 ppm in 2005 (Alley et al., 2007). The recent monthly average [CO_2] recorded at Mauna Loa, Hawaii is 398.58 ppm for June, 2013 (Tans and Keeling, 2013). This concentration exceeds by far the natural range over the last 650,000 years (180 to 300 ppm) as determined from ice cores. The annual atmospheric concentration growth rate was larger during the period between 1995 – 2005 (average = 1.9 ppm per year) than it has been since the beginning of continuous direct measurements (1960 – 2005 average = 1.4 ppm per year), although there is year to year variability in growth rates (Denman et al., 2007; Forster et al., 2007). Atmospheric CO_2 has continued to increase since the TAR and the rate of increase as reported in the IPCC AR4, appears to be change from 3.2 ± 0.1 GtC yr^{-1} in the 1990s to 4.1 ± 0.1 GtC yr^{-1} in the period 2000 to 2005 (Denman et al., 2007). The inter-hemispheric gradient of CO_2 provides additional evidence that the increase in [CO_2] provides additional evidence that the increase in [CO_2] is caused primarily by northern hemispheric sources. The excess [CO_2], at about 0.5 ppm per (GtC yr^{-1}) in the northern hemisphere compared to the southern hemisphere, has increased in proportion to the fossil fuel emission rates (Denman et al., 2007).

Fossil fuel and cement emissions rose from 5.4 ± 0.3 GtC yr^{-1} in the 1980s to 6.4 ± 0.4 GtC yr^{-1} in the 1990s (Marland et al., 2006) and climbing further to 7.2 ± 0.3 GtC yr^{-1} in 2005. The numbers are based upon international energy statistics for the 1980 to 2003 period (Marland et al., 2006) with extrapolated trends for 2004 to 2005. The error of ± 1 standard deviation for fossil fuel and cement emissions is of the order of 5% globally. Cement emissions are small compared with fossil fuel emissions and roughly account for 3% of the total (Denman et al., 2007). Figure 1.1 demonstrates the rise of global fossil fuel emissions from 0.003 GtC at the beginning of the industrial revolution to as high as 8.7 GtC in 2009 (Boden et al., 2010).

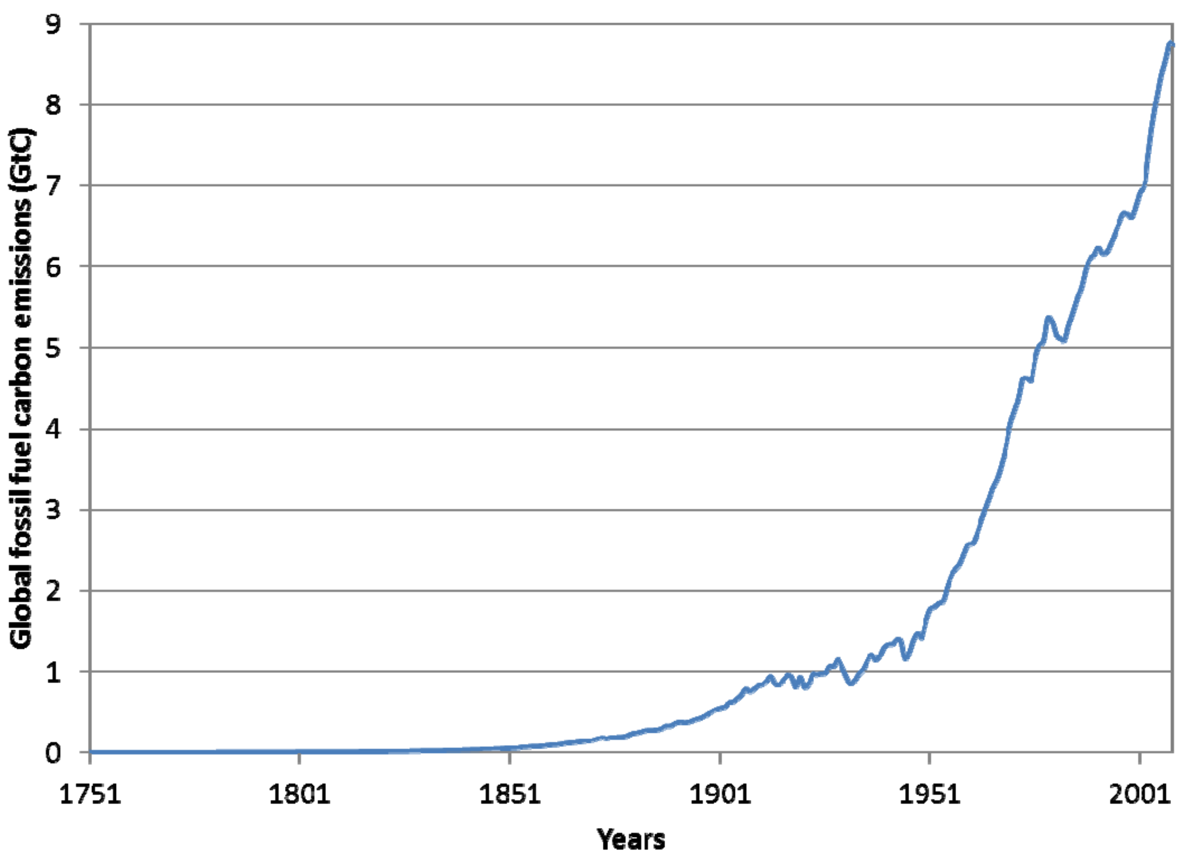

Fig. 1.1. Global fossil fuel carbon emissions plotted from the beginning of the industrial revolution (in GtC). (Data Source: Boden et al. (2010))

Global mean surface temperatures have risen by 0.74 ± 0.18 °C when estimated by a linear trend over the period from 1906 to 2005. As per the IPCC AR4, the rate of warming over the last 50 years (0.13 ± 0.03 °C) is almost double that over the last 100 years (0.07 ± 0.02 °C), with the years 2005 and 1998 being recorded as two of the warmest in the instrumental records of the global surface temperatures. 11 of the 12 years between 1995 to 2006 rank among the 12 warmest years since 1850. It has been observed that after 1979 surface air temperatures over land have risen at about double the ocean rate. Moreover, changes in extremes of temperature are also consistent with warming of the climate. There has been a widespread reduction in the number of frost days in mid-latitude regions, an increase in the number of warm extremes and a decrease in the number of daily cold extremes have been observed in 70 to 75% of the land regions where data are available (Trenberth et al., 2007). Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in greenhouse gas concentrations. Moreover, it is *likely* that increases in greenhouse gas concentrations alone would have cause more warming than observed because volcanic and anthropogenic aerosols have offset some warming that would otherwise have taken place (Denman et al., 2007; Forster et al., 2007; Hegerl et al., 2007).

1.2 Role of Land Use, Land-Use Change and Forestry

During the period between 1850 and 1998, approximately 405 ± 60 GtC has been emitted as carbon dioxide into the atmosphere of which the contribution from land use and land-use change, predominantly from forested areas account for about 33%. The net global carbon flux between terrestrial ecosystems and the atmosphere is the result of a small imbalance between uptake by photosynthesis and release by plant respiration, decomposition of dead organic matter and different forms of disturbance. The direct effects of land use and land-use change have been estimated to have led to a net emission of 1.7 ± 0.8 GtC yr^{-1} during the 1980s and 1.6 GtC yr^{-1} during the 1990s (Watson et al., 2000).

Land use and land-use change are the main factors that affect terrestrial sources and sinks of carbon. Clearing of forests has resulted in a reduction of the global area of forests by almost 20 % during the past 140 years (Watson et al., 2000). During the past two decades, the CO_2 flux caused by land use changes has been dominated by tropical deforestation. Agriculture and exploitation of forest resources have reached into formerly remote areas of old growth forests in contrast to mid-latitudes where exploitation previously eliminated most old growth forests (Denman et al., 2007). From 1959 to 1980, approximately 30% of the emissions from land-use change originated in the extratropics. This extratropical contribution decreased after 1980, reaching zero by 2000. The remaining land-use emissions originated largely from deforestation in tropical America and Asia, with smaller contribution from tropical Africa. From 2000 to 2006, land-use emissions from tropical Asia rose significantly to 0.6 GtC yr^{-1}, whereas emissions from the American tropics decreased from >0.9 GtC in 1990 to 0.6 GtC yr^{-1} in 2006. The emissions from tropical Africa have remained constant at approximately 0.2 GtC yr^{-1} for the last 25 years (Canadell et al., 2007).

However, as described below in section 1.3, different management practices also involving land use land-use change such as reduction of the rate of forest clearing, establishing forests on previously cleared land, ecosystem conservation and change of management practices on cropland, can restore, maintain, and enlarge vegetation and soil carbon stocks.

1.3 Means to reduce atmospheric CO_2 concentration

Despite continuous improvements in energy intensities, global energy use and supply are projected to continue to grow, especially as industrialization is pursued by developing countries. Should there be no substantial change in energy policies, more than 80% of the energy supply will be based on fossil fuels, with consequent implications for GHG emissions (Rogner et al., 2007).

The ultimate objective of any mitigation measure is to achieve stabilization of greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous changes in the climate system. This level should be achieved in a time frame such that the ecosystems get sufficient time to adapt naturally to climate change, to ensure that food production is not under threat and so that economic development could proceed in a sustainable manner (United Nations, 1992). Thus most long-term mitigation studies have focused their efforts on GHG concentration stabilization scenarios and a commonly used target has been the stabilization of the [CO_2]. However several other climate change targets have been chosen in studies such as temperature change, radiative forcing, or climate change impacts (Fisher et al., 2007).

A range of technology options exists for reducing greenhouse emissions and enhancing sinks and reservoirs (Metz and van Vuuren, 2006):

- Energy efficiency improvement.
- Decarbonization of the energy system by increasing the use of low or zero carbon energy sources and/or applying CO_2 capture and storage (CCS).
- Biological carbon sequestration and/or reducing deforestation emissions.
- Reducing other greenhouse gases from industry, agriculture, waste.

In this thesis, only the technological options of enhancing biological sequestration of CO_2 in forests and soils and using bioenergy as means of decarbonizing the energy system are discussed. An important factor affecting both these technology options is the factor of land availability (Metz and van Vuuren, 2006).

1.3.1 Energy from biomass and its potential to reduce [CO_2]

The term biomass energy or bioenergy can refer to any source of heat energy produced from non-fossil biological materials (Field et al., 2008). Biomass sources include forest, agricultural and livestock residues, short-rotation forest plantations, dedicated herbaceous energy crops, the organic component of municipal solid waste and other organic waste streams. These are used as feedstocks to produce energy carriers in the form of solid fuels (chips, pellets, briquettes, logs), liquid fuels (methanol, ethanol, butanol, biodiesel), gaseous fuels (synthesis gas, biogas, hydrogen), electricity and heat (Sims et al., 2007). Before the start of the industrial revolution, biomass energy was the world's dominant energy source (Fernandes et al., 2007) and it is still accounting for approximately 7% of the world's primary energy consumption in 2000 (Fernandes et al., 2007) or approximately 1/3rd of the energy from sources other than fossil fuels (Sabine et al., 2004).

Although much of the recent attention on bioenergy focusses on liquid transportation fuels like ethanol and biodiesel, they currently comprise only 2% of the world's biomass energy (Coyle, 2007; Hall, 1997). Energy from biomass is used widely for cooking and as a source of heat in developing countries and also as a source of industrial heat in the forestry and paper industries (Farla et al., 1997).

On a global scale, the total annual plant growth, or the net primary production (NPP) fixes a quantity of carbon many times larger than that consumed in the industrial energy system. The total carbon emissions from fossil fuel combustion and natural gas flaring was 7.7 billion tons in 2005 (Raupach et al., 2007), while NPP fixed ~57 billion tons of carbon on land and 57 billion tons in the oceans (Behrenfeld et al., 2001). As human appropriation of terrestrial NPP is estimated to be in the range of 23 – 40%, the vast majority of this biospheric NPP is returned to the atmosphere through decomposition and wildfire (Haberl et al., 2007; Vitousek et al., 1986). Total annual NPP in croplands is ~7 billion tons of carbon per year (Potter et al., 1993), which is slightly less than the amount emitted in 2005. The very fact that the fossil fuel energy system already emits more carbon annually than that fixed by the all the croplands, highlights the challenge of substituting a substantial part of the fossil fuel system by biomass (Field et al., 2008).

In an idealized state, the energy from biomass does not contribute to the forcing of climate change with greenhouse gases. A plant used for bioenergy purposes, grows and fixes carbon dioxide from the atmosphere via the process of photosynthesis. Using this plant as a bioenergy source returns this same CO_2 to the atmosphere, with no net change in the amount of carbon in the atmosphere, plants or soils. However, real production systems differ from such an ideal system (Field et al., 2008).

Firstly, the production of bioenergy almost always involves the use of fossil energy for the farming, transportation and the manufacturing stages of the process (Hill et al., 2006). Considering the example of ethanol from corn, one of the more dominant sources of biomass based liquid transportation fuels, we find the picture to be quite depressing. The entire global harvest of corn, converted to ethanol using current technology would yield enough transportation fuels to supply only 6% of the global gasoline and diesel demand (BP, 2007). Furthermore, the fossil fuel energy needed to produce such quantity of fuel would represent 80% to 90% of the energy stored in the ethanol (Farrell et al., 2006; Hill et al., 2006). Combining these and directing the entire global harvest of corn grain to make ethanol, would offset well under 1% of the global emissions from fossil fuel combustion. Thus the Net Energy Balance Ratio (Output/Input) is very low at 1.25 (Hill et al., 2006). Consequently, even in the best case scenario, making ethanol from corn grain is not an effective route for lowering the carbon intensity of the energy system (Farrell et al., 2006). The picture is more promising for other sources of bioenergy with sources like sugarcane and palm oil having a much higher Net Energy Balance Ratio of 8 and 9 respectively (IEA, 2004; Worldwatch, 2006). However, much of the recent enthusiasm for increasing the production of ethanol is based on the prospect of extracting ethanol from cellulose using a class of enzymes responsible for the 'jungle rot' that destroyed many US Army tents in the South Pacific during World War 2 (Field et al., 2008). With ethanol being extracted from cellulose, the extraction could be done from all parts of the plant and the choice of plants would not be restricted to those that produce large amounts of starch or simple sugars. Although this process has not been implemented at an industrial scale, results from pilot installations indicate that the Net Energy Balance could eventually be greater than 4 (Hill et al., 2006).

The change in the carbon content of the site where the bioenergy plantations are carried out is another important factor which determines how effective the specific source of bioenergy is in reducing the carbon intensity of the energy system. Soils and plant biomass are the two largest biologically active stores of terrestrial carbon together containing approximately 2.7 times more carbon than the atmosphere (Schlesinger and Bernhardt, 1997). Converting native habitats to cropland releases CO_2 as a result of burning or microbial decomposition of the organic carbon stored in the biomass and soil. After a rapid initial release from fire used to clear the land, or from the decomposition of the leaves and fine roots, there is a prolonged period of release of GHGs as the coarse roots, branches and other parts of the dead plant decay (Silver and Miya, 2001; Winjum et al., 1998). Fargione et al. (2008) used the term 'carbon debt' for the amount of CO_2 released for the first 50 years of this land conversion. Over time, biofuels from this converted land can repay the carbon debt provided their production and combustion have net GHG emissions that are less than the life cycle emissions of the fossil fuels that they displace. Until this debt is repaid, the biofuels have a greater GHG impact than those of the fossil fuels that they displace. Fargione et al. (2008) concluded that converting rainforests, peatlands, savannas, or grasslands to produce crop-based biofuels in Brazil, Southeast Asia and the United States creates a 'biofuel carbon debt' by releasing 17 to 420 times more CO_2 than the annual GHG reductions that these biofuels would provide by displacing fossil fuels. In contrast, biofuels made from waste biomass or biomass grown on degraded and abandoned agricultural lands, especially when planted with perennials, have little or no carbon debt and thus can offer immediate and sustained reduction of the carbon intensity of the energy system.

1.3.2 The role of forestry in reducing [CO_2]

During the last decade of the 20th century, tropical deforestation and regrowth of forests in the temperate and boreal zones remained the major factors responsible for emissions and removals, respectively. However, there is a disagreement between land observations and estimates by top-down models about the extent to which the carbon loss due to tropical deforestation is compensated for by the expanding forests and a consequent accumulating biomass in the boreal and temperate zones. Estimates by IPCC show that the net uptake by terrestrial ecosystems range from 1.0 to 2.6 PgC yr^{-1} for 1990 (Nabuurs et al., 2007). More recent analyses estimate the terrestrial C sink to be in the range of 2.0 to 3.4 PgC yr^{-1} based on atmospheric CO_2 measurements and inverse modeling, as well as land observations (Canadell et al., 2007; Khatiwala et al., 2009; Le Quéré et al., 2009). Using forest inventory data and long-term ecosystem carbon studies, Pan et al. (2011) estimated a total forest sink of 2.4 ± 0.4 PgC yr^{-1} globally for 1990 to 2007.

The carbon mitigation potentials from different forestry activities like deforestation, forest management and afforestation has a characteristic time sequence of actions, carbon benefits and costs. Relative to a baseline, the largest short-term gains are always achieved through mitigation activities aimed at emission avoidance such as reduced deforestation, fire protection and slash burning. But once an emission has been avoided, the carbon stock in the forest will be maintained or will improve slightly. In contrast, the benefits from afforestation accumulate over years to decades but require up-front action and expenses (Nabuurs et al., 2007).

Among the different forestry mitigation options, the one discussed in this thesis aimed at increasing the forest area through natural reforestation by allowing forests to grow back in natural succession on abandoned crop lands. Such a process typically leads to increases in biomass and dead organic matter carbon pools, and to a lesser extent, in soil carbon pools, whose small, slow increases are often hard to detect within the uncertainty ranges (Paul et al., 2003). On sites with low initial soil carbon stocks (e.g. after prolonged cultivation), afforestation can lead to considerable soil carbon accumulation rates (e.g. Post and Kwon (2000)). On the contrary, on sites with high initial soil carbon stocks (e.g. some grassland ecosystems) soil carbon stocks can decline following afforestation (e.g. Tate et al. (2005)).

1.4 Effects of climate change

In addition to natural factors, climate change constitutes an additional pressure that could change or endanger ecosystems. The IPCC AR4 (Easterling et al., 2007; Fischlin et al., 2007) has highlighted the potential impacts of global change, including the impacts of climate change that can affect the mitigation potential of the forestry sector by either increasing (nitrogen deposition and CO_2 fertilization), or decreasing (negative impacts of air pollution,) the carbon sequestration (Nabuurs et al., 2007). However, recent studies suggest that the beneficial effects of climate change are being overestimated by ignoring some of the feedbacks (Körner, 2004). Moreover, the negative impacts maybe larger than expected (Schröter et al., 2005).

1.5 Biogeophysical effects of a land cover change – a consequence of implementing any land based mitigation measure

While attempting to implement any of the mitigation measures in an attempt to reduce the increase of atmospheric CO_2 concentration, another effect on climate forcing which needs to be considered is the balance between the absorption and reflection of solar energy at the surface of the earth (Schaeffer et al., 2006). Darker vegetation produces local warming while lighter vegetation produces local cooling (Field et al., 2007). While analyzing purely the biogeophysical effect of historical deforestation, Brovkin et al. (2006) found that the global annual mean temperature decreased from 0.13 to 0.25°C. This trend was less pronounced for the tropical regions than the temperate region. This is because in the tropics the effect of a decrease of evapotranspiration and thus precipitation is more dominant while in the temperate regions, it is the snow making effect (increase of albedo) which plays a more dominant role (Claussen et al., 2001).

1.6 Structure

Different modeling studies assessing the net sum of biogeochemical and biogeophysical effects of deforestation of the high latitudes have found a net cooling (Bala et al., 2007; Bathiany et al., 2010; Claussen et al., 2001). However, on comparing the results of especially Bala et al. (2007) and Bathiany et al. (2010) with that of observational studies (Pan et al., 2011a; Prentice et al., 2001a), it was found that there is a possibility that the dominance of the biogeophysical effect of boreal deforestation could be due to an underestimation of the biogeochemical response. Thus in chapter 2, a purely academic study to make a better estimation of the carbon cycle changes under such large-scale deforestation was carried out. Apart from this, in chapter 2, it was also investigated whether bioenergy plantations in the deforested areas, due to avoided usage of fossil fuels, are able to make up for the carbon emitted due to this deforestation.

Research questions:

- What are the total emissions for high latitude large-scale deforestation and how they compare with that of previous studies?
- What are the biogeophysical effects of such deforestation?
- Are bioenergy plantations in the deforested areas able to make up for the carbon losses caused by the emissions?

Removal of existing forest or grass land for bioenergy plantations would lead to a net climate change rather than mitigation as such Land Use Change (LUC) would lead to a net carbon debt and thus a net increase in the [CO_2] (Campbell et al., 2008; Dass et al., 2013; Fargione et al., 2008; Searchinger et al., 2008). However bioenergy plantations on erstwhile agricultural land which has been abandoned for different reasons could be a suitable option (Campbell et al., 2008; Tilman et al., 2006a) as the bioenergy can potentially substitute fossil fuels without causing additional emissions especially from LUC. On the other hand, instead of bioenergy cropping, if such fallow land is allowed to be restored to natural forests or grasslands by natural succession, then there would be a net carbon sequestration (Kurganova et al., 2010; Righelato and Spracklen, 2007; Vuichard et al., 2008).

Research questions:

- How much carbon is saved (from avoided emissions) from bioenergy plantations and how much carbon is sequestered by the re-growing natural vegetation?
- From the above management options, which is the most effective mitigation measure for the temperate abandoned croplands?

Tropical forests have high rates of productivity (Brown, 1993) and a significant proportion of the tropical forest biome is in some state of recovery from past human disturbance (Silver et al., 2000). Although allowing tropical forests to recover from past disturbances provides ecological benefits and results in the sequestration of carbon, this process is likely to be limited in its capacity to reduce the [CO_2] as biomass may eventually reach a maximum sequestration potential (Silver et al., 2000). On the other hand, biofuels derived especially from certain mixtures of native grassland perennials can provide more usable energy and less agrichemical pollution than can corn grain ethanol or soybean biodiesel. Moreover, such bioenergy plants can be grown on abandoned and/or degraded agricultural lands (Tilman et al., 2006a). So such bioenergy plantations have the potential to become another strategy for stemming the rise in [CO_2]. Thus in chapter 4 the amount of carbon sequestered in the re-growing natural vegetation in the abandoned tropical agricultural lands is assessed and compared with the carbon emissions saved by the bioenergy plantations through avoided usage of fossil fuels.

Research questions:

- How much carbon is saved (from avoided emissions) from bioenergy plantations and how much carbon is sequestered by the re-growing natural vegetation?
- From the above management measures, which is the most effective mitigation measure for the abandoned tropical croplands?
- What is the biogeophysical effect of reforestation of the tropical abandoned croplands?

We can appreciate the effects of any mitigation option best if we consider the worst-case scenario as the reference scenario. We used the SRES A2 scenario as it in the only scenario which has an increasing trend of CO_2 emissions even at the end of the 21st century (Nakicenovic et al., 2000b). As the climate and [CO_2] keeps on changing even at the end of the 21^{st} century, in all the above mentioned chapters, we analyze the effects of the above changes separately as well as together.

Research question:

What are the effects of the projected changes in the [CO2] and climate (according to the SRES A2 storyline) on the biophysical bioenergy potential and/or the biomass of natural vegetation?

Vegetation productivity is sensitive to conditions of the climate, [CO_2], as well as different management practices (Norby et al., 2005; Oren et al., 2001; Smith et al., 2000; Witt et al., 2000). To account for projected changes in [CO_2] and climate, and to assess the biogeochemical effects of any land use and land cover change (LULUC), we used the Dynamic Global Vegetation Model (DGVM) LPJmL (Lund-Potsdam-Jena managed Land) (Bondeau et al., 2007) in all of the above mentioned chapters. In addition, to estimate pure biogeophysical effects of deforestation in chapter 2 and reforestation in chapter 4, we use MPI-Earth System Model (MPI-ESM-LR) in the CMIP5 version for pre-industrial simulation (Giorgetta et al., 2013).

Overall research question:

What is the role of bioenergy production in the terrestrial carbon cycle and energy balance?

1.7 Formal remarks

Chapter 2 of my dissertation corresponds to a paper which has been published in the journal Earth System Dynamics (Dass et al., 2013).

I conducted the studies under the supervision and guidance of Dr. Victor Brovkin, Dr. Christoph Müller and Prof. (Dr.) Wolfgang Cramer. Thus in contrast to this introduction, and the summary & conclusions, the next three chapters are written in first person plural. I kindly ask the reader to be indulgent with this kind of imperfection.

Chapter 2: Can bioenergy cropping compensate high carbon emissions from large-scale deforestation of high latitudes?

2.1 Introduction

Afforestation or reforestation is considered as effective carbon sequestration measure because of significant amounts of carbon trapped in the forest biomass. However, the carbon metrics is not the only one in evaluation of the forest impact on climate. Changes in forest cover affect climate through changes in biophysical parameters such as land surface albedo, evapotranspiration, and roughness. This is because albedo of forest canopies is lower than that of other vegetation or bare soil (Alton, 2009). Particularly in boreal latitudes, this albedo difference is much enhanced when snow is present because snow cover is masked by trees but not by herbaceous vegetation (Bonan, 2008; Nobre et al., 2004). If the snow cover period is long enough, the biogeophysical effect due to albedo changes could overcome the biogeochemical effect due to carbon storage in forest. Studies investigating solely the biogeophysical effects of deforestation on a global scale (Bounoua et al., 2002; Brovkin et al., 2006, 2009; Matthews et al., 2003) have found a net cooling. Considering both biogeophysical as well as biogeochemical effects of landuse change, afforestation in the boreal region would increase the warming due to decreased albedo feedback which outweighs the cooling caused by carbon sequestration (Arora and Montenegro, 2011; Betts, 2000). Other numerous modeling studies agree that a net sum of biogeochemical and biogeophysical effects of deforestation of the high latitudes is a cooling (Bala et al., 2007; Bathiany et al., 2010; Claussen et al., 2001).

The dominance of the biogeophysical effect of global boreal deforestation (Bala et al., 2007; Bathiany et al., 2010) could be due to an underestimation of the biogeochemical response.

Bathiany et al. (2010) found that boreal (all land north of 45°N) deforestation results in an immediate global emission of 20 GtC followed by almost no change in the global terrestrial carbon during decades and centuries after deforestation. Bala et al. (2007) estimate the total global emissions from such large scale (all land north of 50°N) deforestation to be 80 GtC. Observational studies have estimated the global carbon stocks of the boreal forests for vegetation to be 57 to 88 GtC (Prentice et al., 2001b) and as per estimates of 2007 the same was found to be 53.9 GtC (Pan et al., 2011b). In addition, the total global carbon stocks of the other carbon pools of the boreal forests, including dead wood, litter and soil amount to 217.6 GtC (Pan et al., 2011b). Therefore, we expect the value of long term emissions because of the slow decomposition of the carbon of these pools to be higher than the vegetation carbon storage.

The area of interest in this study involves all landmass north of 45°N, which is the same as that of Bathiany et al. (2010) but fractionally more than that of Bala et al. (2007). So apart from the boreal forests, the northern part of the temperate forests is also included. As per 2007 estimates, the total living biomass for temperate forests of the northern hemisphere is 38.2 GtC (Pan et al., 2011b). Assuming our area of interest in this study to include approximately half of the temperate forests of the northern hemisphere, the total living biomass in this area would amount to ~73 GtC. We assume that in the event of deforestation, all the vegetation carbon is burnt and emitted to the atmosphere immediately. Apart from this, when land is converted from any form of natural state to crop land, a substantial part of carbon which is already stored in the litter and soil is decomposed and emitted due to soil respiration. Numerous studies unequivocally show that conversion of land from forest to crop-land leads to degradation of soil carbon stocks (Davidson and Ackerman, 1993; Ellert and Gregorich, 1996; Guo and Gifford, 2002; Post and Kwon, 2000). So in addition to immediate emissions there would be long term emissions. Thus it is evident that the total carbon emissions computed in the previous boreal deforestation studies (Bala et al., 2007; Bathiany et al., 2010) are at the lower end of observational estimates.

While we are not proposing large scale deforestation as a mitigation option, we carry out a purely academic study to make a better estimation of the carbon cycle changes under such large-scale deforestation. Vegetation productivity is sensitive to conditions of the climate, atmospheric CO_2 concentration ([CO_2]), as well as different management practices (Norby et al., 2005; Oren et al., 2001; Smith et al., 2000; Witt et al., 2000). To account for projected changes in [CO_2] and climate, and to assess the biogeochemical effects of such land use and land cover change (LULUC), we used the Dynamic Global Vegetation Model (DGVM) LPJmL (Lund-Potsdam-Jena managed Land) (Bondeau et al., 2007). Bathiany et al. (2010) estimated combined biogeophysical and biogeochemical effects. To estimate pure biogeophysical effects of deforestation above 45°N we use MPI-Earth System Model (MPI-ESM-LR) in the CMIP5 version for pre-industrial simulation (Giorgetta et al., 2013).

Bioenergy is a cost effective mitigation measure as the cost of production of bioenergy combined with CCS is almost half compared to that of more efficient forms of renewable energy like solar energy (Magne et al., 2010). As conventional 1st generation biofuels like ethanol or biodiesel have their limitations (Crutzen et al., 2008; Fargione et al., 2008; Melillo et al., 2009; Searchinger et al., 2008), 2nd generation bioenergy technologies (lignocellulosic plant material) could be used in combination, more so because these plants are more tolerant against unfavorable climate and soil conditions (Adler et al., 2007; Schmer et al., 2008). However, apart from destroying landscapes and reducing biodiversity (Melillo et al., 2009), bioenergy plantations lead to considerable land use change. This causes immediate emissions due to burning of above ground biomass, as well as long term emissions owing to decomposition of litter and soil carbon (Houghton et al., 1983). These emissions are dependent on the type of ecosystem being disturbed. For instance, if bioenergy crop plantations are carried out in tropical rainforests or peatlands, it would cause a net 'biofuel carbon debt' by emitting significantly more CO_2 than the respective crop would save (Fargione et al., 2008). Apart from the biogeochemical effect, for areas affected by seasonal snow cover, the cooling contribution of an increased albedo from herbaceous bioenergy plantations is significant (Cherubini et al., 2012a). So the net effect of bioenergy plantations on the climate would depend on the balance between the biogeophysical and biogeochemical effects.

We assume bioenergy to be used directly as a fuel. So the emissions from bioenergy usage could be treated as a single pulse with a short lifetime in the anthroposphere (Cherubini et al., 2012b). Thus, other than the land use emission we can consider bioenergy to be carbon neutral. Apart from computing the emissions from deforestation, we also use LPJmL to investigate whether bioenergy plantations in the deforested areas, due to avoided usage of fossil fuels, is able to make up for the carbon losses due to this deforestation. In order to calculate the avoided emission, we compute the maximum biophysical bioenergy potential from non-woody bioenergy plants in the area of the high latitudes, i.e. all land north of 45°N. By biophysical bioenergy potential, we understand the production of bioenergy for given climatic and environmental conditions, ignoring the technical and economic feasibility. In order to compare similar units we use primary energy, or the energy derived after 100% combustion efficiency, to quantify the biophysical bioenergy potential as we do not specify the form of final energy which is to be actually used (Fischer and Schrattenholzer, 2001). To calculate the emissions saved by avoided burning of fossil fuels, we again assume 100% combustion (EIA, 2008). Finally we examine whether such bioenergy plantation is able to supplement the cooling due to biogeophysical feedback (Bala et al., 2007; Bathiany et al., 2010; Claussen et al., 2001). However we do not discuss other potentially important effects of extensive bioenergy plantations.

2.2 Model and experimental setup

2.2.1 Model description

LPJmL is a dynamic global vegetation, hydrology and agriculture model representing both natural and managed ecosystems at the global scale (Bondeau et al., 2007; Sitch et al., 2003a). The natural vegetation is represented by 9 plant functional types (PFTs), while 12 crop functional types (CFTs), represent the most important crops (Bondeau et al., 2007). LPJmL is driven by monthly fields of temperature, precipitation, cloud cover, [CO_2] and soil texture (Sitch et al., 2003a).

LPJmL has been recently extended to simulate the cultivation of cellulosic energy crops on dedicated biomass plantations. The detailed description is provided by Beringer et al. (2011). However we have excluded energy trees as otherwise bioenergy trees would negate the biogeophysical cooling (mainly from increased albedo) caused by deforestation of the high latitudes.

For every experimental simulation, a spin-up simulation is carried out for 1000 years, repeating the climate and land use of the first 30 years, (1901-1930) in order to bring the distribution of natural vegetation and carbon pools into equilibrium (Bondeau et al., 2007; Sitch et al., 2003a). This is followed by a 390 year spin-up with gradually expanding land use patterns to account for the effects of historic land use on soil carbon pools.

The Earth System model developed at the Max Planck Institute for Meteorology in Hamburg, Germany, (MPI-ESM) includes the atmospheric model ECHAM6 in T63 (1.9° x 1.9°) resolution with 47 vertical levels described by Stevens et al. (2013), the oceanic model MPI-OM at approx. 1.6° resolution with 40 vertical layers (Jungclaus et al., 2006), and the land-surface model JSBACH (Raddatz et al., 2007) sharing the horizontal grid of the atmospheric model. This grid set-up is a low-resolution version (LR) of the model used for centennial-time scale simulations in CMIP5. A detailed description of the model and an evaluation of the model performance is given by Giorgetta et al. (2013).

2.2.2 Model setup

Climate projections differ between different GCMs primarily because of the uncertainty of parameterizations. For example, the global average temperature projection for the SRES A2 scenario has an approximately 66% probability of ranging from 2.0 to 5.4 °C, at the end of the 21st century, relative to the end of the 20th century (Solomon et al., 2007). To account for this variability, LPJmL was driven with 21st century climate projections from an ensemble of 19 different general circulation models' (GCM) implementations of the SRES A2 scenario (Nakicenovic et al., 2000a) as listed in Table 2.1(appx). The climate scenarios for the individual scenarios have been prepared by calculating the anomalies relative to the 1971-2000 average for each GCM and month of the 2001-2099 period and applied to the observed 1971-2000 baseline climate. Detailed description is given in Gerten et al. (2011). All these GCMs participated in the World Climate Research Program's Coupled Model Intercomparison Project phase 3 (Meehl et al., 2007) and were used in the IPCC's Fourth Assessment Report (IPCC, 2007). Figures 2.01a and 2.01b demonstrate the mean annual change in temperature and precipitation respectively from the beginning of the 20th century to the end of the 21st century. The rise in temperature becomes more intense with increasing latitude, with temperature increases in the extreme high latitudes of more than 8°C. This is referred to as 'polar amplification' (Holland and Bitz, 2003). The precipitation change on the contrary shows a spatially heterogeneous pattern with most areas experiencing an increase while only small patches experience decreasing annual precipitation. The high variability in temperature and precipitation change patterns among the individual GCMs is illustrated in Figure 2.02.

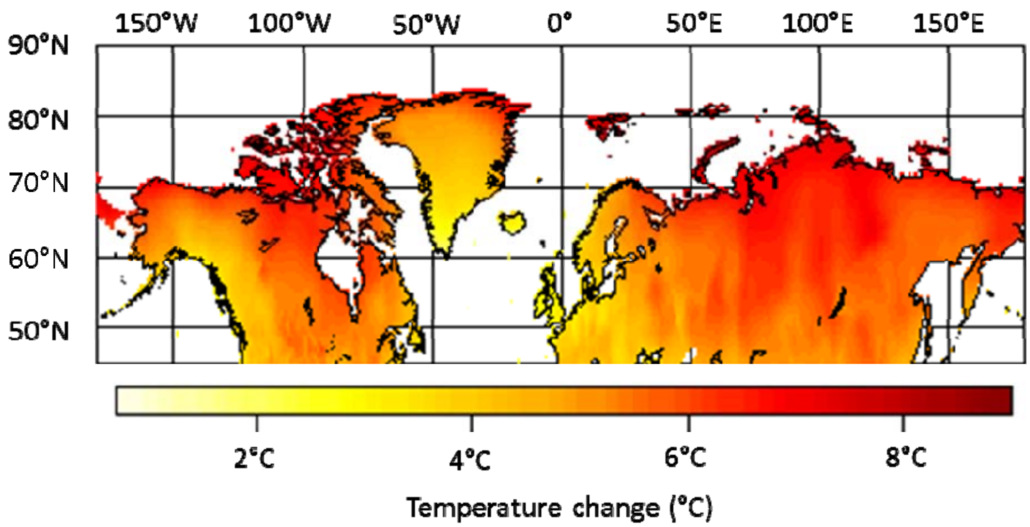

Figure 2.01a: Temperature (°C) difference of the annual means between the end of the 21st century and the beginning of the 20th century. The values are a mean of 19 GCMs.

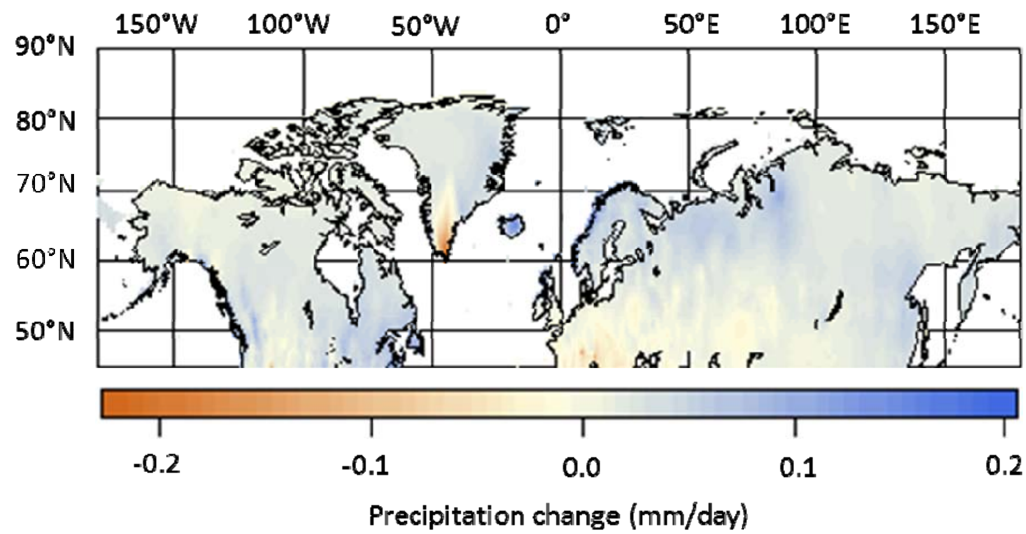

Figure 2.01b: The same as Fig. 2.01a but for Precipitation change (mm/day)

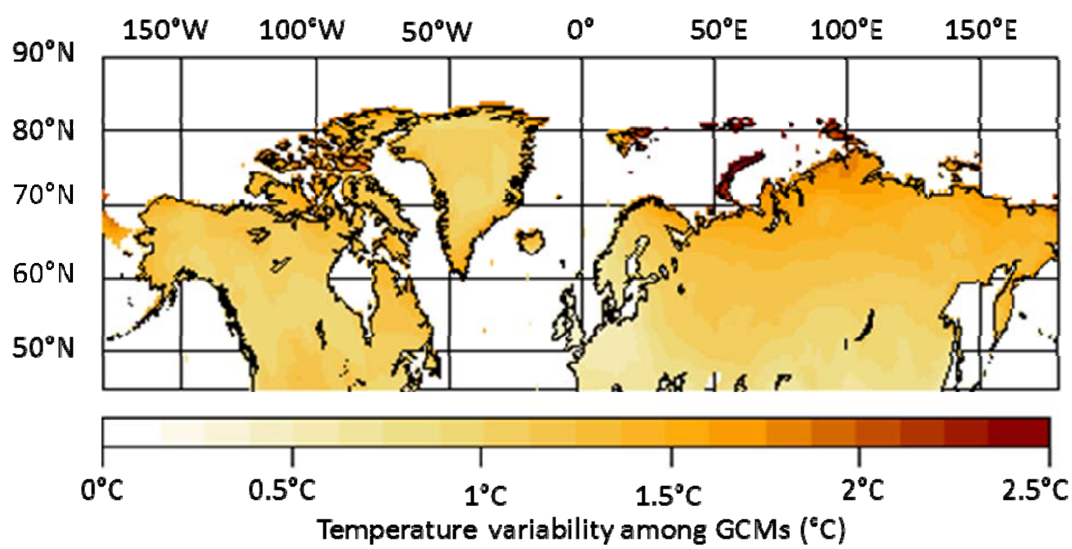

Figure 2.02a: The variability among the 19 GCMs for the values of Temperature (°C) plotted in Fig. 1.1a is demonstrated by the Standard Deviation.

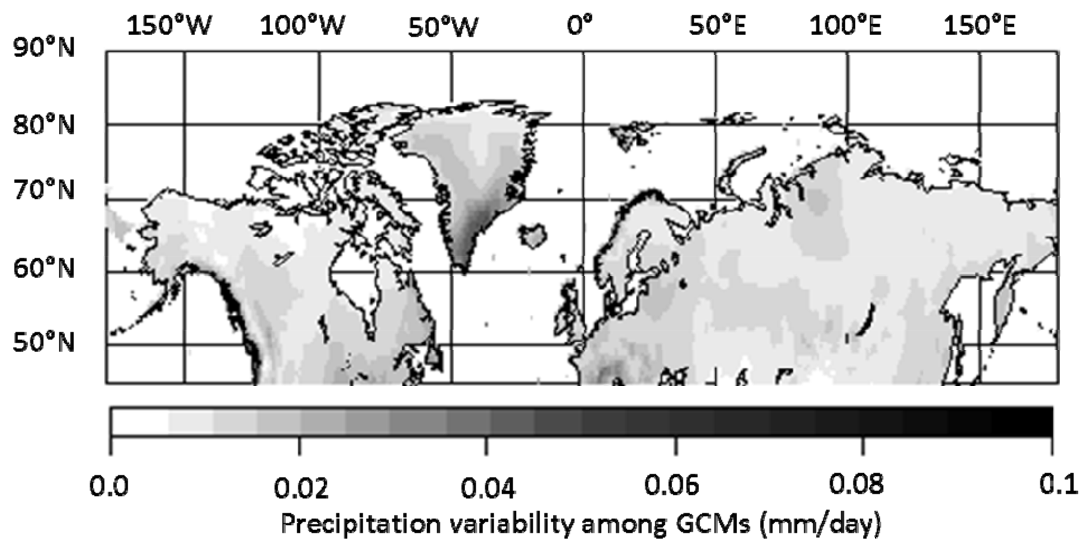

Figure 2.02b: The same as Fig. 2.02a but for Precipitation (mm/day)

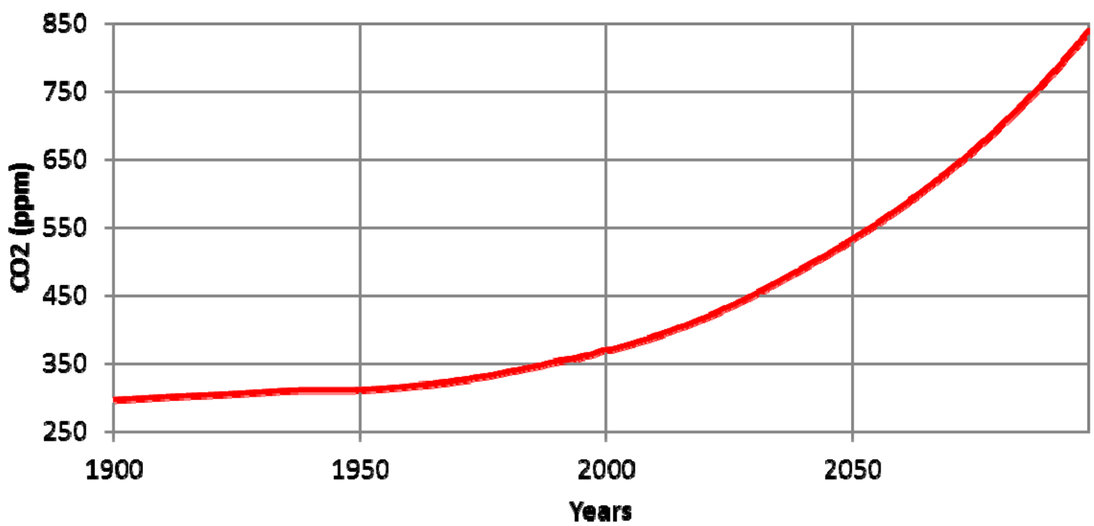

Figure 2.03: Trend of CO_2 (ppm) according to SRES A2 scenario plotted from the beginning of the 20th century to the end of the 21st century.

2.2.3 Land management scenarios

While it could be theoretically possible to remove all natural vegetation from the high latitudes, much of the cleared land could not be directly used for bioenergy production unless specific soil and terrain restrictions are eliminated by additional management efforts. As a result we calculate the biophysical bioenergy potentials, using LPJmL for different scenarios on management efforts ranging from conservative or more plausible where all restrictions are assumed to hold (or there is no management to eliminate these) to idealistic, where no restrictions are considered (or all restrictions are assumed to be eliminated). Soil and terrain restrictions are based on the Global Agro-Ecological Zonal (GAEZ) data set (Fischer et al., 2000). The characterization of the suitability of land resources for agricultural production includes all relevant components of soils and landform, which are basic for the supply of nutrients and physical support to plants. Climatic constraints of the GAEZ data set are ignored in this study as LPJmL already uses climate data as an input and thus crop growth simulated by this model is already restricted by climate. The different land management scenarios used in this study, as tabulated in Table 2.4, are:

i.) **MAXL:** Land with any constraint of unsuitable terrain or unsuitable soil properties, including unsuitable soil fertility, is assumed to be unavailable for farming. Unsuitable terrain mean those areas that have severe terrain constraints (i.e. greater than 16% slope or areas with greater than slight constraints (Fischer et al., 2000)). In addition we assume that land currently occupied by built area and crop land (Erb et al., 2007) is considered to be unavailable for bioenergy plantations. The remaining land is thus available for bioenergy crop plantations. As a result, we consider this to be the most plausible of all the scenarios.

ii.) **CROPL:** Areas currently occupied by built area and cropland (Erb et al., 2007) in addition to 'generally unsuitable soil' and unsuitable terrain are considered to be unavailable for bioenergy plantations. 'Generally unsuitable soil' includes constraints of unsuitable soil depth, drainage, texture and chemistry but not soil fertility as it is considered to be managed for example by the use of fertilizers.

iii.) **SOILL:** 'Generally unsuitable soil' in addition to unsuitable terrain is assumed to be unavailable to farming. Thus the remaining area is available for bioenergy crop plantations.

iv.) **TERL:** All areas are assumed to be available for bioenergy plantations except areas with unsuitable terrain.

v.) **UNLIM:** All terrain and soil limitations are assumed to be managed, (e.g. terrain by terrace farming; soil drainage by mixing clay and sandy soil; soil structure by plough etc.). As all land area is considered to be available for bioenergy plantations, we consider this scenario to be the most idealistic.

The number of restrictions decreases in sequence of scenarios from MAXL to UNLIM and as a result the area available to bioenergy production increases (Fig. 2.04 and Table 2.4).

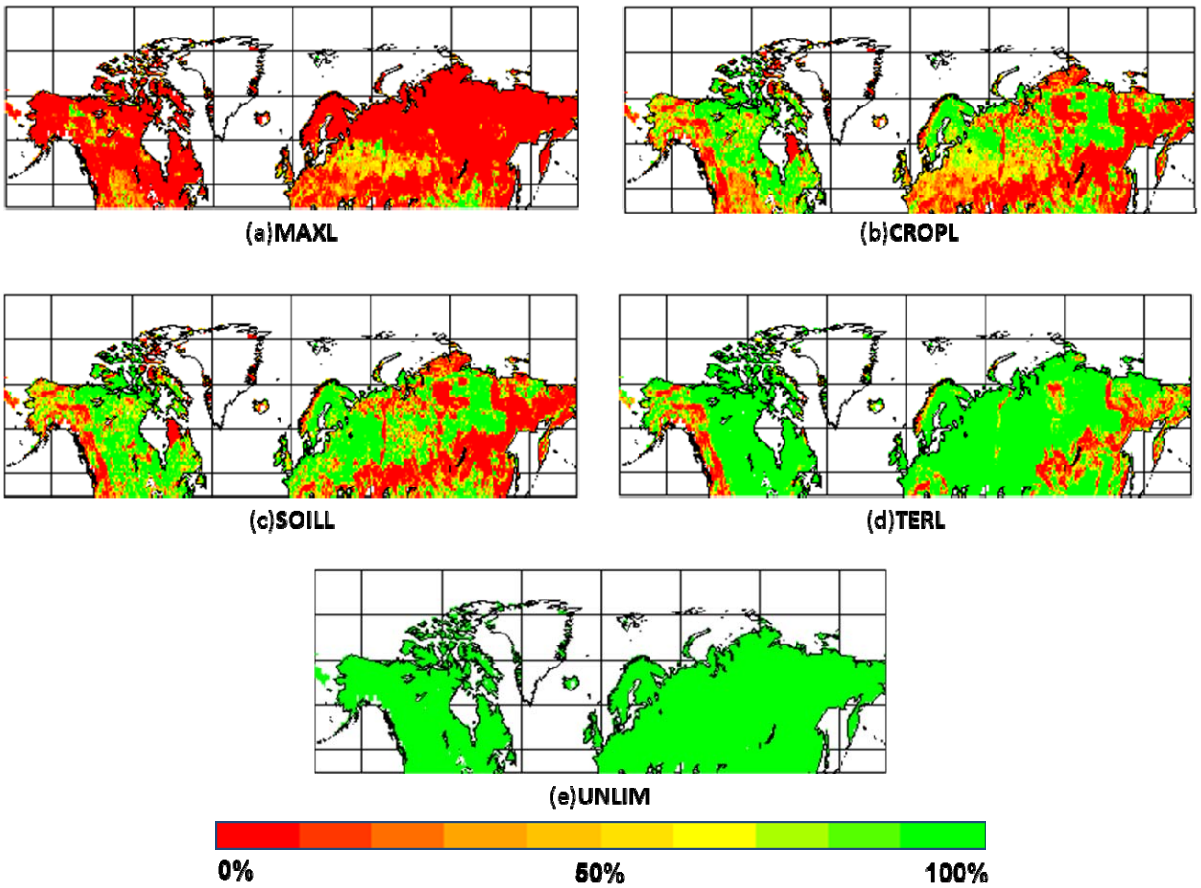

Figure 2.04: Percentage of area (of each 0.5° * 0.5° grid cell) used for bioenergy crop plantations for land management scenarios (a) MAXL, (b) CROPL, (c) SOILL, (d) TERL, (e) UNLIM. Green symbolizes complete availability while red stands for unavailability of that grid cell for bioenergy crop plantation.

Table 2.4. Different land management scenarios, their restrictions included, the corresponding area available for bioenergy plantations, the corresponding emissions and resultant increase in temperature because of that at the end of the 21^{st} century

Scenario	**Restrictions**	**Area (Million Hectares)**	**Long term emissions (GtC)**	**Total emissions at end of 21^{st} century (GtC)**	**Increase of global mean temperature at end of 21^{st} century only due to emissions (°C)**
MAXL	Terrain + Soil (depth, drainage, texture, chemical) + Built area + Cropped land + Soil fertility	536.7	-13.7 ± 8.2	168.5 ± 8.6	0.12 to 0.32
CROPL	Terrain + Soil (depth, drainage, texture, chemical) + Built area + Cropped land	1,787.7	83.7 ± 12.0	266.0 ± 12.5	0.20 to 0.53
SOILL	Terrain + Soil (depth, drainage, texture, chemical)	2,073.2	101.1 ± 12.3	283.4 ± 12.8	0.22 to 0.57
TERL	Terrain	3,121.4	172.6 ± 14.0	354.9 ± 14.5	0.27 to 0.72
UNLIM	None	3,801.4	231.7 ± 15.0	414.0 ± 15.5	0.32 to 0.84

2.2.4 Crop management

In the LPJmL version used in this study, as described in details by Fader et al. (2010), the management intensity, i.e. the degree of crop production control and input application (fertilizer, technology, labor, weed, and disease control, etc.) is represented by three parameters: LAI_{max}, HI_{max} and α-a**,** where LAI_{max} , which is country specific, refers to the maximal attainable leaf area index of a crop, the HI_{max} refers to the maximal harvest index while the α-a parameter scales leaf level biomass production to stand level. Due to the simplified treatment of agricultural management in the model, the management intensity values that result in the best approximation of the 1999-2003 national yields reported by FAOSTAT (2009) are used here (for details see Fader et al. (2010)). Sowing dates are computed internally based on past climate experience as described by Waha et al., (2012).

2.2.5 Allocation of bioenergy plantations on deforested areas

The spatial pattern of crop production is prescribed via the historical land use data set from 1700 to 2005 as described by Fader et al. (2010) which has been extended to explicitly assign areas to the cultivation of sugarcane based on data of MIRCA2000 (Portmann et al., 2010), because sugarcane had been implemented into the model at a later stage (Lapola et al., 2009). In this study, the land use pattern of 2005 is assumed to remain constant for all the years beyond 2005 in the 'CTRL' (control) simulation.

In the experimental simulations (scenarios MAXL to UNLIM), the land use remains the same as CTRL until 2010, when all land north of 45° in the Northern Hemisphere is cleared of its natural vegetation. After leaving this land fallow for one year, only suitable areas (varies according to the different land management scenarios as described in section 2.2.3) are planted with herbaceous crops (including bioenergy grass) such that those crops return maximum primary bioenergy yield (MJ/ha). Areas unsuitable for bioenergy plantations are allowed to be naturally re-vegetated with only herbaceous vegetation. In this study LPJmL is parameterized such that on deforestation 100% of the above ground biomass, including 2/3 of the sap wood (as it is assumed that 1/3 of the sap wood is in the roots and thus belongs to the below ground carbon) is burnt and released to the atmosphere while the rest goes to the litter. The forest litter consequently enters the soil carbon pool and is then decomposed. This type of forest clearing is representative of the 'slash and burn' method. This assumption of emitting all the carbon of the above ground biomass comes from the fact that even in natural forest fires as much as 90% of the carbon at the ground layer of a severely burnt forest is consumed (Michalek et al., 2000). This assumption has also been used in earlier studies e.g. by Grünzweig et al. (2004). For the calculation of the biophysical bioenergy potential of individual crop types, we assume that 50% of crop dry matter is carbon (Rojstaczer, 2001). The primary energy content per gram of crop dry matter is based on the Energy research Centre of the Netherlands Phyllis database (ECN, 2007) and as listed in Table 2.2(appx).

The land use of the area deforested in this experiment is dynamic and depends on which crop would provide maximum energy yield for that particular year. Different crops have different temperature requirements for optimal photosynthesis as shown in Table 2.3(appx) and the mix of most suitable land use types reflects the heterogeneity in climate. As an example, the land use pattern for the UNLIM scenario for the end of the 21st century is shown in Fig. 2.05, with the extremely unproductive regions (having yields of less than 2 tDM/ha) masked out and the yield pattern (UNLIM scenario) is shown in Fig. 2.06. After annual harvest, all parts of the plant other than the storage organs are left on the field and as a result enter the litter followed by the soil carbon pool. It should be noted that for this illustration, as described in the UNLIM scenario, we allowed all land to be planted with crops irrespective of the suitability. As a result, even the extreme high latitudes have been planted with crops but the yield in these areas is too low to significantly affect the overall biophysical bioenergy potential.

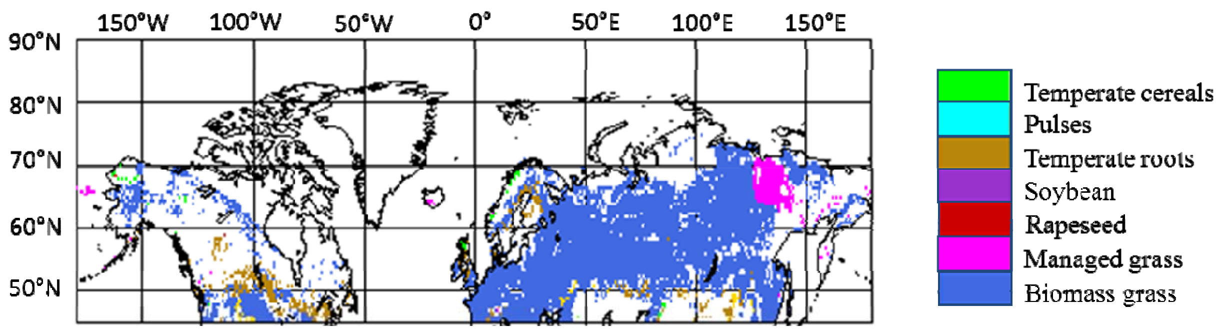

Figure 2.05: The Land Use pattern at the end of the 21st century for the UNLIM scenario with areas having extremely low yielding areas (less than 2 tDM/ha) masked out.

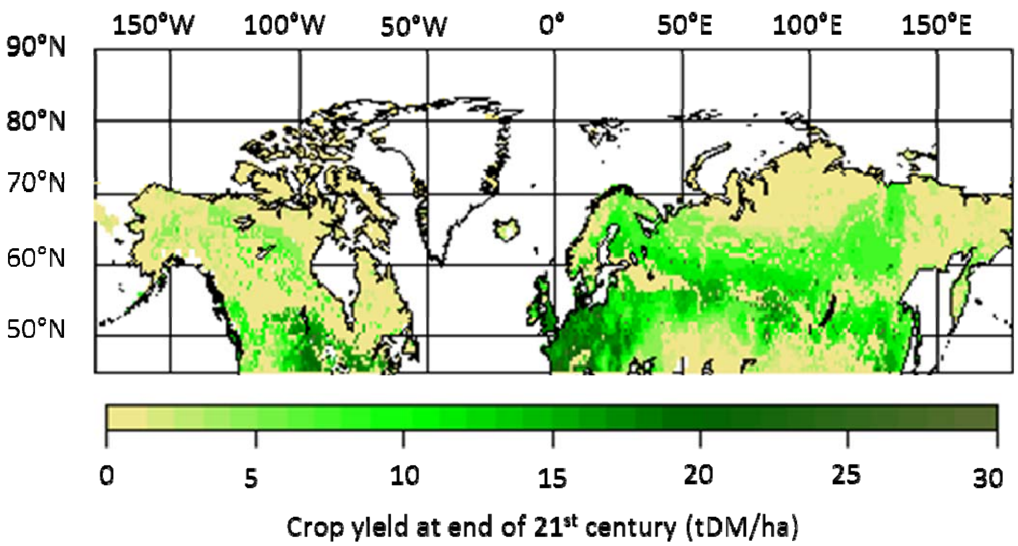

Figure 2.06: The crop yield (tDM/ha) at the end of the 21st century for the UNLIM scenario. The values plotted are a mean of the 19 values simulated by LPJmL as a result of using climate data simulated by 19 GCMs.

To assess the pure biogeophysical effect of extensive deforestation, in the additional experiment with MPI-ESM, we replace all woody PFTs north of 45°N with grasses, keeping [CO_2] fixed as the pre-industrial value. We conduct this simulation for 30 years.

2.3 Results

We find that the large scale deforestation of the area north of 45°N would lead to immediate C-emission of 182.3 ± 0.7 GtC. This immediate emission would be followed by long term changes in the litter and soil carbon pools, which range from a sequestration of 13.7 ± 8.2 GtC for the most plausible, MAXL scenario to an emission of 231.7 ± 15.0 GtC for the most idealistic scenario, UNLIM, by the end of the 21st century, as shown in Table 2.4 and Fig. 2.07. The long term emissions are dependent on the area of the land under bioenergy cultivation as the remaining land deemed unsuitable for cropping is allowed to revert to natural grasslands and thereby sequester carbon, especially in the soil and litter pools. As soil and litter pools of grasslands have more carbon compared to forests (Conant et al., 2001; Guo and Gifford, 2002), the litter and soil carbon pools of MAXL scenario is greater than the CTRL scenario. It should be noted that since LPJmL is an offline model and since MPI-ESM is run with a prescribed [CO_2], the emissions reported above does not influence the climate forcing of the simulations.

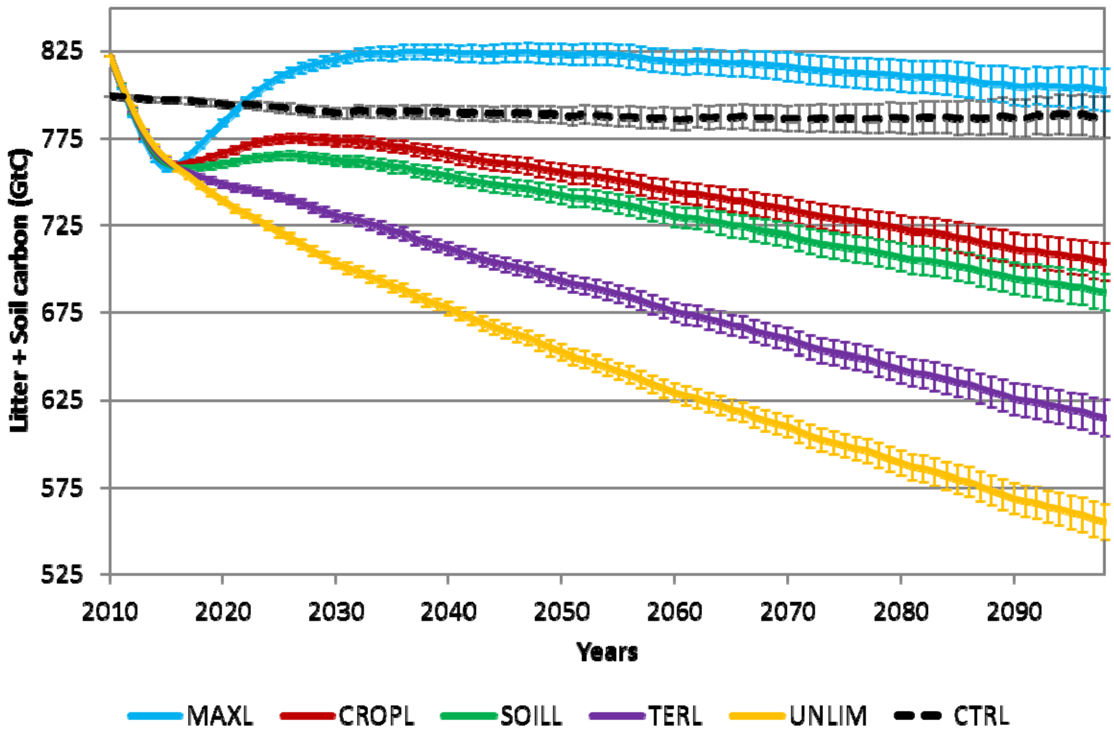

Figure 2.07: Long term carbon emissions from the litter and soil carbon pools of the respective land management scenarios (solid colored lines) compared with that of CTRL (dashed black line). The mean of an ensemble of 19 values is shown by the thick line while the error bars represent the uncertainty (1 Standard Deviation). After an initial decrease, the carbon pools of soil and litter start recovering as natural grassland is allowed to regrow on areas not used for bioenergy cropping. The difference in carbon pools of the different land management scenarios is because of the different extents of land under bioenergy cultivation. MAXL, the most plausible scenario has the least land under cultivation and thus has the most land under natural grassland. As grassland soils have more carbon than that of woody forests, the sum of litter and soil carbon of MAXL exceeds that of CTRL.

With anthropogenic climate warming, plant productivity is expected to increase in cooler regions due to the fertilization effect of increased [CO_2] and increased temperatures metabolically enhancing photosynthesis (Melillo et al., 1993). This is reflected in the biophysical bioenergy potential which is proportional to the corresponding crop productivity, shown as a 30 year moving average in Fig. 2.08. This phenomena is also demonstrated in Fig. 2.06 where the high latitude of Alaska (USA), northern Canada and parts of northern Norway and Sweden have significantly high crop yields. This is because the climate change, according to SRES A2 storyline, leads to an increase in temperature and precipitation in these areas, as demonstrated by Fig. 2.01. Both climate change and increasing [CO_2] lead to increasing biophysical bioenergy potentials north of 45°N, where the climate effect is about twice as large as the effect of increasing [CO_2]. In combination, the two drivers show an amplifying effect on the increase of biophysical bioenergy potentials (Fig. 2.08).

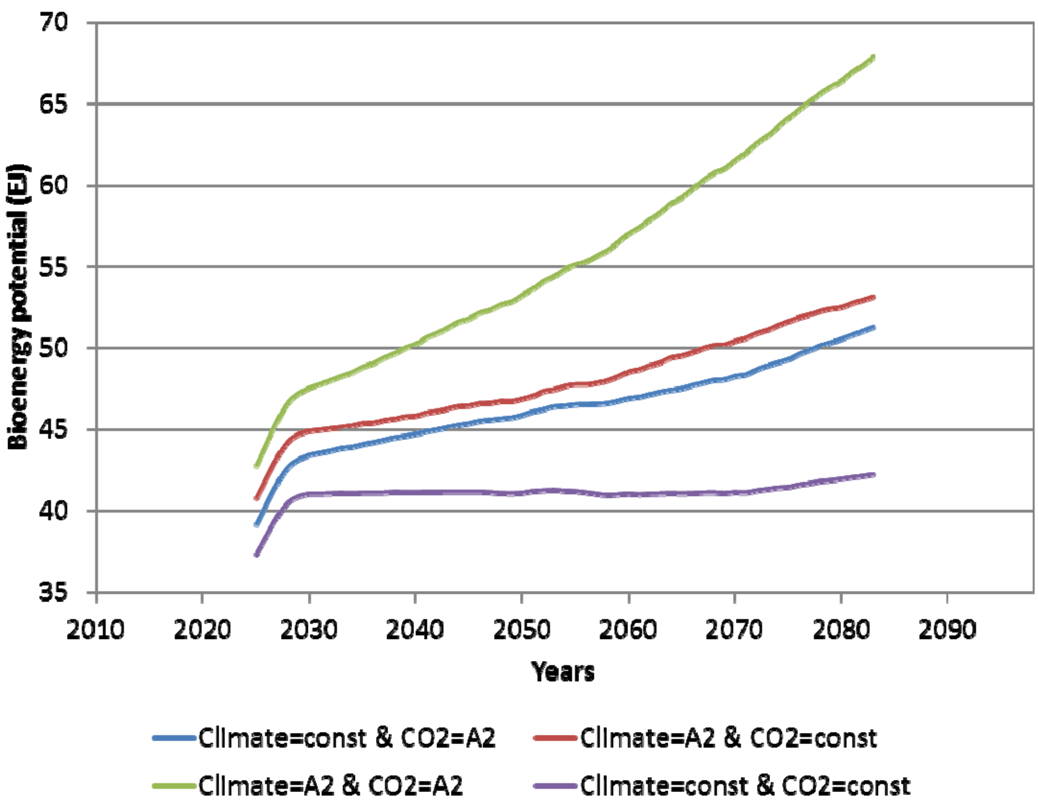

Figure 2.08: Sensitivity of biophysical bioenergy potentials of the most plausible scenario, i.e. MAXL to changes in climate (simulated by ECHAM5 model only) and/or CO_2 shown as a 30

year moving average. The purple line at the bottom stands for the scenario where there is no change in climate or CO_2, while the green line at the top represents the scenario where both climate as well as CO_2 change according to the SRES A2 scenario. The landuse for all the scenarios remain constant. Since perennial bioenergy grasses needs a few years to reach full productivity in LPJmL, the total bioenergy potential is lower in the first years.

Biophysical bioenergy potentials of the deforested area are strongly sensitive to the different land management scenarios. With increasing land availability for bioenergy cropping, the cumulative biophysical bioenergy potential increases with decreasing constraints on land management efforts (Fig. 2.09). Reflecting the uncertainty in climate projections, biophysical bioenergy potentials are also sensitive to the selection of the GCM realization of the SRES A2 emission scenario. This uncertainty increases with the area assumed to be available for bioenergy production (Fig. 2.09). The bioenergy potentials at the end of the 21st century along with the uncertainty have also been tabulated in Table 2.5.

Table 2.5. The bioenergy potentials, the cumulative carbon saved by avoided burning of fossil fuels and the corresponding potential additional cooling of the respective land management scenarios

Scenario	**Bioenergy potential at end of 21st century (30 yr mean) (EJ yr^{-1})**	**Cumulative carbon saved at end of 21st century (avoided fossil fuel burning) (GtC)**	**Additional cooling caused by bioenergy cropping at end of 21st century (°C)**	**Net change of global mean temperature (net biogeochemical effects only) (°C)**
MAXL	68.1 ± 5.6	102.2 ± 5.1	0.08 to 0.21	+0.04 to +0.11
CROPL	177.3 ± 16.5	280.0 ± 19.7	0.22 to 0.59	-0.02 to -0.06
SOILL	233.4 ± 20.0	366.0 ± 22.6	0.29 to 0.77	-0.08 to -0.20
TERL	320.9 ± 28.1	499.4 ± 31.3	0.40 to 1.05	-0.13 to -0.33
UNLIM	373.8 ± 33.4	569.5 ± 36.6	0.46 to 1.20	-0.14 to -0.35

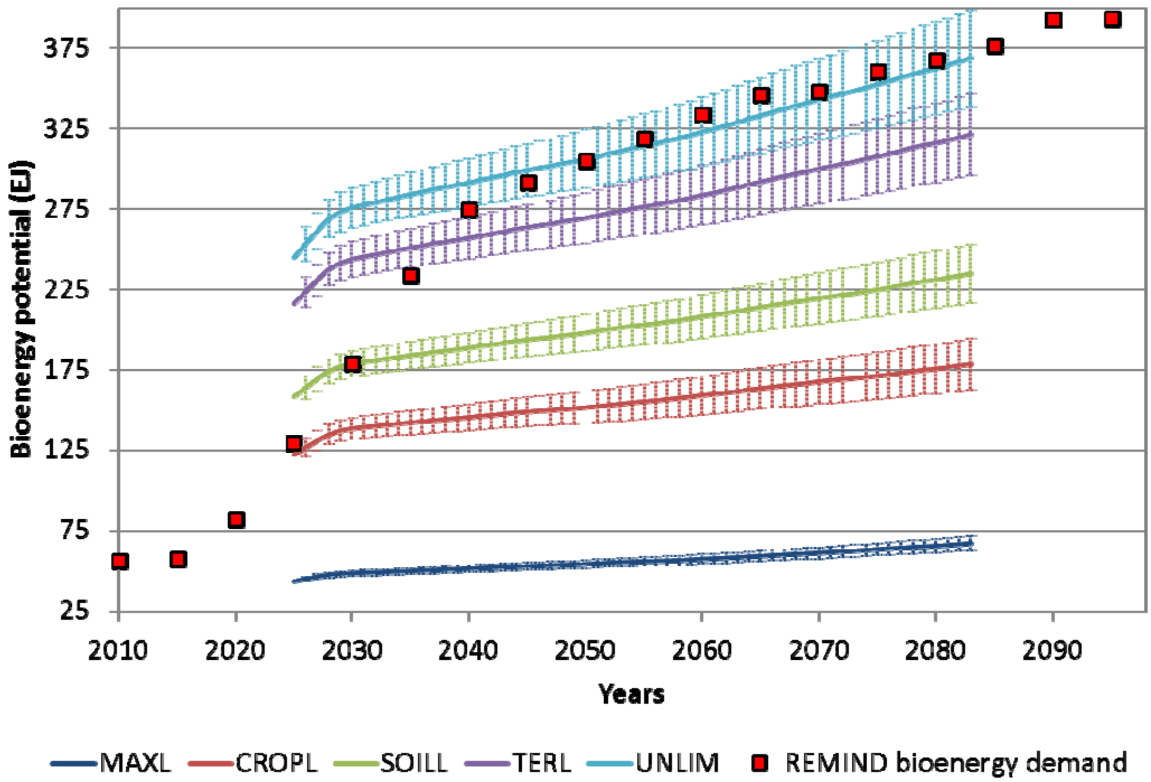

Figure 2.09: Total biophysical bioenergy potentials of the area north of 45°N for the respective land management scenarios. To put the potentials into perspective, we have plotted the Bioenergy demand (red dots) as simulated by REMIND-R for the 'Biomass-max' scenario (Leimbach et al., 2010b). The values plotted are a 30 year moving average. The thick line represents the mean of 19 values while the uncertainty (1 Standard Deviation) is shown by the error bars. Since perennial bioenergy grasses needs a few years to reach full productivity in LPJmL, the total bioenergy potential is lower in the first years.

Assuming 20.9 gC to be emitted per MJ of fossil fuel burnt (an average of all stationary and transportation fuels and considering 100% combustion efficiency) (EIA, 2008), this means that 1.4 ± 0.1 GtC yr^{-1} to 7.8 ± 0.7 GtC yr^{-1} of fossil fuel emissions could be saved at the end of the 21st century if the biophysical bioenergy potential would be fully exploited. Over the entire time frame of this study, bioenergy plantations could thus cumulatively save 102.2 ± 5.1 GtC to 569.5 ± 36.6 GtC (Table 2.5). To convert these saved emissions into avoided warming, we use a metric of transient climate sensitivity to cumulative emissions suggested by Matthews et al. (2009) and evaluated for Earth System models taking part in the climate model intercomparison project 5 (CMIP5) by Gillett et al. (2013). They concluded that observationally-based estimate of global mean warming to cumulative emissions at CO_2 doubling ranges from 0.8 to 2.1 K per 1,000 GtC emissions. While this metric is simplified and linear, it could be used as a first-order simplified method in our study since it accounts for response of the ocean carbon system on multi-decadal timescale. Applying this metric to the range 102.2 to 569.5 GtC of cumulative saved emissions at the end of the 21st century, we can estimate an avoided warming of 0.08 to 1.2°C (Table 2.5) due to extensive bioenergy crop plantations on the deforested area north of 45°N. This is in addition to the predominantly albedo driven cooling from the large-scale deforestation of the high latitudes.

To analyze the changes in temperature from purely biogeophysical effects of such large-scale deforestation, we analyze the results from the additional experiment with MPI-ESM. To exclude the small trend during the first few years, we report changes averaged over the last 20 years of the 30-year experiment. We find a decrease in the global mean annual near surface air temperature by 0.35°C and the regional cooling by more than 4°C compared to the control simulation (Fig. 2.10). This temperature change is mainly a result of an increase in albedo, reflected by the increase in the surface upwelling shortwave radiation (Fig. 2.11). The biogeophysical effects of boreal deforestation could also be understood by analyzing the change of surface energy balance, as tabulated in Table 2.6(appx).

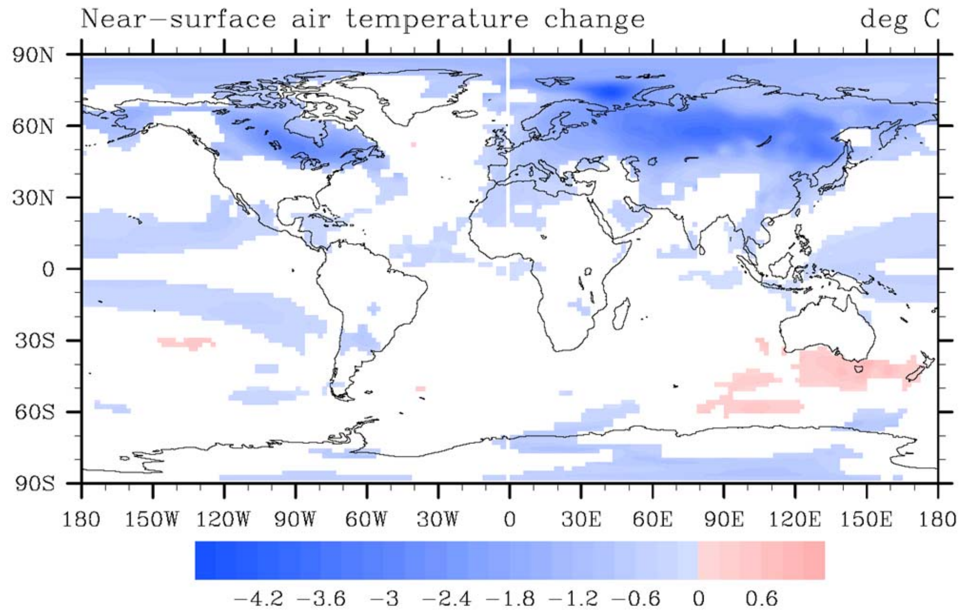

Figure 2.10: The change of annual near-surface air temperature (°C) in response to high latitude deforestation. Shown is the difference between the MPI-ESM boreal deforestation experiment, averaged over the last 20 years and the pre-industrial control simulation. Shown are only statistically significant changes ($p<0.05$)

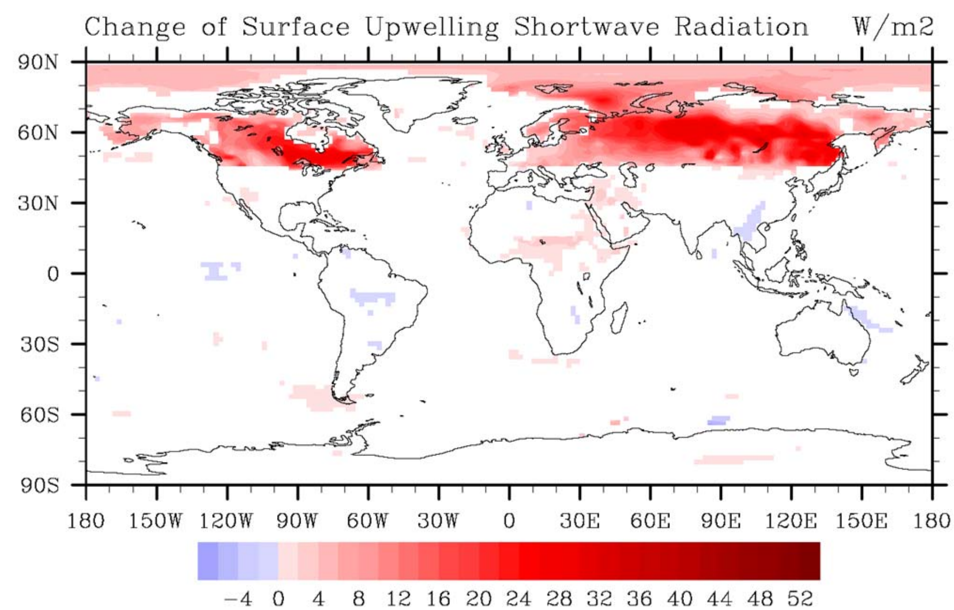

Figure 2.11: The same as Figure (1.10) but for the change of annual surface upwelling shortwave radiation (W/m^2)

We assume in this study that bioenergy production is carbon neutral (except for the land use change emissions). Thus in spite of the large emissions due to the large scale deforestation, bioenergy production could potentially lead to savings of carbon emissions in the long term if the 'carbon debt' caused by the deforestation is 'repaid' (Fargione et al., 2008) by the carbon saved by the avoided use of fossil fuels. However as evident from Fig. 2.12, this cannot be achieved within the 21^{st} century in the most realistic land use scenario MAXL. It takes more than 60 years in the unlimited or most idealistic scenario UNLIM to repay this carbon debt. Using the metric of transient climate sensitivity to cumulative emissions (Gillett et al., 2013; Matthews et al., 2009) and subtracting the cumulative carbon saved from the total emissions at the end of the 21^{st} century, but ignoring biogeophysical feedback, we estimate that the global anthropogenic warming is increased by 0.04°C to 0.11°C for the MAXL scenario as the carbon debt is not neutralized within the 21^{st} century. However, for the less constrained and more hypothetical scenarios, the global anthropogenic warming of 0.02°C to 0.35°C could be theoretically avoided under the scenarios CROPL, SOILL, TERL and UNLIM (Table 2.5).

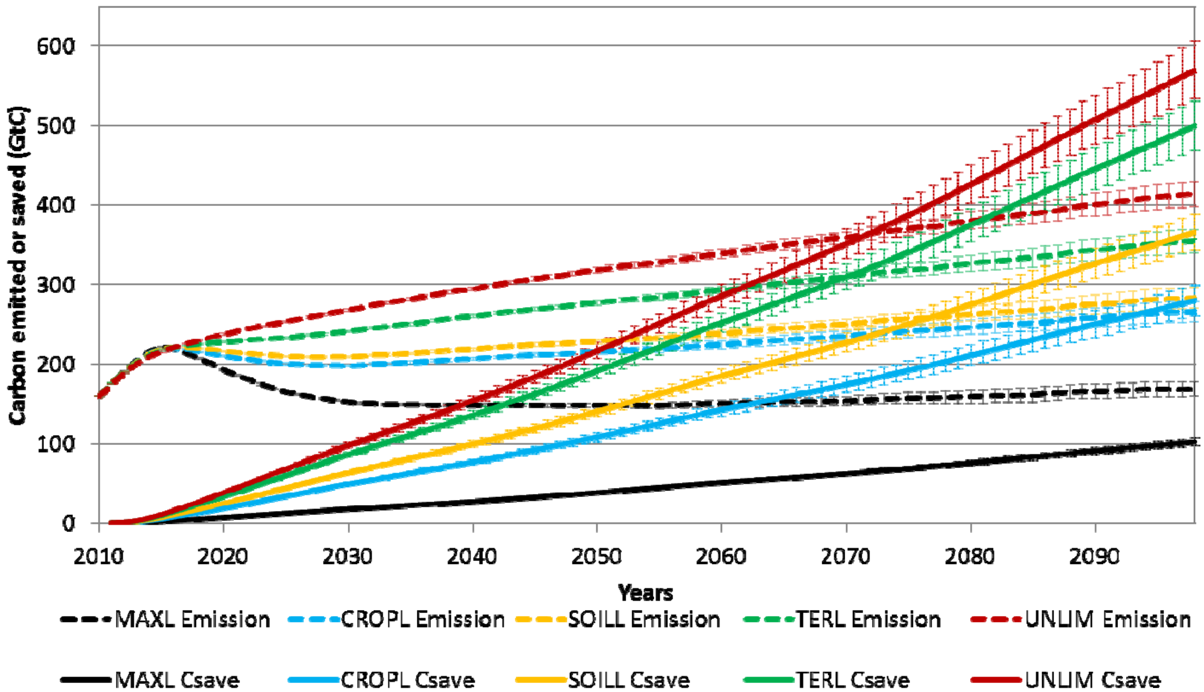

Figure 2.12: Time to repay carbon debt for the respective scenarios. We show the Total emissions incurred due to bioenergy cultivation (dashed line) and the carbon emissions saved potentially for each of the scenarios through avoided use of fossil fuels (solid line) with each color unique to the respective land management scenarios. The time taken for the lines of the respective scenarios (colors) to intersect gives us the time to repay the carbon debt. While the thick or dashed line represents the mean of 19 values, the uncertainty (1 Standard Deviation) is shown by the error bars.

2.4 Discussion

The conclusion that a biogeophysical cooling would dominate over a biogeochemical warming as a result of deforestation of the high latitudes, as suggested by previous studies (Bala et al., 2007; Bathiany et al., 2010) is being re-assessed here. There is a significantly large disparity between previous and this study in the deforestation-induced carbon emissions. Bathiany et al.

(2010) had concluded that boreal deforestation or removal of all vegetation other than grass would result in a net global cooling of 0.25°C as biogeophysical effects dominate over the immediate emission of 20 GtC. They found the trend in global terrestrial carbon close to zero as the enhanced productivity of the tropics compensate for the slow soil respiration of the cold regions. On the other hand, Bala et al. (2007) had found a reduction of global mean temperature by 0.8°C at the end of the 21st century as cooling biogeophysical effects overwhelmed an emission of 80 GtC due to tree removal. Our study using LPJmL suggests that the clearing and consequently burning of all natural vegetation, woody and herbaceous, from the land north of 45°N results in the immediate emission of ~182 GtC which is much higher. Moreover, it is followed by long term changes in the litter and soil carbon pools ranging from a sequestration of ~14 GtC for the most realistic scenario (MAXL) to an emission of ~232 GtC for the most idealistic scenario (UNLIM) by the end of the 21st century.

The mismatch in the carbon emissions reflects the difference in how 'deforestation' is simulated in these studies. In (Bala et al., 2007) deforestation meant removal of trees, in (Bathiany et al., 2010) it meant the removal of all vegetation other than grass and as immediate emissions, only 50% of the above ground vegetation carbon was released to the atmosphere. In this study using LPJmL, deforestation meant complete removal of any kind of natural vegetation, leaving behind bare ground. This mismatch in the carbon emissions also reflects the different representation of the carbon cycle in LPJmL (Bondeau et al., 2007; Sitch et al., 2003a), JSBACH (Raddatz et al., 2007) (land surface model of MPI-ESM) and INNCCA (Bala et al., 2005; Thompson et al., 2004). In general, compared to observations (Prentice et al., 2001b) JSBACH underestimates carbon pools of plant and litter in the boreal latitudes (Bathiany et al., 2010). In the pre-industrial experiment with MPI-ESM, we find that the equilibrium boreal carbon storage (for pre-industrial

[CO_2]) is 29 MgC/ha averaged over all land north of 45°N, which is an underestimation compared to the range of observed values of 42 to 64 MgC/ha (Prentice et al., 2001b). On the contrary, the average vegetation carbon for the same region computed by LPJmL is 53.2 MgC/ha which is within the range of observed values as mentioned above.. However, compared to observational data, LPJmL overestimates the immediate emissions. According to 2007 estimates, the carbon stock in the living biomass in the boreal forest and half of the temperate forests of the northern hemisphere amounts to ~73 GtC (Pan et al., 2011b) and this study computes the immediate emissions, or the carbon emitted when the living biomass is burnt completely to be ~182 GtC. Compared to satellite data, LPJ (predecessor of LPJmL and represents only natural vegetation) also over predicts the coverage of deciduous broadleaved vegetation in the boreal forests of Canada and Eurasia (Sitch et al., 2003a). Hickler et al. (2006) found that while comparing vegetation modeled by LPJ with potentially occurring vegetation, the agreement is reasonably good for all vegetation types of the high latitudes except for temperate conifer forests. Brovkin et al., (2012) show that LPJmL overestimates litter stocks in the polar tundra region while the woody litter is underestimated in all other regions. These disagreements thus have its consequent effects on the carbon cycle. Apart from this, it is well documented that LPJmL is able to reproduce key features of the global carbon cycle (Jung et al., 2008; Luyssaert et al., 2010).

With respect to the biogeophysical feedback, the albedo of herbaceous bioenergy crops is essentially similar to grass, especially when covered by snow in the winter months (Robinson and Kukla, 1984). Moreover it has often been observed that even shrubs and consequently herbaceous crops are bent over and buried by a depth of snow that is less than their height when erect (Bewley et al., 2010). Thus when covered by snow all herbaceous crops would have a similar albedo as even tall grasses would be bent over by snow. This means that if the forests of high latitudes were hypothetically removed and planted with bioenergy crops, we could expect a similar biogeophysical effect as we find in our additional experiment with MPI-ESM (a reduction in global mean annual temperature by 0.35°C for complete boreal deforestation). We also find that this biogeophysical effect is similar to other large-scale deforestation experiments e.g. (Bala et al., 2007; Bathiany et al., 2010).

Even though biophysical bioenergy potentials can be substantial, for instance in projected high bioenergy demand scenarios (Leimbach et al., 2010a, 2010b), these are strongly dependent on the assumption of how much of the deforested area could effectively and efficiently be managed. Bright et al. (2011) who study the effects of bioenergy production from production forests of Norway on the radiative forcing also found that in the long term the negative radiative forcing from avoided fossil fuel emission (biogeochemical effect) plays a more active role compared to the negative forcing due to albedo changes (biogeophysical effect).

Various studies show that the soil carbon does reduce after forest clearing followed by agriculture, but the magnitude of CO_2 emissions from soils could be overestimated if the change in bulk density of the soil isn't considered (Karhu et al., 2011; Murty et al., 2002). Our study also shows a decrease of soil carbon after conversion of land cover from forest to agriculture. However as LPJmL does not estimate the change in soil bulk density, it would overestimate the emissions from soils.

In order to compare similar units of energy we have computed and compared only primary energy, i.e. assuming 100% combustion efficiency. However, during the commercial exploitation of this bioenergy, there is a loss of energy when plant material is converted from its natural form to a form which can be commercially used. This feedstock conversion efficiency ranges from as low as 17% for sugarcane to around 50% for corn and wheat to as high as approximately 100% for soy and palm oil (Bruckner et al., 2011). Similarly fossil fuels, have varying moisture and ash content and thus have different energy densities (Reed, 2010). On top of this there is loss of energy depending on different energy conversion efficiencies of the final device which is being powered by the respective fuels.

The long term fertilization effects due to increasing temperature and CO_2 simulated by LPJmL and as shown in Fig. 2.08 are optimistic, as nitrogen dynamics and its limiting effect on CO_2 fertilization (Oren et al., 2001; Reich et al., 2006) are omitted here. Thus the increasing trend of productivity shown in this study assumes that current management intensity levels can be maintained also with respect to soil fertility. Moreover, while most of the area investigated in this study is permafrost, the carbon dynamics of permafrost are not represented here. So we ignore the additional CO_2 and CH_4 emissions from permafrost soils due to climate change (Koven et al., 2011; Schaefer et al., 2011; Schneider von Deimling et al., 2012; Zimov et al., 2006) and disturbance (Myers-Smith et al., 2007).

The climate and CO_2 data used by LPJmL is according to the SRES A2 scenario, which doesn't include any form of climate mitigation (Nakicenovic et al., 2000a). We thus get an increasing trend of biophysical bioenergy potentials as CO_2 and temperature continuously increase over the 21^{st} century. The mitigating effect of large-scale bioenergy production on climate is not considered here. To include these feedbacks, a full coupling of the carbon cycle and the climate system would be necessary.

The different land management scenarios assumed here involve different management measures. All forms of management especially the application of fertilizers and agricultural machinery would result in additional emissions. For example, a 2002 report suggested that the production of ammonia consumed about 5% of global natural gas production, which is somewhat under 2% of the world energy production (International Fertilizer Industry Association, 2002). Irrespective of management, there would be additional emissions for other agriculture based activities like crop harvest and transportation, which have not been considered here.

Carrying out such a large-scale deforestation would be impractical and in reality one would only deforest those areas which would be suitable for bioenergy cropping. However we do not perform such an experiment with LPJmL as otherwise this study would not be comparable with that of Bala et al. (2007) and Bathiany et al. (2010). In a study by Brovkin et al. (2013) we see that the changes in climate simulated by ESMs are relatively small in comparison with interannual variability of climate and are difficult to detect when the land use changes are small. For this reason, small scale deforestation experiments are not carried out in the boreal deforestation experiments using MPI-ESM.

2.5 Conclusions

Comparing this study's results to those of Bathiany et al. (2010) and Bala et al. (2007), we find much higher carbon emissions from such LULCC both for immediate as well as long term emissions. If bioenergy is to be produced in the suitable parts of the deforested area, considering limitations in terrain, soil conditions and land that is currently built or cropped, it saves carbon emissions through avoided combustion of fossil fuels, thereby reducing the carbon debt. However, if we were to only consider the biogeochemical effects, then there would be a net increase in the anthropogenic warming as the carbon emissions would not compensated for by the end of the 21st century by the most realistic scenario as this scenario only involves about 14% of the total deforested area.

Given the strong impact on the land's biosphere carbon cycle, the omission of additional emissions from management and transportation and non-assessment of other detrimental effects such as destruction of landscapes and reduction of biodiversity, all studies, including this, have not promoted large-scale deforestation as a measure to mitigate anthropogenic climate change. Not only because of the strong response of the land's biosphere carbon cycle but also because of the detrimental effects on pristine ecosystems and biodiversity, large-scale deforestation projects must remain theoretical academic questions. The balance of biogeophysical versus biogeochemical feedbacks, however, needs further consideration in earth system models.

Appendix

Table 2.1(appx): The following are the list of GCMs and the corresponding sponsoring institutes whose climate projections were used in this study:

Model No.	Model Name	Sponsoring Institute
1	BCCR-BCM2.0	Bjerknes Centre for Climate Research, Norway
2	CGCM3.1	Canadian Centre for Climate Modelling and Analysis, Canada
3	CNRM-CM3	Météo-France / Centre National de Recherches Météorologiques, France
4	CSIRO-MK3.0	Commonwealth Scientific and Industrial Research Organisation, Atmospheric Research, Australia
5	CSIRO-MK3.5	Commonwealth Scientific and Industrial Research Organisation, Atmospheric Research, Australia
6	GFDL-CM2.0	U.S. Department of Commerce / National Oceanic and Atmospheric Administration (NOAA) / Geophysical Fluid Dynamics Laboratory (GFDL), USA
7	GFDL-CM2.1	U.S. Department of Commerce / National Oceanic and Atmospheric Administration (NOAA) / Geophysical Fluid Dynamics Laboratory (GFDL), USA
8	GISS-ER	National Aeronautics and Space Administration (NASA) / Goddard Institute for Space Studies (GISS), USA
9	INGV-SXG	Instituto Nazionale di Geofisica e Vulcanologia, Italy
10	INM-CM3.0	Institute for Numerical Mathematics, Russia
11	IPSL-CM4	Institut Pierre Simon Laplace, France

12	MIROC3.2(M)	Center for Climate System Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan
13	ECHO-G	Meteorological Institute of the University Bonn, Meteorological Research Institute of the Korea Meteorological Administration (KMA), and Model and Data Group, Germany/Korea
14	ECHAM5/MPI-OM	Max Planck Institute for Meteorology, Germany
15	MRI-CGCM2.3.2	Meteorological Research Institute, Japan
16	CCSM3	National Center for Atmospheric Research, USA
17	PCM	National Center for Atmospheric Research, USA
18	UKMO-HadCM3	Hadley Centre for Climate Prediction and Research / Met Office, UK
19	UKMO-HadGEM1	Hadley Centre for Climate Prediction and Research / Met Office, UK

Table 2.2(appx): CFTs of LPJmL and the primary energy per CFT (ECN 2007).

CFT	CFT Name	Examples	Energy in kiloJoules per gDM (Phyllis HHV)
1	temperate cereals	Wheat grain	18.2
2	rice	Rice	15.3
3	maize	Maize	17.7
4	tropical cereals	Millet	18.9

5	pulses	Pulses	17.2
6	temperate roots	Potato/Beet	17.7
7	tropical roots	Cassava	17.3
8	oil crops sunflower	Sunflower oil (seeds)	27.8
9	oil crops soybean	Soybean oil (seeds)	23.4
10	oil crops groundnut	Groundnut oil (seeds)	29.4
11	oil crops rapeseed	Rapeseed oil (seeds)	28.1
12	sugarcane	Sugarcane	17.0
13	managed grass	Others (managed grass)	18.6
15	biomass grass	Avg. of Miscanthus & Switchgrass	18.5
16	biomass tree	Avg. of Poplar & Eucalyptus	20.0

Table 2.3(appx): Lower and upper temperature limits for optimal photosynthesis for all CFTs

CFT	CFT Name	Lower Temp - Optimal Photosynthesis (°C)	Upper Temp - Optimal Photosynthesis (°C)
1	temperate cereals	12	17
2	rice	20	45
3	maize	21	26
4	tropical cereals	20	45
5	pulses	10	30
6	temperate roots	10	30
7	tropical roots	20	45

8	oil crops sunflower	25	32
9	oil crops soybean	28	32
10	oil crops groundnut	20	45
11	oil crops rapeseed	12	17
12	sugarcane	18	30
13	managed grass C3/C4	10/20	30/45
14	biomass grass	15	45
15	biomass tree	15	30

Table 2.6(appx): The annual surface energy balance averaged over land cells north of 45N over the last 20 years of the MPI-ESM boreal deforestation experiment. Values for the experiments are given as deviations of boreal deforestation experiment (ΔDef) from the control climate (CTRL). All fluxes are in Wm^{-2}, surface temperature in °C. SW = short-wave radiation; LW = long-wave radiation; LH = surface upwards latent heat flux; SH = surface upwards sensible heat flux; Temp = near surface air temperature.

Values	**CTRL**	**ΔDef**
Surface upwelling SW (proxy for albedo)	30.7	+12.4
net SW (downwards - upwards)	86.9	-8.0
net LW (downwards - upwards)	-43.6	+1.5
Net Radiation (SW + LW)	43.3	-6.5
LH	30.3	-3.7
SH	11.7	-2.8
Temp	-2.8	-1.9

Chapter 3: Abandoned temperate croplands as a mitigation measure – reforestation vs. bioenergy plantations

3.1 Introduction

Removal of existing forest or grass land for bioenergy plantations would lead to a net climate change rather than mitigation as such Land Use Change (LUC) would lead to a net carbon debt (Campbell et al., 2008; Dass et al., 2013; Fargione et al., 2008; Searchinger et al., 2008). However bioenergy plantations on erstwhile agricultural land which has been abandoned for different reason could be a sustainable option (Campbell et al., 2008; Tilman et al., 2006a). On the other hand, instead of bioenergy cropping, if such fallow land is allowed to be restored to natural forests or grasslands by natural succession, then there would be a net carbon sequestration (Kurganova et al., 2010; Righelato and Spracklen, 2007; Vuichard et al., 2008). In this chapter we thus investigate whether it is more effective to allow fallow agricultural land of the temperate and boreal regions to reforest by regrowth of natural vegetation and thereby mitigate by sequestering carbon or to implement bioenergy plantations and mitigate through avoided emissions.

Most forests of the world are recovering from a past disturbance and one of the most widespread and abrupt LUC was triggered by the end of the Soviet Union (USSR) and the abrupt change of its agricultural practices in the early 1990s, which lead to abandonment of large tracts of agricultural land (Henebry, 2009; Vuichard et al., 2008). The extent of this LUC ranges from 20 million ha (Vuichard et al., 2008) to 30.2 million ha (Kurganova et al., 2010). Most of this area has been covered by herbaceous plants (Vuichard et al., 2008). In China, the government had implemented several ecological restoration projects. This has resulted in the increase of areas planted through afforestation and reforestation from 12.7 million ha to 17.4 million ha for the period 1970-80 and then to 23.1 million ha in 1994-98 (Fang et al., 2001). In Europe, agricultural land has been abandoned at the rate of 0.7 million ha yr^{-1} in the 2nd half of the 20th century, as a result of which the extents of forests and grasslands have increased respectively at the rate of 0.58 and 0.11 million ha yr^{-1} (Churkina et al., 2010). In the United States of America (USA), where the northern part of the country lies in the temperate region, forest land increased by 0.8 million ha between 1997 and 2002 (Smith et al., 2004). The forest area of the north of the USA also shows an increasing trend between the beginning of the 20th century and the beginning of the 21st century (Smith et al., 2004) and forests area allowed to grow on cutover timberland and marginal cropland that reverted back to forest (MacCleery, 1993). Pan et al., (2011), who used forest age to study forest disturbance found that the regrowth of young forests in Canada was mainly after natural disturbances like fire and insect outbreaks.

It is well known that disturbances affect carbon stocks and fluxes. So when forests are allowed to recover on historically disturbed land, we can expect net sequestration by forests. The carbon sink in temperate forests increased by 17% in the period of 2000 – 2007 compared to 1990 – 1999 (Pan et al., 2011a). The abrupt LUC precipitated by the fall of the Soviet Union was responsible for a carbon sink of 373 gC m^{-2} or 64 TgC over the domain considered for the period of 1991 – 2000, which translates to an annual carbon sink of 46.7 $gCm^{-2}yr^{-1}$ (Vuichard et al., 2008). The value of the carbon sink was estimated to be 74 ± 22 $TgCyr^{-1}$ for the total area of abandoned lands in the Russian federation (Kurganova et al., 2010). Shvidenko and Nilsson (2003) observed the carbon sequestration rate in Russian forests for 1961 – 1998 to be ~31 $gCm^{-2}yr^{-1}$. In China, the total forest biomass carbon increased by 4.75 PgC over the period of 1980 – 1998 (Fang et al., 2001). In Europe, decadal budgets indicate that there has been a continuous increase in net carbon storage from 85 $TgCyr^{-1}$ in 1980s to 108 $TgCyr^{-1}$ in 1990s to 114 $TgCyr^{-1}$ in 2000 – 2007 (Churkina et al., 2010). The carbon sink of the USA increased by 33% from 1990s to 2000s (Pan et al., 2011a).

Bioenergy is a cost effective mitigation measure as the cost of production of bioenergy combined with CCS is almost half compared to that of more efficient forms of renewable energy like solar energy (Magne et al., 2010). As conventional 1st generation biofuels like ethanol or biodiesel have their limitations (Crutzen et al., 2008; Fargione et al., 2008; Melillo et al., 2009; Searchinger et al., 2008), 2nd generation bioenergy technologies (lignocellulosic plant material) could be used instead, more so because these plants are more tolerant against unfavorable climate and soil conditions (Adler et al., 2007; Schmer et al., 2008). However, if bioenergy plantations were to replace regrowth of natural vegetation, then the potential improvement in ecosystem functions and services like prevention of deforestation, regional climate regulation and increase in biodiversity that would have been achieved by the restoration of natural land cover would be lost (Cook and Beyea, 2000).

In this study we assume bioenergy to be used directly as a fuel. So the emissions from bioenergy usage could be treated as a single pulse at harvest with a short lifetime in the anthroposphere as the time span between the carbon emission from harvest and sequestration from regrowth after plantation is very short (Cherubini et al., 2012b). Thus, other than the Land Use (LU) emission we can consider bioenergy to be carbon neutral. In this study, bioenergy plantations are carried out on agricultural land which has been lying fallow for 5 to 20 years. As this time is quite short for a proper forest to re-grow, the LU emissions would also be negligible.

Vegetation productivity is sensitive to conditions of the climate, atmospheric CO_2 concentration ([CO_2]), as well as different management practices (Norby et al., 2005; Oren et al., 2001; Smith et al., 2000; Witt et al., 2000). To account for projected changes in [CO_2] and climate, we used the Dynamic Global Vegetation Model (DGVM) LPJmL (Lund-Potsdam-Jena managed Land) (Bondeau et al., 2007), a model which handles not only forests and grasslands but also crops and has been recently extended to simulate the cultivation of cellulosic energy crops on dedicated biomass plantations. The cellulosic energy crops include two tree species and one fast growing grass (Beringer et al., 2011). We investigate the amount of carbon sequestered by the end of the 21st century by the re-growth of natural vegetation in the agricultural land lying fallow between 1990 and 2005 and compare it with the amount of carbon emissions saved by bioenergy plantations in these abandoned agricultural lands due to avoided usage of fossil fuels. We establish which of the two is a better mitigation measure. In order to calculate the avoided emission, we compute the biophysical bioenergy potential from bioenergy plants in the abandoned agricultural land of the temperate region and calculate the amount of carbon that would have been emitted for an equivalent amount of fossil fuel energy. By biophysical bioenergy potential, we understand the production of bioenergy for given climatic and environmental conditions, ignoring the technical and economic feasibility. In order to compare similar units we use primary energy, or the energy derived after 100% combustion efficiency, to quantify the biophysical bioenergy potential. We do not specify the form of final energy which is to be actually used (Fischer and Schrattenholzer, 2001). To calculate the emissions saved by avoided burning of fossil fuels, we again assume 100% combustion (EIA, 2008).

3.2 Model and experimental setup

The description of the model and the way crops are managed in this model is already given in sections 2.1 and 2.2 respectively of chapter 2 of this thesis.

3.2.1 Model setup

As mentioned in chapter 2, climate projections differ between different GCMs primarily because of the uncertainty of parameterizations. For example, the global average temperature projection for the SRES A2 scenario has an approximately 66% probability of ranging from 2.0 to 5.4 °C, at the end of the 21st century, relative to the end of the 20th century (Solomon et al., 2007). To account for this variability, LPJmL was driven with 21st century climate projections from an ensemble of 19 different general circulation models' (GCM) implementations of the SRES A2 scenario (Nakicenovic et al., 2000b)as listed in Table 2.1(appx) of chapter 2. Plant productivity is sensitive to changes in climate as well as [CO_2] (Melillo et al., 1993). Thus the uncertainty of climate projections of the ensemble of 19 different GCMs is responsible for the uncertainty of the carbon sequestered by natural vegetation or the carbon emissions saved by the bioenergy plantations. In Figures 3.03, 3.04, and 3.05, the uncertainty is demonstrated by error bars representing ± 1 Standard Deviation while the trend is shown by a smoothened spline with the 'smooth.spline' function of the R language and using a 'spar' value of 1 (Chambers and Hastie, 1992; Green and Silverman, 1994; Hastie and Tibshirani, 1986). The climate scenarios for the individual scenarios have been prepared by calculating the anomalies relative to the 1971-2000 average for each GCM and month of the 2001-2099 period and applied to the observed 1971-2000 baseline climate. Detailed description is given in Gerten et al. (2011). All these GCMs participated in the World Climate Research Program's Coupled Model Intercomparison Project phase 3 (Meehl et al., 2007) and were used in the IPCC's Fourth Assessment Report (IPCC, 2007). Figures 3.01a&b demonstrate the mean annual change in temperature and precipitation respectively from the end of the 20th century to the end of the 21st century. The rise in temperature becomes more intense with increasing latitude, demonstrating the phenomena of 'polar amplification' (Holland and Bitz, 2003). The precipitation change on the contrary shows a spatially heterogeneous pattern with higher latitudes experiencing an increase while lower latitudes, especially Mediterranean Europe experiencing decreasing annual precipitation.

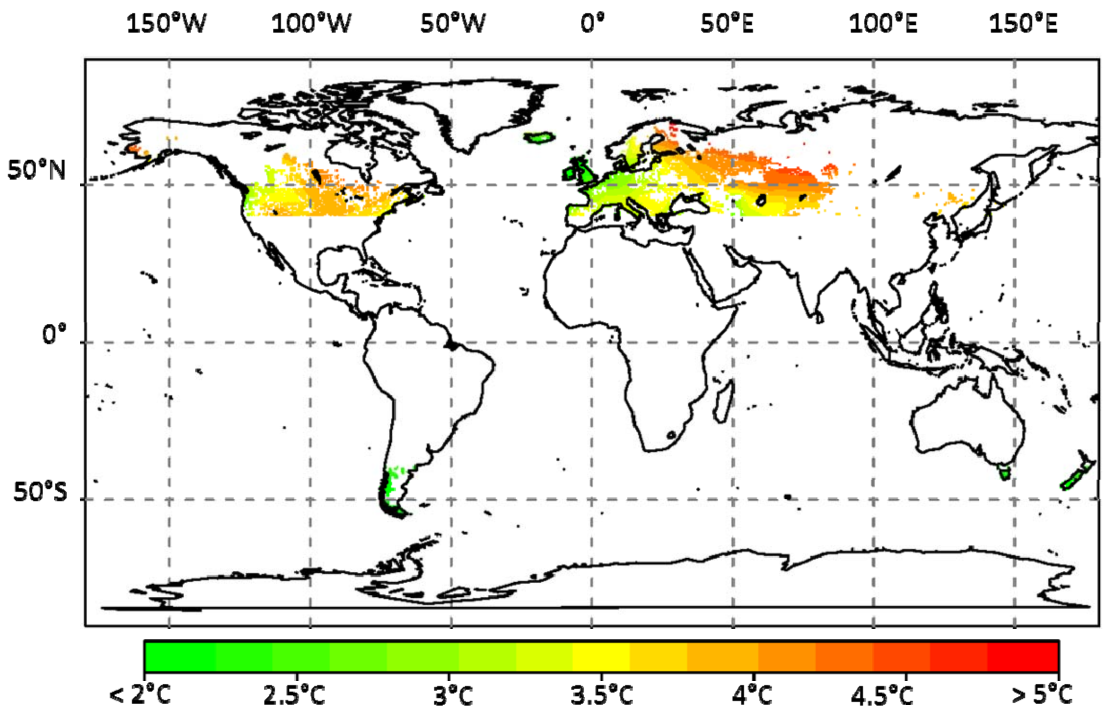

Figure 3.01a: Change of temperature (in °C) from the end of the 20th century to the end of the 21st century only for the area under study, i.e. the temperate croplands abandoned from 1990 to 2005. The change is according to the SRES A2 scenario. The values represented in the map are the mean of 19 GCM values.

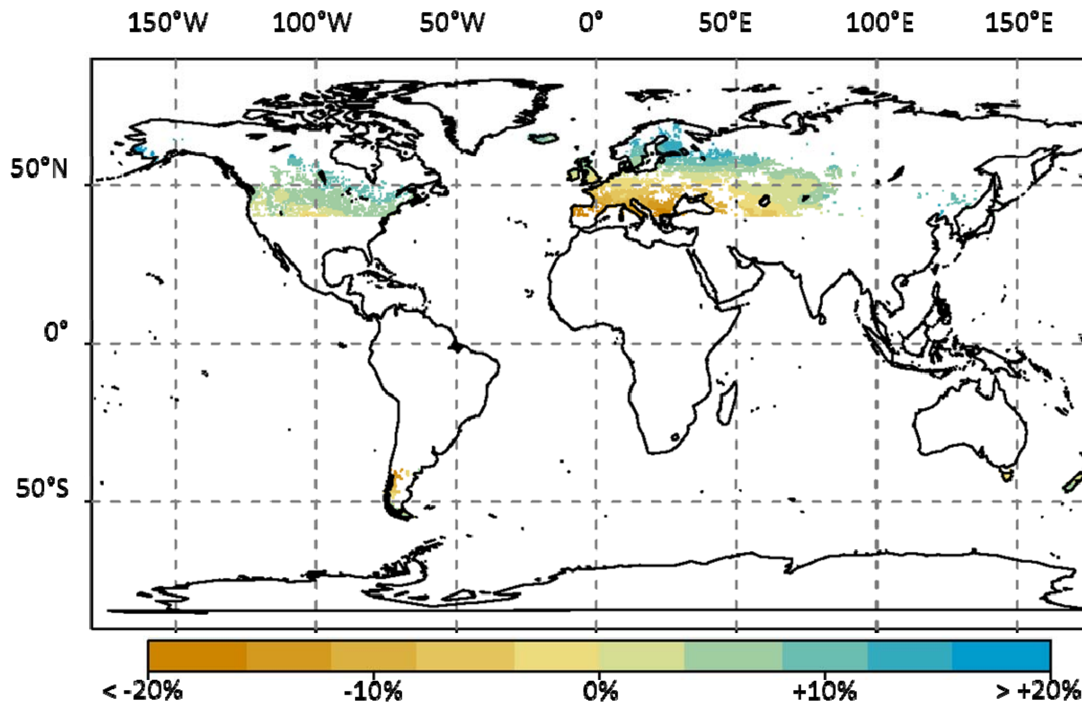

Figure 3.01b: The same as Fig. 3.01a but for percentage change in precipitation

As in Chapter 2, to account for the CO_2 fertilization effects, simulations were run with [CO_2] time series of the SRES A2 scenario which is underlying the climate projections used. In this scenario, [CO_2] rises from ~350ppm from the end of the 20th century to ~850ppm at the end of the 21st century (Fig. 2.03).

3.2.2 Scenarios of treatment of abandoned agricultural land

Although abandonment of agricultural land had started in the middle of the 20th century and is different for different regions, one of the most widespread and abrupt LUC was triggered by the end of the Soviet Union and the fall of its agricultural structures in the early 1990s, as is demonstrated in Fig. 3.02a. Thus in this study, we consider only the agricultural area which was abandoned from 1990 to 2005, as is shown in Fig. 3.02b. The total area of abandoned land amounts to 33.7 million hectares.

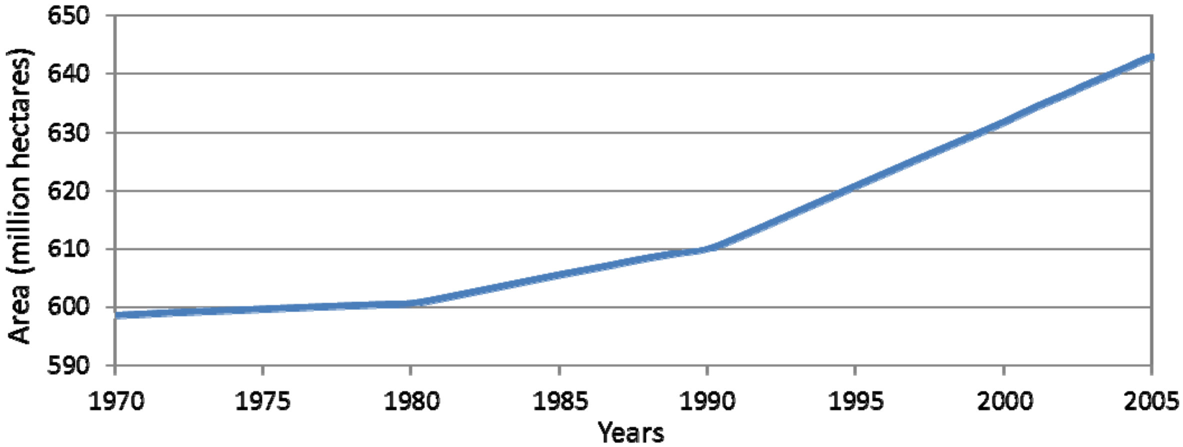

Figure 3.02a: Area of abandoned agricultural land of the temperate region. Although it increases from 1970, the steepest increase is seen from 1990 to 2005

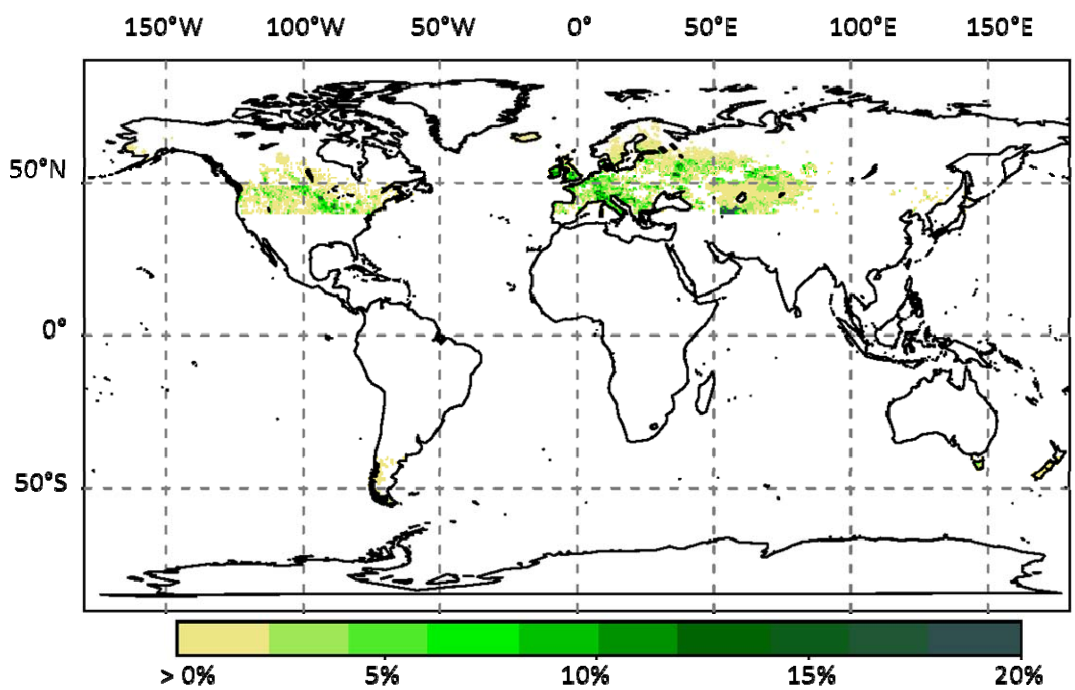

Figure 3.02b: Total land abandoned from 1990 to 2005 and shown as a percentage of each pixel

In the scenario NATVEG, the progressively abandoned agricultural land is reclaimed by re-growing natural vegetation. In LPJmL, herbaceous PFTs are allowed to establish on non-vegetated land while woody PFTs are allowed to establish on any illuminated or open ground not currently occupied by any other woody PFTs. Shading reduces the establishment of woody PFTs. However woody PFTs are competitively dominant over herbaceous PFTs in the absence of fire disturbance (Sitch et al., 2003a). Thus with favorable climatic conditions, even if grasslands had established after agricultural land abandonment, it would be succeeded by forests unless strong fire disturbance would reduce the forest fraction.

As the historical LU data is available only till 2005 (Fader et al., 2010), we consider the LU of 2005 to remain constant till the end of the 21st century. In order to assess the carbon sequestered solely by the regrowth of natural vegetation on abandoned agricultural land we also investigate the scenario NOLUC as a control scenario, where the LU is considered to remain constant after 1990, i.e. there is no abandonment of crop lands after 1990. To measure the efficacy of bioenergy plantations over natural vegetation as a mitigation measure, we investigate the following three bioenergy scenarios where before 2010 the LU was the same as NATVEG. At the year 2010, the natural vegetation which has grown on the abandoned crop lands were replaced by:-

a. CROP: Food crops such that those crops return maximum primary bioenergy per pixel per year.
b. GRASS: Bioenergy grass representing *Miscanthus* and other switchgrass species.
c. TREE: Bioenergy tree representing temperate species such as poplars and willows.

In this study LPJmL is parameterized such that on deforestation all the above ground biomass, including 2/3 of the sap wood is burnt and released to the atmosphere while the rest goes to the litter. For the calculation of the biophysical bioenergy potential of individual crop types, we assume that 50% of crop dry matter is carbon (Rojstaczer, 2001). The primary energy content per gram of crop dry matter is based on the Energy research Centre of the Netherlands Phyllis database (ECN, 2007) and as listed in Table 2.2(appx) of chapter 2.

As in most DGVMs, the LU of each grid cell is defined as a fraction. Thus to calculate the carbon pools as well as the carbon harvested from the abandoned crop lands, similar to the method followed by Vuichard et al. (2008) we multiply the respective values of each grid cell with the fraction of the grid cell which was abandoned.

3.3 Results

We find that the regrowth of natural vegetation in the temperate agricultural lands abandoned from 1990 to 2005 would lead to the sequestration of 1582.5 ± 368.6 gCm^{-2} including the above ground and below ground carbon pools by the end of the 21st century. This translates to a total of 0.5 ± 0.1 GtC for the entire area of interest. Fig 3.03 shows the increase in the sum of carbon pools from the end of the 20th century to the end of the 21st century, calculated as an average over only the study area i.e. tropical abandoned croplands. It is apparent that the rate of carbon sequestration is higher in the beginning of the 21st century and stabilizes towards the end. The distance between the blue and red lines is a measure of the carbon sequestered only due to regrowth of natural vegetation on abandoned agricultural lands. The error bars demonstrate the uncertainty of the carbon pools which are due to the range of climate projections of different GCMs.

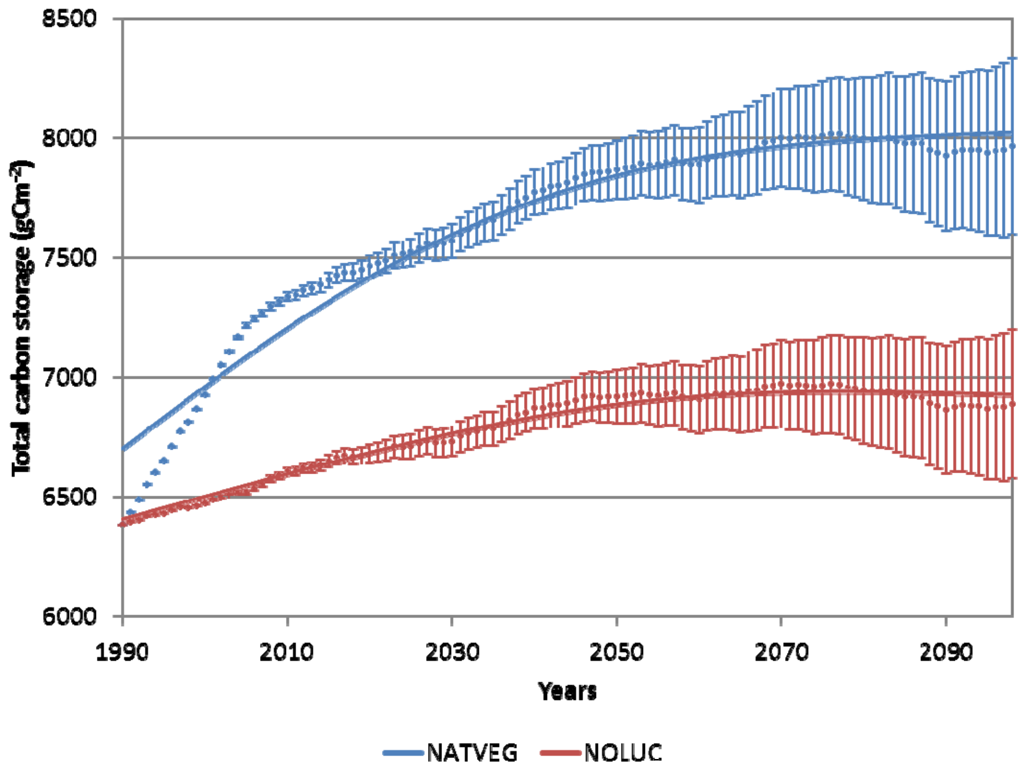

Figure 3.03: Changes in the carbon storage of the NATVEG and NOLUC scenarios, averaged over only the study area i.e. temperate abandoned croplands. The dots and the error bars represent the raw data and it uncertainty respectively. The trend is shown as a spline (solid lines) in order to neglect the inter-annual variability.

With anthropogenic climate warming, plant productivity is expected to increase in cooler regions due to the fertilization effect of increased [CO_2] and increased temperatures metabolically enhancing photosynthesis (Melillo et al., 1993). However, in this study (Fig. 3.04) we find that [CO_2] has by far the most dominating effect on causing the increase of productivity of natural vegetation. When [CO_2] is allowed to increase according to the SRES A2 scenario, keeping climate and LU constant, we find a strong increase in productivity, reflected by the increase in biomass. On the contrary when the climate is allowed to change according to the SRES A2 scenario, keeping [CO_2] and LU constant, the biomass decreases. This is because a changing climate leads to a decrease in precipitation and thus a decrease in water available for plant growth. Changes in the LU change scenario doesn't affect the rate of increase of biomass as is apparent from the violet line in Fig. 3.04, which is almost parallel to the green line.

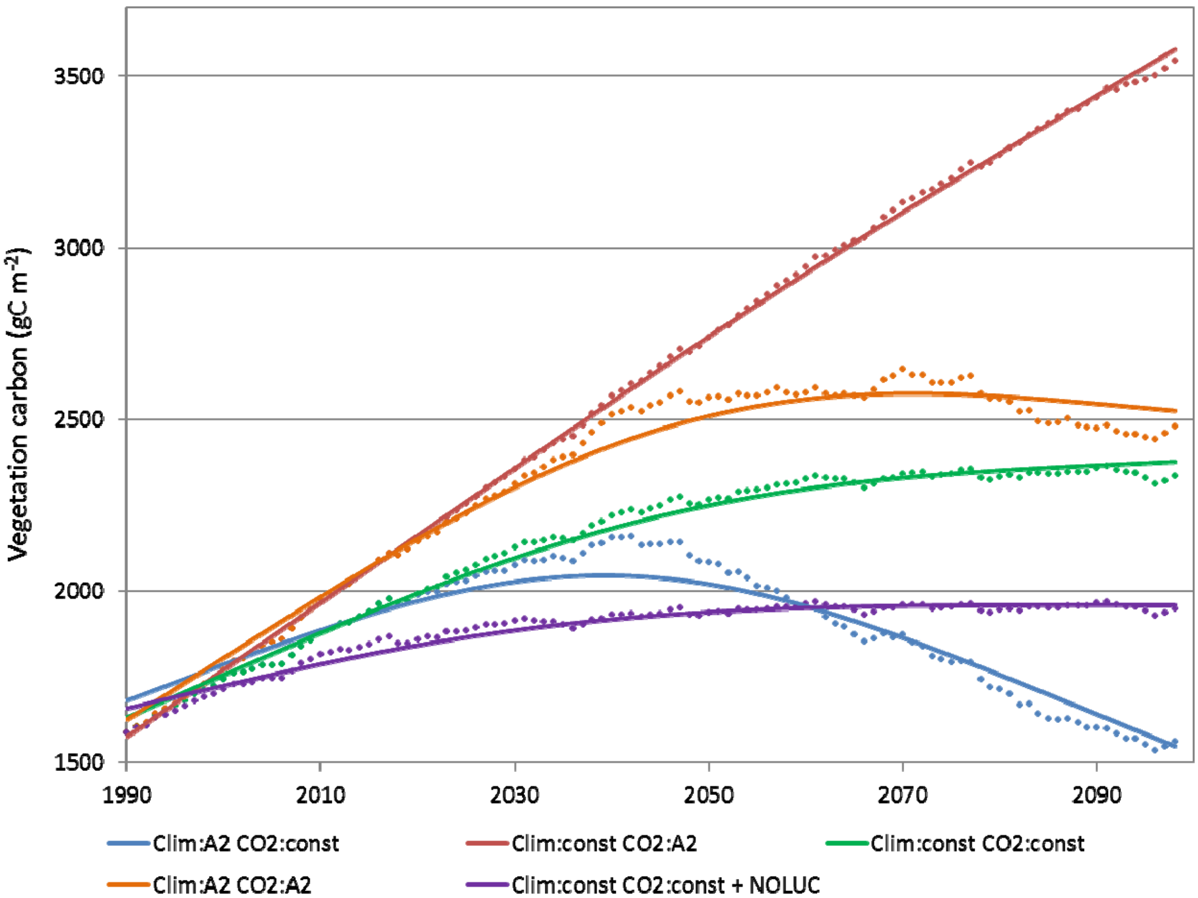

Figure 3.04: Response of vegetation carbon to different scenarios of varying or constant climate and/or [CO_2] and/or LU. This identifies the factor which has the most dominating influence in the change of biomass. Here 'Clim' = Climate; 'CO2' = [CO_2]; 'const' = constant (maintaining inter-annual variability); 'A2' = changing according to SRES A2 scenario; 'NOLUC' = No agricultural land abandonment after 1990.

To judge whether the effectiveness of bioenergy plantations as a mitigation measure is better than natural vegetation regrowth, the abandoned agricultural land was planted according to the scenarios CROP, GRASS or TREE. We assume in this study that bioenergy production is carbon neutral (except for the LUC emissions). In this study, the bioenergy crops, grasses and trees were planted in 2010 on agricultural land which had been abandoned progressively from 1990 to 2005. Given this short period of time for which the area of interest has laid fallow, the natural vegetation regrowth and thus the amount of carbon sequestered is expected to be limited. We find that the immediate emissions, averaged only for the study area, which are a result of removing the natural vegetation, burning it and releasing the carbon of the above ground biomass, including 2/3rd of the sap wood into the atmosphere, amounts to 128.7 ± 1.3 gCm^{-2} which is extremely small considering the total amount of carbon saved by the end of the 21st century. Moreover, as we can see from Fig. 3.02b, amongst the pixels where agricultural land has abandoned, almost all of them have less than 50% abandonment. This means that the bioenergy plantations doesn't involve significant long term emissions too as the carbon cycle of every pixel is dominated by the dominant vegetation which has been left undisturbed.

To compute the avoided emissions of the bioenergy plantations, as in the previous study, while we assume 20.9 gC to be emitted per MJ of fossil fuel burnt (an average of all stationary and transportation fuels and considering 100% combustion efficiency) (EIA, 2008), the primary energy content (in kilo Joules) of each crop functional type per gram of dry matter is given in Table 2.2(appx) of chapter 2. Thus bioenergy plantations would lead to carbon savings by avoided usage of fossil fuels. Taking this into account, we see from Fig. 3.05 that bioenergy crops have the potential to save more carbon than bioenergy grass or trees.

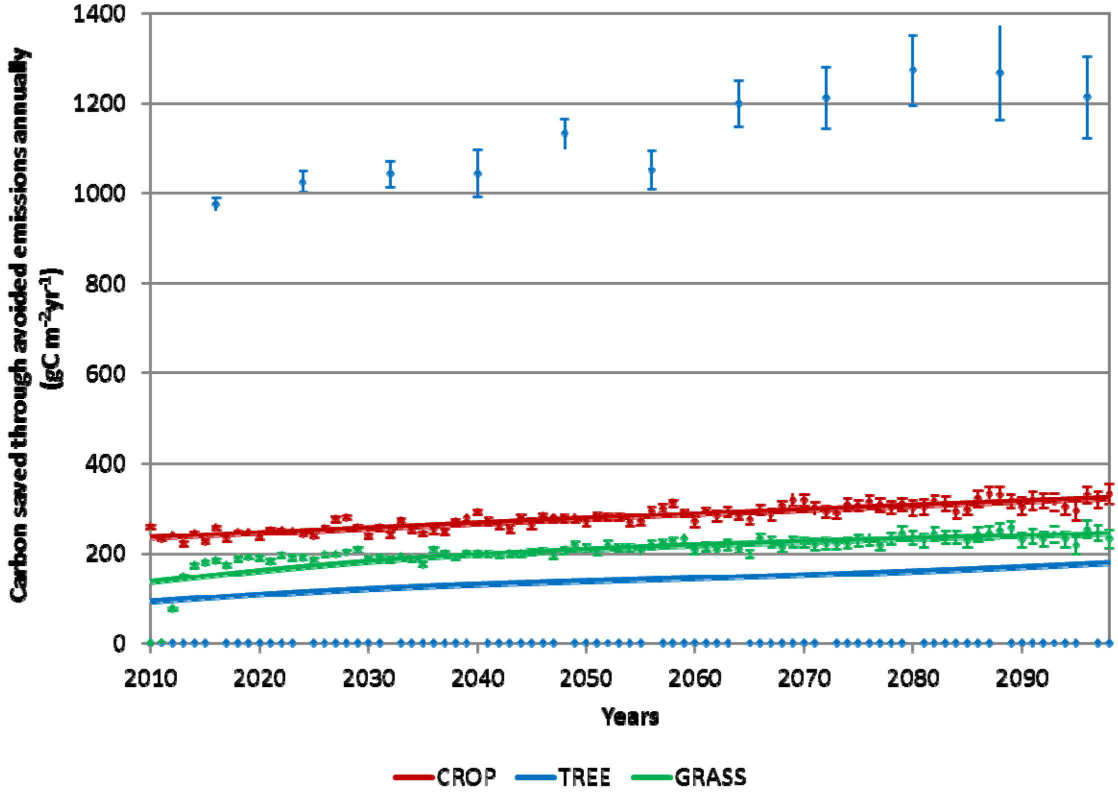

Figure 3.05: Carbon saved annually through emissions prevented by avoided combustion of fossil fuels (averaged over the study area only). Since bioenergy trees are harvested every 8 years, the annual carbon saved for the TREE scenario is much higher than the other scenarios for every 8th year and zero for the rest of the years. The representation of the dots, error bars and solid lines are the same as that of Fig 3.03. For comparing annual carbon saved for the three scenarios, the spines (solid lines) are to be compared instead of the raw data (dots).

At the end of the 21st century, comparing the cumulative carbon saved by the different mitigation scenarios (Fig. 3.06), we find that the carbon saved by the bioenergy scenarios exceed that of NATVEG by a little less than two orders of magnitude. For the entire area of interest, at the end of the 21st century, CROP has the highest cumulative carbon savings of 8.4 ± 0.3 GtC followed by GRASS saving 6.2 ± 0.3 GtC followed by TREE saving 4.2 ± 0.2 GtC.

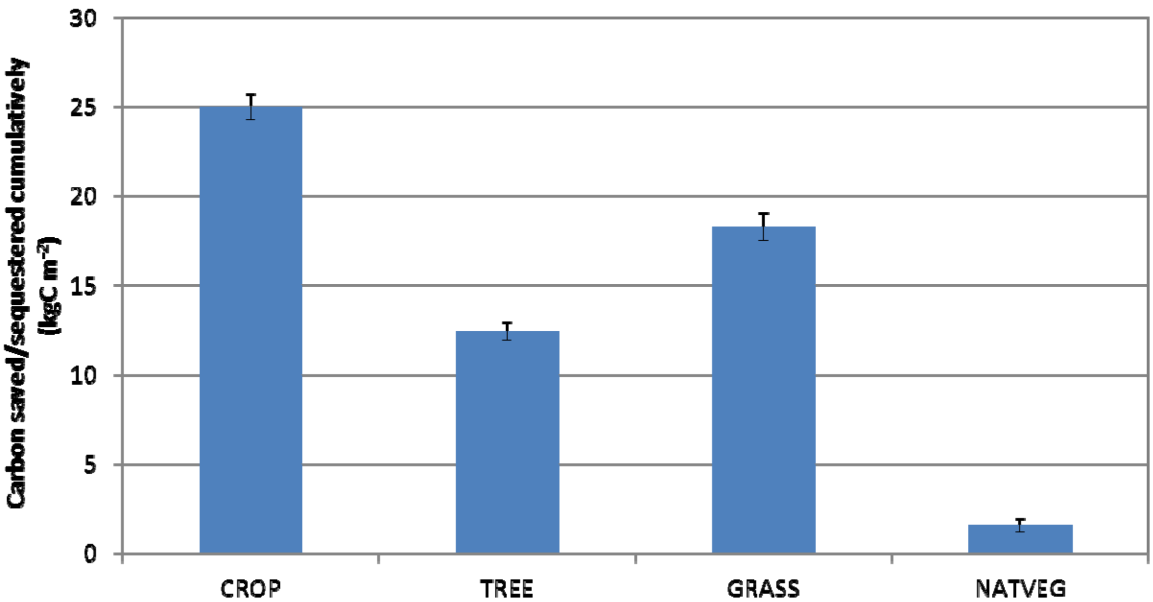

Figure 3.06: Carbon saved (bioenergy scenarios) or sequestered (NATVEG) cumulatively by the end of the 21st century (averaged over the study area only).

3.4 Discussion

The conclusion that the bioenergy plantations are a far more effective mitigation measure compared to re-growing forests on abandoned agricultural lands of the temperate region is robust as the cumulative total of the carbon saved by the bioenergy plantations because of the emissions saved by the avoided burning of fossil fuels is more than an order of magnitude higher than the total carbon sequestered by the regrowth of natural vegetation by the end of the 21st century. Moreover, the total carbon emissions saved per year by the bioenergy plantations are small but a significant percentage of the global anthropogenic fossil fuel carbon emissions according to the SRES A2 scenario (Nakicenovic et al., 2000b). In 2010, the bioenergy plantations save up to 1.2% of the global anthropogenic fossil fuel carbon emissions while at the end of the 21st century, as the projected anthropogenic emissions increase, bioenergy plantations can only save up to 0.4%.

Amongst the bioenergy options, the biophysical bioenergy potential computed for the CROP scenario is not completely realistic as the abandoned crop lands are likely to be depleted of nutrient. As discussed later, the model LPJmL does not account for the effects of soil nutrients and thus the value computed for the CROP scenario could be potentially achieved after management measures (and consequent investments and emissions) are implemented to restore the soil nutrients to its pre-disturbed state. On the contrary, GRASS, which represents 2nd generation or lignocellulosic biofuels like *Miscanthus* and other switchgrass species, has the second highest biophysical bioenergy potential and also has the ability to grow in unfavorable climatic and soil conditions (Adler et al., 2007; Schmer et al., 2008). This finding is in line with Valentine et al., (2012) who concluded that lignocellulosic bioenergy crops is the best option for dedicated crops as it does not compete directly for use for food and also does not require large inputs in terms of annual cultivation and fertilizer application. The conclusions of a review paper by Monti et al., (2011) where they found a net CO_2 abatement for switchgrass grown on former arable lands also reflects the above mentioned findings of this chapter. Zimmermann et al., (2011) studying *Miscanthus* plantations on farms also found that such plantations lead to carbon sequestration by increasing the soil organic carbon in both the scenarios of former grassland and former tilled land being replaced by *Miscanthus* plantations.

In this study we also concluded that change of [CO_2] according to the SRES A2 scenario had a beneficial effect on plant biomass because of the effect of fertilization. This CO_2 fertilization effect (Friedlingstein et al., 1995) is debatable as there is limited experimental evidence. Norby et al. (2005), analyzing the response of Net Primary Productivity (NPP) to elevated levels of CO_2 in free-air CO_2 enrichment experiments in forest stands, found that the response, depending on the leaf area indices, was attributable to increased light absorption or increased light-use efficiency. On the other hand, climate change according to the same scenario had a detrimental effect as increasing temperatures acted as a stress. This finding was reflected in a paper by Cao and Woodward (1998) who concluded that in response to climate change, the net ecosystem production would increase significantly but this response would decline as the CO_2 fertilization effect would become saturated and would be diminished by climatic factors. This has also been reflected by Pongratz et al., (2012) where an experiment simulating a geo-engineered climate and thereby stabilizing the climate without affecting the rise in [CO_2] had found a resultant increase in crop yields.

The regrowth of natural vegetation in the 1st decade, i.e. in the 1990s of the NATVEG scenario has induced a mean net carbon sequestration rate of 54.2 gC m^{-2} yr^{-1}. This appears reasonable though slightly higher compared to the carbon sequestration rate of 47 gC m^{-2} yr^{-1} in the 1990s in a study by Vuichard et al., (2008) where the area of interest was much smaller as they studied only the abandoned crop lands of former USSR. The carbon sequestration rate computed in this study for the 1st three decades (1990 - 2020) is 36 ± 1.5 gC m^{-2} yr^{-1} is a better estimate as it eliminated the effect of inter-annual variability. This appears to be comparable to the observed carbon sequestration rates of the Russian forests 1961-1998 which is ~ 31 gC m^{-2} yr^{-1}(Shvidenko and Nilsson, 2003).

However the main conclusion of this study doesn't agree with that of Righelato and Spracklen, (2007) who concluded that the avoided emissions in temperate zones appear to be similar to the carbon assimilation by forest restoration. The probable reason for this disagreement is the difference in methodology of computation of both avoided emissions as well as carbon sequestration. For computation of carbon sequestered by converting croplands to natural vegetation, Righelato and Spracklen, (2007) had considered only US regions and while calculating avoided emissions, instead of computing primary energy, they had only considered the commercially exploitable bioenergy crops and had also taken into account the loss of energy incurred in converting the crop to a commercially exploitable form.

Compared to satellite data, LPJ (predecessor of LPJmL and represents only natural vegetation) also over predicts the coverage of deciduous broadleaved vegetation in the boreal forests of Canada and Eurasia (Sitch et al., 2003a). Hickler et al., (2006) found that while comparing vegetation modeled by LPJ with potentially occurring vegetation, the agreement is reasonably good for all vegetation types of the mid to high latitudes except for temperate conifer forests. Brovkin et al., (2012) show that LPJmL overestimates litter stocks in the polar tundra region while the woody litter is underestimated in all other regions. These disagreements thus have its consequent effects on the carbon cycle. Apart from this, it is well documented that LPJmL is able to reproduce key features of the global carbon cycle (Jung et al., 2008; Luyssaert et al., 2010).

In this study the LU is assumed to be constant after 2005 in all scenarios except NOLUC, where the same is considered to be constant after 1990. This is unrealistic as LU and thus distribution and extent of abandoned crop lands is expected to change in the near future in response to changing human population and economic status (Feddema et al., 2005). The importance of LU in determining the carbon sequestration potential of natural vegetation is shown in Fig. 5 by the difference in the green and violet lines. Though unrealistic, this facilitates the study of the effects of only climate change and thereby reduce the uncertainty of future projections.

To compute the avoided emissions of the bioenergy plantations we needed to compare similar units of energy as we need to ignore the different conversion efficiencies of different technologies employed to covert bioenergy feedstock to its fuel form and consider bioenergy sources which are not commercially available. Thus we have computed and compared only primary energy, i.e. assuming 100% combustion efficiency, which is optimistic. However, during the commercial exploitation of this bioenergy, there is a loss of energy when plant material is converted from its natural form to a form which can be commercially used. This feedstock conversion efficiency ranges from as low as 17% for sugarcane to around 50% for corn and wheat to as high as approximately 100% for soy and palm oil (Bruckner et al., 2011). Similarly fossil fuels, have varying moisture and ash content and thus have different energy densities (Reed, 2010). On top of this there is loss of energy depending on different energy conversion efficiencies of the final device which is being powered by the respective fuels. Thus the final mitigation potential of each bioenergy source would be less compared with what has been computed in this study thereby reducing the discrepancy between the carbon sequestered by natural vegetation re-growth and carbon emissions saved through bioenergy production by avoided burning of fossil fuels.

The long term fertilization effects due to increasing temperature and CO_2 simulated by LPJmL and as shown in Fig. 3.05 are optimistic, as dynamics of nutrients like nitrogen and phosphorous and its limiting effect on CO_2 fertilization (Goll et al., 2012; Oren et al., 2001; Penning de Vries et al., 1980; Reich et al., 2006; Seastedt and Vaccaro, 2001) are omitted here. Since we are simulating crop or natural vegetation growth on land which was previously cropped and later abandoned, there is a high probability that these lands are depleted of these nutrients (Drechsel et al., 2001). This means that the productivity of the vegetation in the study area simulated in this chapter assumes that the soil of the study area has been managed so that the soil nutrients have been restored to their pre-disturbed state.

Immediately after abandonment of crop lands, there is an initial decrease in the total carbon stock, which reflects the drop in productivity following the sudden absence of fertilizer application and other such forms of management, which had helped to increase the productivity. This is followed by an increase in carbon stock as natural vegetation reclaiming abandoned crop lands sequester carbon (Lyuri et al., 2010). The ability of LPJmL to demonstrate this phenomenon would also lead to a better understanding of the effects of cropland reclamation by natural vegetation.

As discussed in section 2.4 of the previous chapter, the different land management scenarios assumed here involve different management measures. All forms of management especially the application of fertilizers and agricultural machinery would result in additional emissions. For example, a 2002 report suggested that the production of ammonia consumed about 5% of global natural gas production, which is somewhat under 2% of the world energy production (International Fertilizer Industry Association, 2002). Irrespective of management, there would be additional emissions for other agriculture based activities like crop harvest and transportation, which have not been considered here.

3.5 Conclusions

Comparing the mitigation potentials of bioenergy plantations and that of re-growing natural vegetation on agricultural land abandoned after 1990, we find that bioenergy plantations are more effective as the total carbon potentially saved by avoided burning of fossil fuels is more than an order of magnitude higher than total carbon sequestered by natural vegetation by the end of the 21st century. The carbon emissions saved per year by the bioenergy plantations are small but form a significant percentage of the global anthropogenic fossil fuel carbon emissions. For the entire area of study, involving 33.7 million hectares, the bioenergy plantations potentially save from about 26.5 to 30.5 GtC while natural vegetation re-growth sequesters ~ 0.5 GtC by the end of the 21st century. Among the bioenergy options, the mitigation potential of herbaceous lignocellulosic bioenergy grass species like *Miscanthus* and different switchgrass species is highest provided we ignore the mitigation potential of bioenergy food crops as they could be unsuitable for nutrient deficit soils. This is also significant as 2nd generation or lignocellulosic bioenergy species have shown their ability to grow in unfavorable climatic and soil conditions, do not have significant management requirements and also do not compete with food crops. Moreover, as the area of interest in this study involves agricultural land which was abandoned in the near past, they are all accessible areas. This means that bioenergy plantation in these areas being technically feasible, would increase the energy security and eventually help in reducing anthropogenic fossil fuel carbon emissions.

Given the importance of the effect of accounting for nitrogen and phosphorous as well as considering different scenarios of future LUC, these elements should be considered in future studies to provide a more realistic estimation of the mitigation potential of abandoned crop lands in the near future.

Chapter 4: Using abandoned tropical croplands as a mitigation measure – is reforestation more effective than bioenergy plantations?

4.1 Introduction

Tropical deforestation and land use change have a significant impact on the global carbon cycle through increased rates of carbon (C) emissions to the atmosphere and the loss of above- and below-ground C accumulation and storage capacity (Brown et al., 1996a; Fearnside, 2000). Currently the world's forests are estimated to be a net C source, primarily because of anthropogenic disturbance in the tropics which contain fifty-two percent of the world's forests and which have the highest rates of deforestation and land conversion globally (Brown et al., 1996a, 1996b; Watson et al., 2000). Thus the tropical forest biome is considered a net source of CO_2 to the atmosphere contrary to mid and high latitude forests (Detwiler and Hall, 1988; Dixon et al., 1994b; Houghton et al., 1993). Although the condition of forests change even in the absence of human interference, humans influence the pace and extent of such change as forests are subjected to controlled and uncontrolled uses such as overharvesting and degradation. At the same time, some areas of harvested and degraded forests or agricultural and pasture lands are abandoned and revert naturally or are converted to forests or plantations (Brown et al., 1996a; Parrotta et al., 1997). With an increase of population and economic growth, there is an increased demand for food while there is little increase in yields per unit area. Thus, to meet this demand, an increase in agricultural land is required. In the tropics, this land generally comes from forest lands. Most of the high yielding agricultural lands in the tropics are already used for such and thus the new lands being cleared are increasingly on marginal soils which demand larger areas to maintain yields. Such marginal lands are also more vulnerable to damage because of the terrain or low soil fertility. This leads to another cause for tropical deforestation: agricultural lands, especially on marginal soils become so damaged that they are useless for food production, and are thereby abandoned, forcing further deforestation. Much of the land currently being cleared of forests is replacing land that was degraded (Brown, 1993).

The tropical region has most of the forests (43%) and has most of the C pool in the vegetation of forests (64%) (Brown et al., 1996a). Tropical forests also account for approximately 33% of the terrestrial net primary production (Sabine et al., 2004). This shows that the tropical region has a significant potential to reduce the increase in atmospheric CO_2 concentration [CO_2]. This could be achieved by essentially three categories of forest management (Brown et al., 1996a; Canadell and Raupach, 2008):

1. Management for conservation – conserve existing C pools and thereby prevent emissions
2. Management for storage – expand existing C pools by increasing area and/or density of the pools
3. Management for substitution – increasing transfer of biomass C into products that can replace fossil-fuel-based energy

Deforestation is generally in response to an increased demand for food (Bajracharya, 1983; Barrett, 1999; Brown, 1993). Thus the first category of forest management is difficult to implement unless one disregards food security. However the other two categories could be implemented even on abandoned crop lands which would thus not affect the food security. In this chapter of the thesis we investigate the ability of management options in reducing the increase in [CO_2] by increasing storage or enhancing substitution.

Reforestation and restoration of tropical forests from abandoned and degraded agricultural and pasture lands is one of the proposed strategies for mitigating atmospheric C emissions (Houghton et al., 1993) as it has the potential to contribute to C storage directly through sequestration of C into biomass and soil C pools (Richter et al., 1999) and more so because of the rapid growth rates of trees for tropical plantations as well as natural successions (Montagnini and Porras, 1998). Tropical forests have high rates of net primary production and store approximately 216 GtC in the above ground biomass (Brown, 1993; Dixon et al., 1994a). A significant proportion of the tropical forest biome is in some state of recovery from past human disturbance (Silver et al., 2000). It was estimated that there were approximately 490 x 10^6 ha of mature tropical forests in the 1980s and 540 x 10^6 ha of tropical forests had been logged, cleared, fallowed or were in plantations (Lugo and Brown, 1993). Accumulation of aboveground biomass by the recovering forests performs many important ecosystem functions in addition to storing C like reducing erosion and nutrient leaching, ameliorating microclimatic conditions, and providing shelter for wildlife (Silver et al., 2000). Research on tropical forest secondary succession suggests that such a process could act as a significant C sink for atmospheric carbon (Lugo and Brown, 1992; Silver et al., 2000). However this process of reforestation and restoration of abandoned and degraded land is likely to be limited in its capacity to reduce the [CO_2] as biomass may eventually reach a maximum sequestration potential (Silver et al., 2000).

Studies using flux tower measurements in the Brazilian Amazon show that compared to pastures, forests have lower albedo, higher net radiation and higher evapotranspiration (Randow et al., 2004; da Rocha et al., 2004). Climate model simulations also show that tropical forests, when compared with pasture lands, maintain high rates of evapotranspiration, decrease surface air temperature and increase precipitation (Bonan, 2008). Thus apart from biogeochemical effects, restoration of tropical forests would lead to biogeophysical effects as well.

Biofuels derived from certain mixtures of native grassland perennials which require low levels of input but have a high diversity (LIHD) can provide more usable energy and less agrichemical pollution than can corn grain ethanol or soybean biodiesel. Moreover, LIHD biofuels can be grown on abandoned and/or degraded agricultural lands (Tilman et al., 2006b). Thus such bioenergy plantations have the potential to become another strategy for mitigating the atmospheric C emissions more so because such an approach provides environmental benefits without creating food-fuel competition for land or releasing carbon stored in forests (Campbell et al., 2008). Cai et al. (2011) found that planting second generation bioenergy crops on abandoned and degraded croplands and LIHD perennials on grassland with marginal productivity, on a global scale, may fulfill 26 – 55 % of the current world liquid fuel consumption, without affecting the use of land with regular productivity for conventional crops and without affecting the current pasture land. However, as stated in section 3.1 of chapter 3, if bioenergy plantations were to replace regrowth of natural vegetation, then the potential improvement in ecosystem functions and services like prevention of deforestation, regional climate regulation and increase in biodiversity that would have been achieved by the restoration of natural land cover would be lost (Cook and Beyea, 2000).

In this study, as in chapters 2 & 3, we assume bioenergy to be used directly as a fuel. So the emissions from bioenergy usage could be treated as a single pulse at harvest with a short lifetime in the anthroposphere as the time span between the carbon emission from harvest and sequestration from regrowth after plantation is very short (Cherubini et al., 2012b). Thus, other than the Land Use (LU) emission we can consider bioenergy to be carbon neutral. In this chapter, as in the 3rd chapter, bioenergy plantations are carried out on agricultural land which has been lying fallow for 5 to 20 years. As this time is quite short for a proper forest to re-grow, the LU emissions would also be negligible.

As stated in chapters 2 & 3, vegetation productivity is sensitive to conditions of the climate, atmospheric CO_2 concentration ([CO_2]), as well as different management practices (Norby et al., 2005; Oren et al., 2001; Smith et al., 2000; Witt et al., 2000). To account for projected changes in [CO_2] and climate, we thus used LPJmL (Bondeau et al., 2007) the same model used in the 1st and 2nd studies of this thesis. We investigate the amount of carbon sequestered by the end of the 21st century by the re-growth of natural vegetation in the agricultural land lying fallow between 1990 and 2005 and compare it with the amount of carbon emissions saved by bioenergy plantations in these abandoned agricultural lands due to avoided usage of fossil fuels. We establish which of the two a better mitigation measure is. We calculate the avoided emissions in the same way as we did for the previous two chapters of this thesis. Moreover, to estimate pure biogeophysical effects of tropical reforestation, as we did in the 1st study of this thesis, we used the simulation data from MPI-Earth System Model (MPI-ESM-LR) in the CMIP5 version for pre-industrial simulation (Giorgetta et al., 2013).

4.2 Model and experimental setup

The description of the models LPJmL and MPI-ESM-LR, and the way crops are managed in this model is already given in sections 2.1 and 2.2 respectively of chapter 2 of this thesis.

4.2.1 Background climate scenarios

As mentioned in chapter 2, climate projections differ between different GCMs primarily because of the uncertainty of parameterizations. LPJmL was driven with 21st century climate projections from an ensemble of 19 different general circulation models' (GCM) implementations of the SRES A2 scenario (Nakicenovic et al., 2000b)as listed in Table 2.1(appx) of chapter 2 and the reasons have been explained in the first chapter. Plant productivity is sensitive to changes in climate as well as [CO_2] (Melillo et al., 1993). Thus the uncertainty of climate projections of the ensemble of 19 different GCMs is transferred into the uncertainty of the carbon sequestered by natural vegetation or the carbon emissions saved by the bioenergy plantations. In Figures 4.03, 4.04, and 4.05, the uncertainty is demonstrated by error bars representing ± 1 Standard Deviation while as in chapter 3, the trend is shown by a smoothened spline with the 'smooth.spline' function of the R language and using a 'spar' value of 1 (Chambers and Hastie, 1992; Green and Silverman, 1994; Hastie and Tibshirani, 1986). Details of the climate scenarios have been provided in the first chapter. Figures 4.01a&b demonstrate the mean annual change in temperature and precipitation respectively from the end of the 20th century to the end of the 21st century for the study area, i.e. the abandoned tropical croplands abandoned from 1990 to 2005. For Fig. 4.01b, we masked out areas showing a change of ±5% as we do not consider this change to be significant. While the entire area of interest experiences and increase of temperature, the intensity of change differs spatially. The smaller increase of temperature of the tropics (Fig. 4.01a) compared to the respective figures of the previous two chapters shows that the rise in temperature becomes less intense with decreasing latitude thereby demonstrating the phenomena of 'polar amplification' (Holland and Bitz, 2003). On the other hand, the change of precipitation (Fig. 4.01b) shows that most of the study area does not demonstrate a significant change of precipitation. This is also reflected later in Fig. 4 where the small distance between the purple solid line and the black dashed line shows that there is not much change in biomass if the precipitation is kept constant.

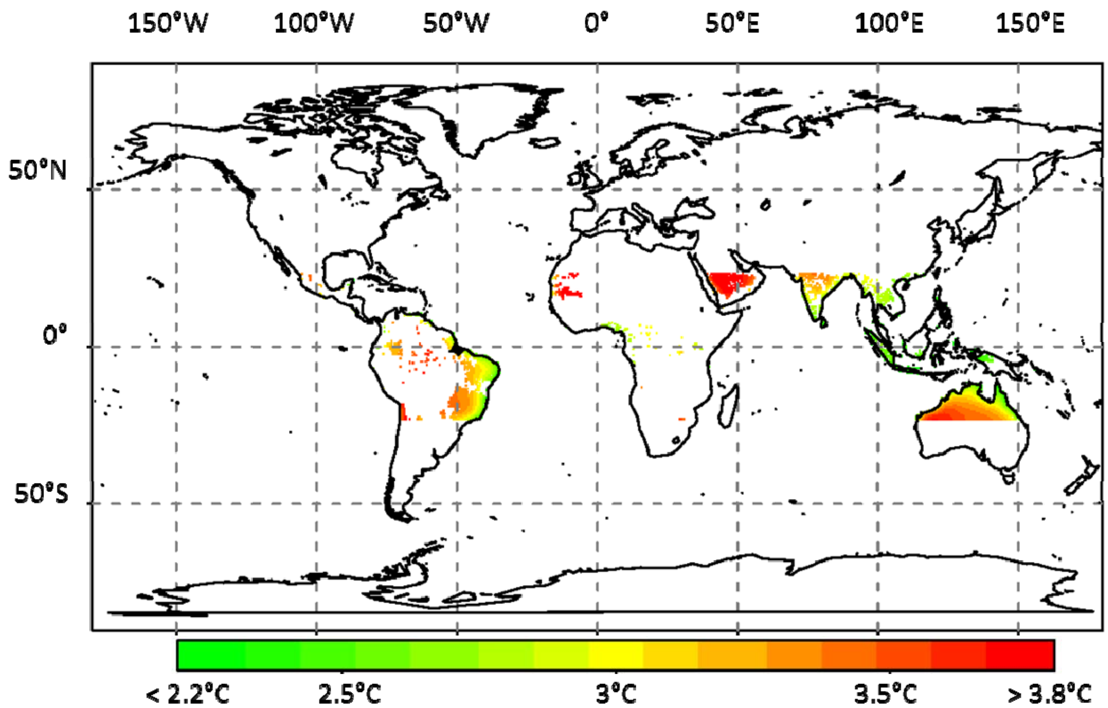

Figure 4.01(a): Change of temperature (in °C) from the end of the 20th century to the end of the 21st century displayed only for the area under study, i.e. the tropical croplands abandoned from 1990 to 2005. The change is according to the SRES A2 scenario. The values represented in the map are the mean of 19 GCM values.

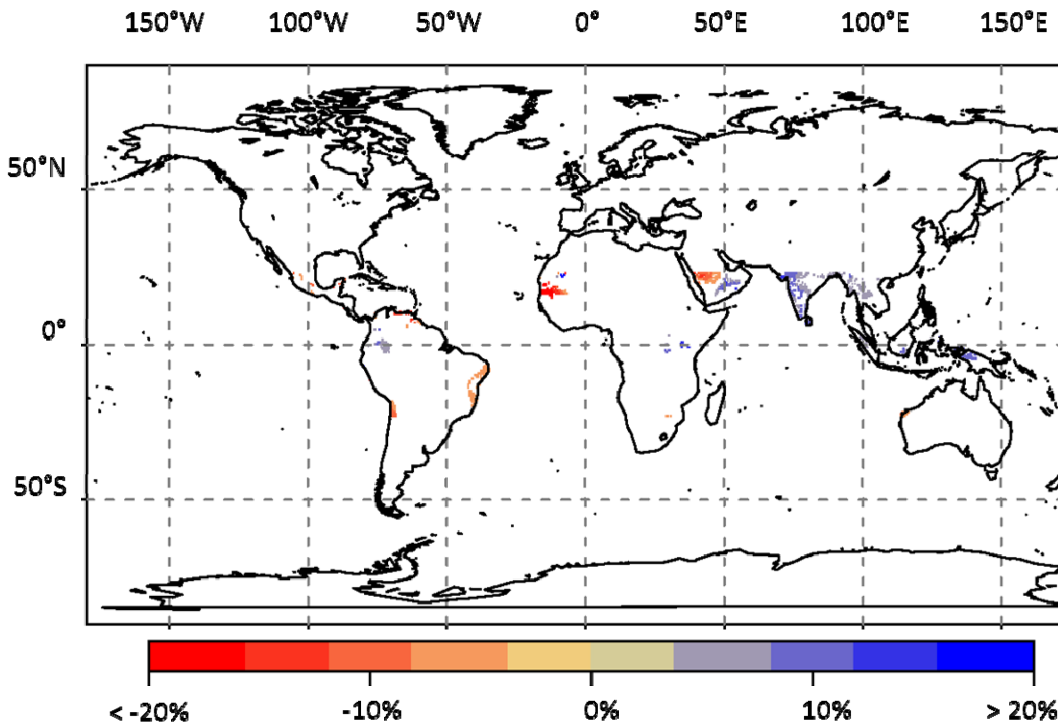

Figure 4.01(b): Percentage change in precipitation at the end of the 21st century relative to the end of the 20th century, displayed only for the study area. A change of ±5% has been maskedout as we do not consider this change to be significant. The change is according to the SRES A2 scenario. The values represented in the map are the mean of 19 GCM values.

To account for the CO_2 fertilization effects, as in the previous two studies, simulations were run with [CO_2] time series of the SRES A2 scenario which is underlying the climate projections used. The change in [CO_2] is the same as chapter 2 and has been demonstrated in Fig. 2.03 of the same chapter.

4.2.2 Scenarios of Land Use Change (LUC)

Unlike the temperate region, the tropics have not experienced an abrupt political/economic event as drastic as the collapse of the Soviet Union to accelerate the abandonment of croplands to such a large extent. Agricultural land, especially those that are marginal, having difficult terrain and/or low soil fertility, get so damaged over the course of time that they are no longer suitable for food production and are thus abandoned. Although there is no reason to choose a specific time frame for this study, we consider only the agricultural area which was abandoned from 1990 to 2005 in order to be consistent with the 2nd study of this thesis. This area is shown in Fig. 4.02. The total area of abandoned land amounts to 35.9 million hectares. The latitudinal extent of this area of interest ranges from 23° north and south of the equator.

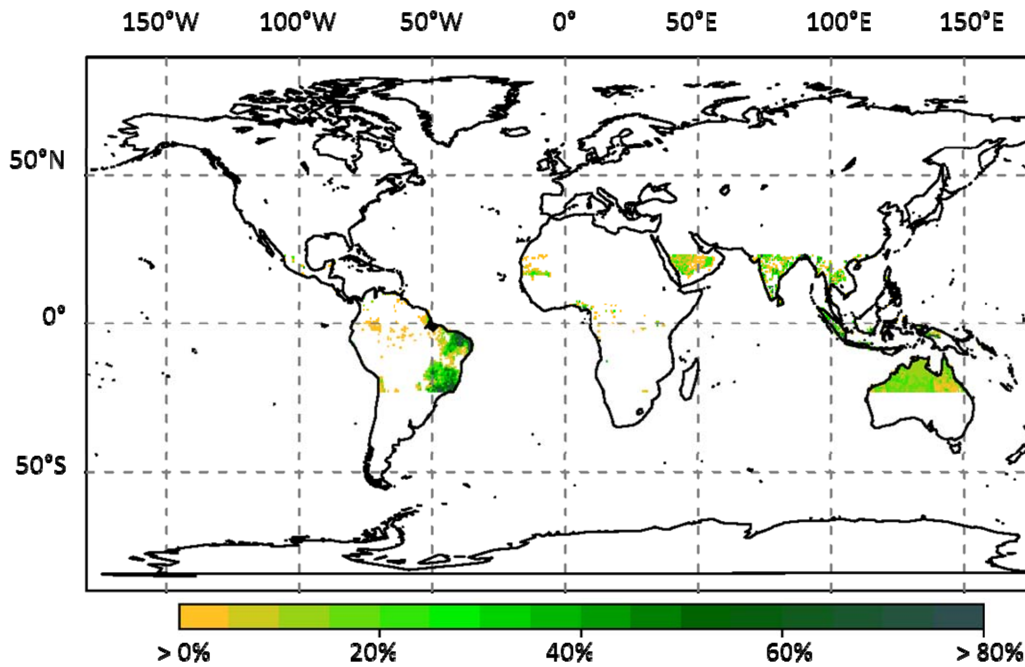

Figure 4.02: Total land abandoned from 1990 to 2005 and shown as a percentage of each pixel.

The scenarios remain the same as that of the 3rd chapter. Thus the scenarios implemented are NATVEG, NOLUC, CROP, GRASS and TREE.

It should be noted that scenarios GRASS and TREE include lignocellulosic perennials and thus it would be feasible to grow them on abandoned croplands since these plants are more tolerant against unfavorable climate and soil conditions (Adler et al., 2007; Schmer et al., 2008). The CROP scenario is purely hypothetical as in reality it would not be possible to grow food crops in these tropical abandoned crop lands as that is the reason why they have been abandoned in the first place. However we still study this scenario to investigate the mitigation potential of such a scenario if the soil was hypothetically restored to its condition prior to human disturbance.

In this study LPJmL is parameterized such that on deforestation event all the above ground biomass, including 2/3 of the sap wood is burnt and released to the atmosphere while the rest goes to the litter. For the calculation of the biophysical bioenergy potential of individual crop types, we assume that 50% of crop dry matter is carbon (Rojstaczer, 2001). The primary energy content per gram of crop dry matter is based on the Energy research Centre of the Netherlands Phyllis database (ECN, 2007) and as listed in Table 2.2(appx) of Chapter 2.

A study by Brovkin et al. (2013) found that the changes in climate simulated by the ESMs are relatively small in comparison with inter-annual variability of climate and are difficult to detect when the land use changes are small. Apart from this, the area potentially available for carrying out reforestation is limited as large areas are already covered by forests. For this reason experiments with small scale changes in land use are not carried out using MPI-ESM. Thus to assess the biogeophysical effects of tropical forest restoration, in this study, MPI-ESM is used to look into the effects of extensive reforestation instead of that of only abandoned crop lands. Moreover, instead of computing the effects of extensive reforestation directly, we compute the inverse of the effects of extensive tropical deforestation (replacement of all woody PFTs with grasses from 23°N to 23°S), keeping the [CO_2] fixed as the pre-industrial value. We conduct this simulation for 30 years. This means that the analysis of biogeophysical changes of a hypothetical complete reforestation is based on a hypothetical completely deforested state of the tropics.

4.3 Results

We find that the regrowth of natural vegetation in the tropical agricultural lands abandoned from 1990 to 2005 would lead to the sequestration of 3136.8 ± 350.5 gCm^{-2} including the above ground and below ground carbon pools by the end of the 21st century, calculated as an average over only the study area i.e. tropical abandoned croplands. This translates to a total of 1.1 ± 0.1 GtC for the entire area of interest. Fig. 4.03 shows the increase in the sum of carbon pools from the end of the 20th century (1990) to the end of the 21st century (2098). It is apparent that the rate of carbon sequestration is higher in the beginning of the 21st century and stabilizes towards the end. The distance between the blue and red lines is a measure of the carbon sequestered only due to regrowth of natural vegetation on abandoned agricultural lands. The error bars demonstrate the uncertainty of the carbon pools which are due to the range of climate projections of different GCMs.

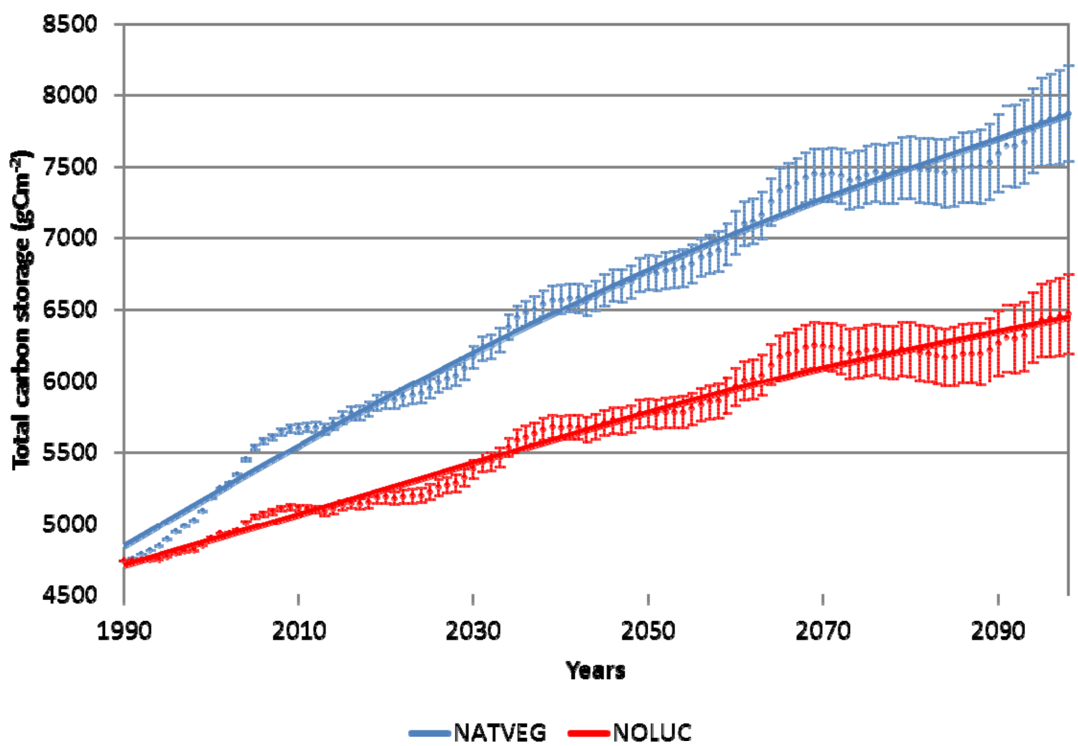

Figure 4.03: Changes in the carbon storage of the NATVEG and NOLUC scenarios, averaged over only the study area i.e. tropical abandoned croplands. The dots and the error bars represent the raw data and it uncertainty respectively. The trend is shown as a spline (solid lines) in order to neglect the inter-annual variability.

We investigate the effects of climate change (according to the SRES A2 scenario) on the biomass of the natural vegetation re-growing the abandoned agricultural lands. To get a better understanding, we look at the effects of changing temperature (T), precipitation (P), atmospheric CO_2 concentration (CO2) on the change of biomass of the due to natural vegetation regrowth. To do so we compare the change in biomass between a scenario where the above factors (individually or together) are kept constant and the scenario where all factors change according to the SRES A2 scenario (ALL: A2). In this chapter, as shown in Fig. 4.04, we find that changing [CO_2] according to the SRES A2 scenario has by far the most dominating effect on increasing the biomass of the natural vegetation as fixing the [CO_2] leads to a significant drop in the biomass compared to the 'ALL: A2' scenario. This means that if the [CO_2] is allowed to increase according to the SRES A2 scenario, then there is a resultant increase in the productivity and thus the biomass of the natural vegetation. On the contrary, when the temperature or precipitation is fixed ('T: const' or 'P: const'), we find a significant increase in biomass compared to the 'ALL: A2' scenario. This means that if the temperature and/or the precipitation is allowed to change according to the SRES A2 scenario then they act as a stress thereby decreasing the increase of biomass. All the scenarios are compared with the black dashed line and the green line. The black dashed line represents the scenario where all factors change according to the SRES A2 scenario and natural vegetation regrowth takes place on abandoned crop lands. The green line represents the scenario where not only are T, P, and [CO_2] kept constant, the abandoned crop lands are maintained so, as in the NOLUC scenario of Fig. 4.03.

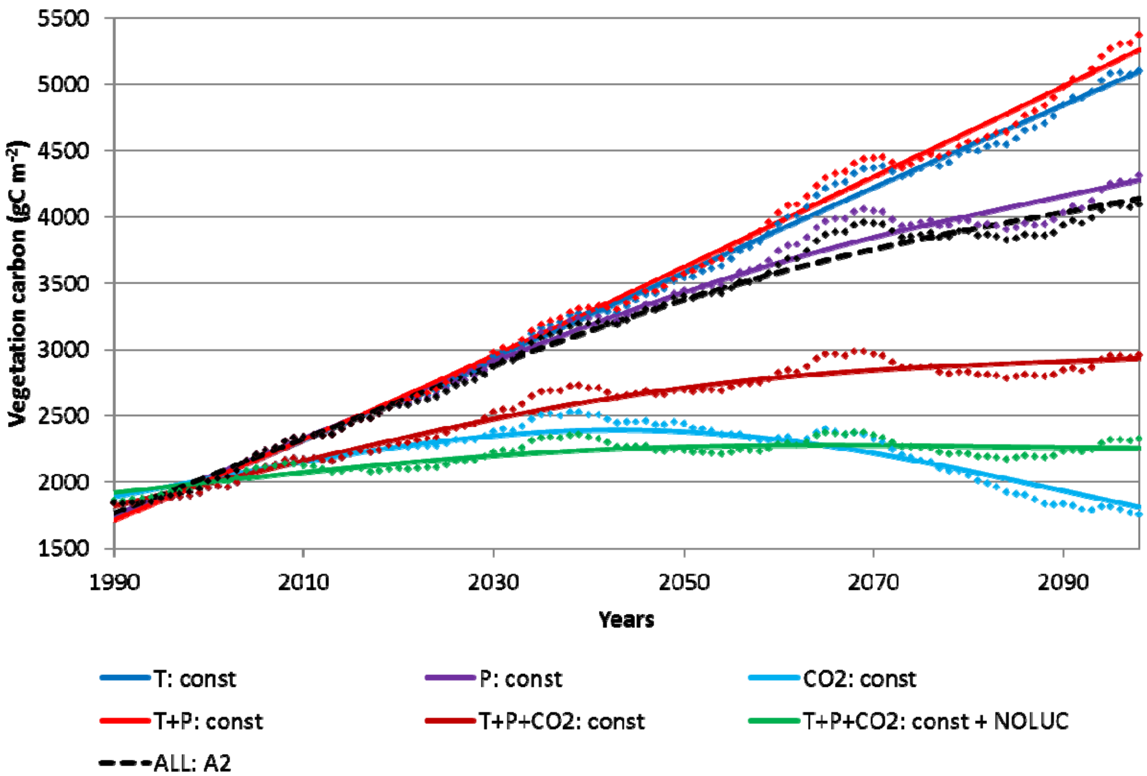

Figure 4.04: Response of vegetation carbon (averaged over the study area only) to different scenarios where climate and/or [CO_2] and/or LU were kept constant to identify the effect of the respective factor on the change of biomass. This identifies the factor which has the most dominating influence in the change of biomass. Here 'Clim' = Climate; 'CO2' = [CO_2]; 'const' = constant (maintaining inter-annual variability); 'A2' = changing according to SRES A2 scenario. The 'ALL A2' scenario is represented by a dashed and not a solid line as it is the only scenario where nothing is allowed to remain constant. The representation of the dots and solid lines are the same as that of Fig 4.03.

To judge whether the effectiveness of bioenergy plantations as a mitigation measure is better than natural vegetation regrowth, the abandoned agricultural land was planted according to the scenarios CROP, GRASS or TREE. We assume in this study that bioenergy production is carbon neutral (except for the LUC emissions). In this study, the bioenergy crops, grasses and trees were planted in 2010 on agricultural land which had been abandoned progressively from 1990 to 2005. Given this short period of time for which the area of interest has laid fallow, the natural vegetation regrowth and thus the amount of carbon sequestered is expected to be limited. We find that the immediate emissions, averaged only for the study area, which are a result of removing the natural vegetation, burning it and releasing the carbon of the above ground biomass, including 2/3rd of the sap wood into the atmosphere, amounts to 142.9 ± 1.1 gCm^{-2} which is extremely small considering the total amount of carbon saved by the end of the 21st century.

To compute the avoided emissions of the bioenergy plantations, as in the previous 2 studies, while we assume 20.9 gC to be emitted per MJ of fossil fuel burnt (an average of all stationary and transportation fuels and considering 100% combustion efficiency) (EIA, 2008), the primary energy content (in kilo Joules) of each crop functional type per gram of dry matter is given in Table 2.2(appx) of chapter 2. Thus bioenergy plantations would lead to carbon savings if the combustion of an equivalent amount of fossil fuels were avoided. Taking this into account, we see from Fig. 4.05 that bioenergy crops have theoretically the highest potential to save carbon when compared to bioenergy grass or trees.

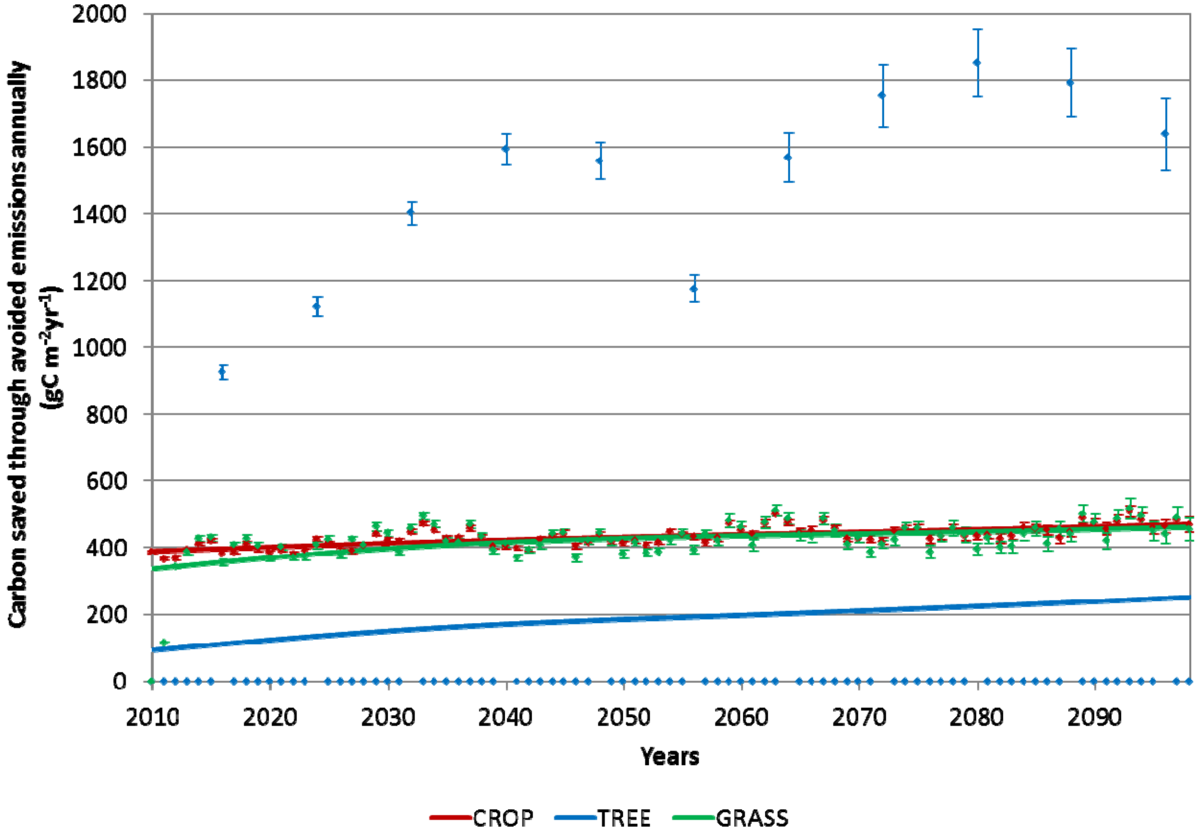

Figure 4.05: Carbon saved annually through emissions prevented by avoided combustion of fossil fuels (averaged over the study area only). Since bioenergy trees are harvested every 8 years, the annual carbon saved for the TREE scenario is much higher than the other scenarios for every 8th year and zero for the rest of the years. The representation of the dots, error bars and solid lines are the same as that of Fig 4.03. For comparing annual carbon saved for the three scenarios, the spines (solid lines) are to be compared instead of the raw data (dots).

At the end of the 21st century, comparing the cumulative carbon saved by the different mitigation scenarios (Fig. 4.06), we find that the carbon saved by the bioenergy scenarios exceed that of NATVEG by more than an order of magnitude. For the entire area of interest, at the end of the

21st century, CROP has the highest cumulative carbon savings of 13.8 ± 0.3 GtC followed by GRASS saving 13.4 ± 0.4 GtC followed by TREES saving 5.9 ± 0.2 GtC.

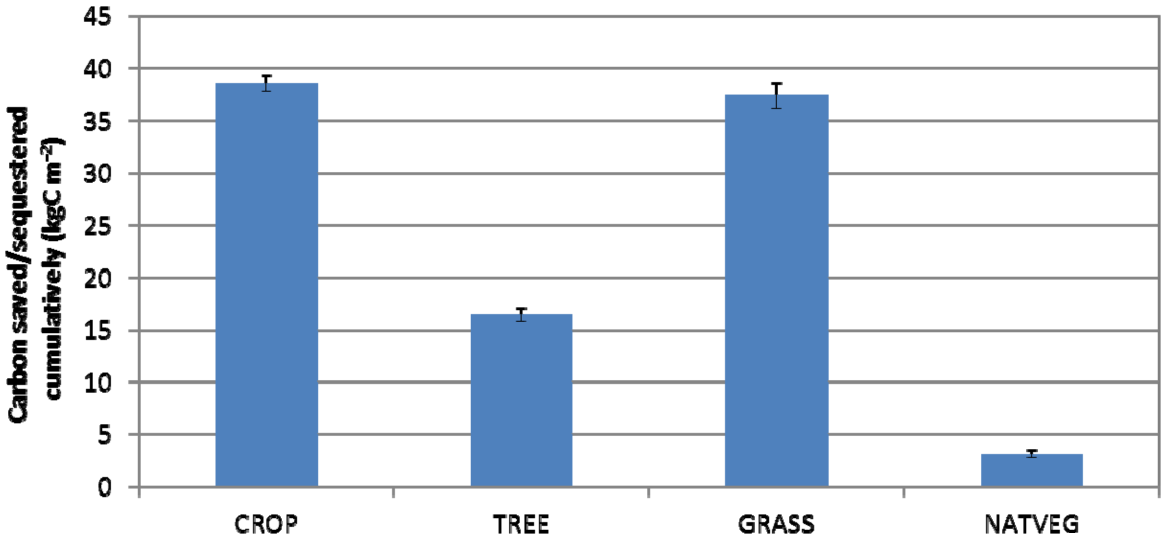

Figure 4.06: Carbon saved cumulatively through avoided emissions (bioenergy scenarios) from 2010 to 2098 compared with the total carbon sequestered (NATVEG scenario) from 1990 to 2098 (averaged over the study area only).

To assess purely the biogeophysical effects of tropical reforestation, we analyze the results from the additional experiment with MPI-ESM. As stated earlier, we analyze a hypothetical complete reforestation based on a hypothetical completely deforested state of the tropics. However reforestation is not possible on all available tropical land as climatic conditions are not favorable for the growth of woody vegetation in deserts and grasslands. Thus to limit out analysis only to those areas where reforestation has taken place, we analyze the change in biogeophysical effects per absolute change in woody fraction (trees and shrubs). To exclude the small trend during the first few years, we report changes averaged over the last 20 years of the 30-year experiment. Since the reforestation of the entire tropics from a completely deforested state is not realistic, we would be interested in the regional biogeophysical effects rather than the global effects. Analyzing the biogeophysical effects of such a hypothetical extensive reforestation, we find that there is a decrease in albedo, leading to a decrease in the surface upwelling shortwave radiation and an increase in the surface upwards latent heat flux, showing that reforestation leads to an increase in evapotranspiration (Fig 4.07 a&b). Looking into the changes of temperature (Fig 4.08a), we find a significant decrease of temperature of up to 1.5°C in equatorial regions of South America, Africa and parts of south-east Asia. However there are also areas, especially in the drier regions of the tropics which experience an increase of temperature of up to 0.9°C. It is also apparent that reforestation of the tropics leads to a significant increase of precipitation (Fig 4.08b). The biogeophysical effects of tropical reforestation could also be understood by analyzing the change of surface energy balance, as tabulated in Table 4.1(appx).

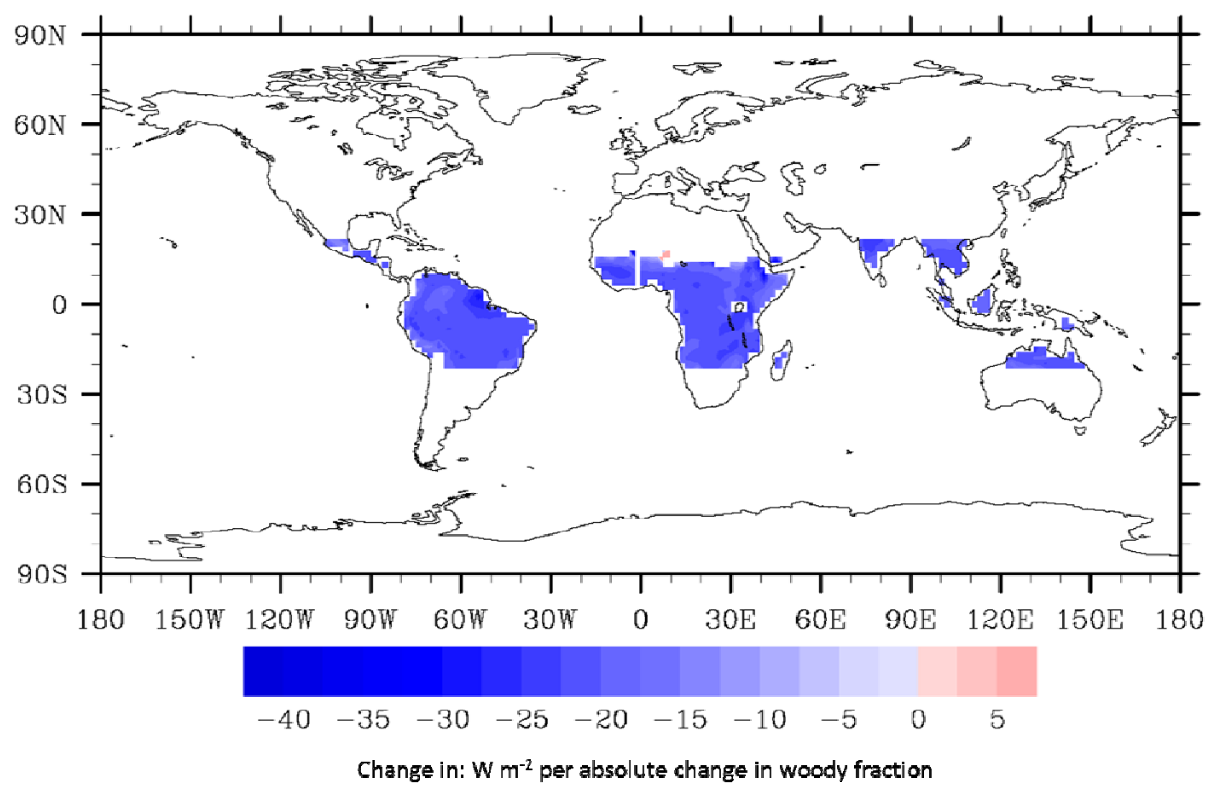

Figure 4.07a: The change of annual surface upwelling shortwave radiation of the tropics in response to extensive reforestation of a completely deforested state of the tropics. Shown is the inverse of the difference of the MPI-ESM tropical deforestation experiment, averaged over the last 20 years and the pre-industrial control simulation. Shown are only statistically significant changes ($p<0.05$).

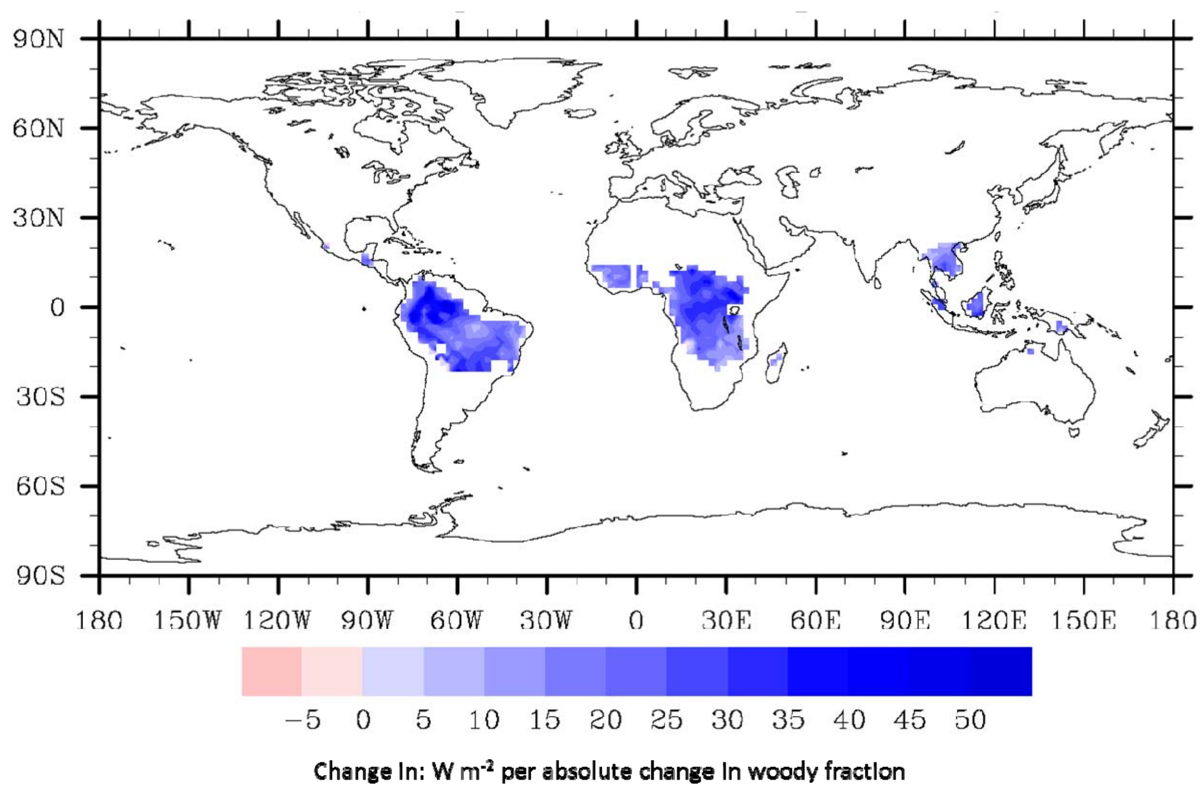

Figure 4.07b: The same as Fig 4.07a but for the change of annual latent heat flux.

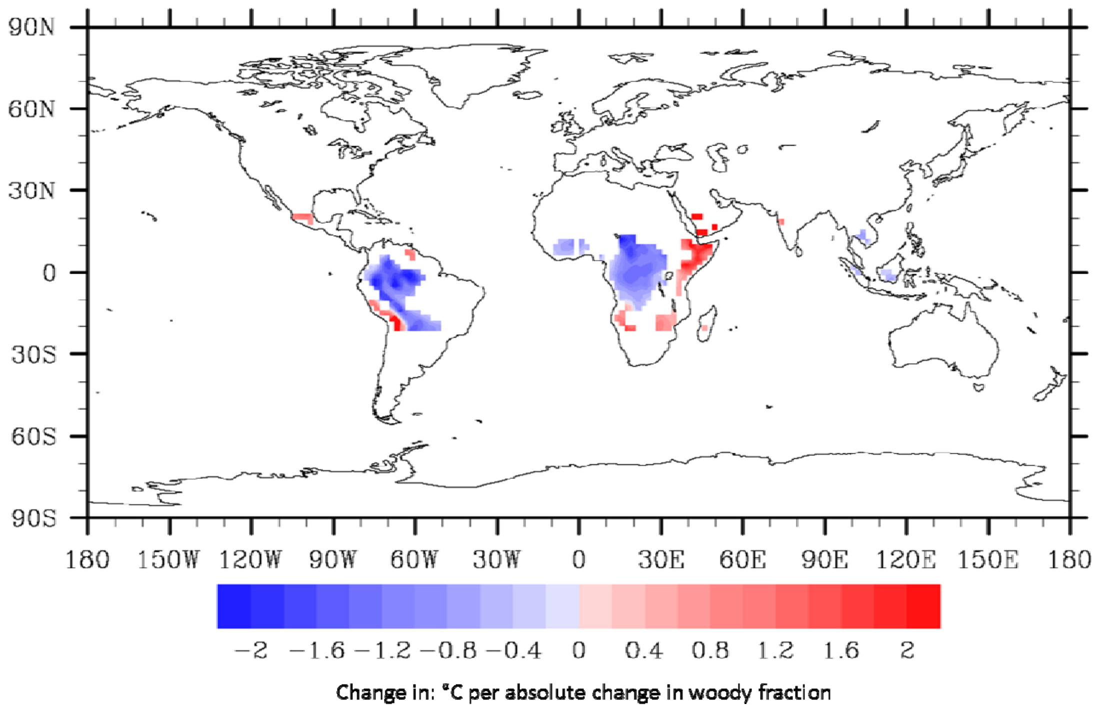

Figure 4.08a: The same as Fig 4.07a but for the change of annual near surface air temperature

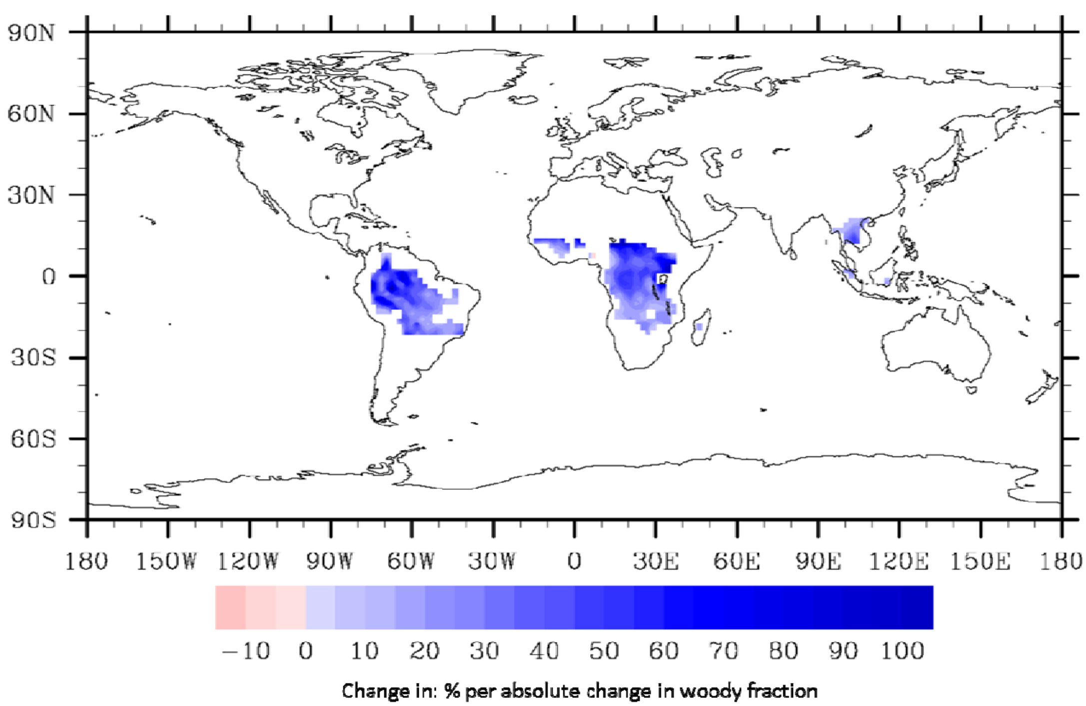

Figure 4.08b: The same as Fig 4.07a but for the percentage change of annual precipitation.

4.4 Discussion

The conclusion that the bioenergy plantations on tropical abandoned croplands are a more effective mitigation measure compared to the re-growth of forests by natural succession is robust as the cumulative total of the carbon saved by the bioenergy plantations because of the emissions saved by the avoided burning of fossil fuels is more than an order of magnitude higher than the total carbon saved by the re-growth of natural vegetation by the end of the 21st century. Moreover, the total carbon emissions saved per year by the bioenergy plantations are small but a significant percentage of the global anthropogenic fossil fuel carbon emissions according to the SRES A2 scenario (Nakicenovic et al., 2000b). In 2010, the bioenergy plantations save up to 2% of the global anthropogenic fossil fuel carbon emissions. At the end of the 21st century, as the projected anthropogenic fossil fuel carbon emissions increase much more compared to the increase in biophysical bioenergy potential, the bioenergy plantations can only save up to 0.6%.

As stated earlier, the CROP scenario was purely hypothetical as food crops could not grow on degraded land. Thus the conclusion that the biophysical bioenergy potential of GRASS is almost as high as that of CROP implies that high investments (and consequent emissions) need not be made to restore the soil of the abandoned croplands to its state prior to disturbance. Amongst the realistic bioenergy options, GRASS, which in the model LPJmL represents the growth and productivity characteristics of *Miscanthus* and other switch-grass cultivars (Beringer et al., 2011) and could potentially also represent low-input high-diversity (LIHD) mixtures of native grassland perennials, has the highest biophysical bioenergy potential. This finding is in line with Valentine et al. (2012) who concludes that lignocellulosic bioenergy crops is the best option for dedicated bioenergy crops as it does not compete directly for use of food and also does not require large inputs in terms of annual cultivation and fertilizer application. In a review paper, Monti et al. (2011) also found a net CO_2 abatement for switchgrass grown on former arable lands. Zimmermann et al. (2011) studying *Miscanthus* plantations on farms also found that such plantations lead to carbon sequestration by increasing soil organic carbon in both the scenarios of former grassland and former tilled land being replaced by *Miscanthus* plantations. This is also in line with conclusion by other studies that bioenergy derived from lignocellulosic species, especially low-input high-diversity (LIHD) mixtures of native grassland perennials, especially when grown on abandoned crop lands is more sustainable than the conventional varieties (corn grain ethanol and/or soybean biodiesel) as it provides more usable energy, causes less agrichemical pollution, avoids the food-fuel competition for land and prevents releasing carbon stored in forests (Cai et al., 2011; Campbell et al., 2008; Tilman et al., 2006b).

Lugo et al. (1988) found that the rate of above ground C accumulation in plantations range from 80 to 1500 gC m^{-2} yr^{-1} during the 1st 26 years following establishment. The regrowth of natural vegetation in the first 26 years of the NATVEG scenario has induced a mean net carbon sequestration rate of 23 gC m^{-2} yr^{-1}. Although the value computed in this study appear less compared to the latter value, it is reasonable as in this study the regrowth of natural vegetation is by natural succession and not by plantations. Studies show that for natural succession from abandoned tropical cropland to forest, the increase in total carbon stock due to carbon sequestration is about 400 – 800 gC m^{-2} over the first 30 years (Palm et al., 1999; Watson et al., 2000). In this study we find that the mean increase in carbon stock due to the same reason is 11.3 Mg C ha^{-1} which appears to be quite reasonable.

However, as in the case of the previous study, the main conclusion of this study does not agree with that Righelato and Spracklen (2007) who concluded that forestation of an equivalent area of land would sequester significantly more carbon over a 30 year period than the emissions avoided by the use of biofuels. The probable reason for this disagreement is the difference in methodology of computation of both avoided emissions as well as carbon sequestration. For computation of carbon sequestered by converting croplands to natural vegetation, Righelato and Spracklen (2007) had considered only US regions and while calculating avoided emissions, instead of computing primary energy, they had only considered the commercially exploitable bioenergy crops and had also taken into account the loss of energy incurred in converting the crop to a commercially exploitable form.

In this chapter, as in the previous chapter we also found that the change of [CO_2] according to the SRES A2 scenario had a beneficial effect on plant biomass because of the effect of fertilization. As discussed in the previous chapter, this CO_2 fertilization effect (Friedlingstein et al., 1995) is debatable as there is limited experimental evidence. Norby et al. (2005), analyzing the response of Net Primary Productivity (NPP) to elevated levels of CO_2 in free-air CO_2 enrichment experiments in forest stands, found that the response, depending on the leaf area indices, was attributable to increased light absorption or increased light-use efficiency. On the contrary, change of temperature and precipitation according to the same scenario had a detrimental effect as the respective changes acted as a drought stress (Dale et al., 2001; Hanson and Weltzin, 2000). This finding, as discussed in the previous chapter, was reflected in a paper by Cao and Woodward (1998) who concluded that in response to climate change, the net ecosystem production would increase significantly but this response would decline as the CO_2 fertilization effect would become saturated and would be diminished by climatic factors. Pongratz et al. (2012), in an experiment simulating a geo-engineered climate, i.e. a situation where the climate was stabilized without affecting the rise in [CO_2], had found a resultant increase in crop yields.

It is well documented that LPJmL is able to reproduce key features of the global carbon cycle (Jung et al., 2008; Luyssaert et al., 2010). The model LPJ (predecessor of LPJmL and represents only natural vegetation) has been tested successfully against a wide range of observations, including short-term flux measurements of carbon and water, satellite based observations of leaf phenology and photosynthetic activity, and others (Dargaville et al., 2002; Sitch et al., 2003b). Comparisons of site-scale measurements of CO_2 exchange under ambient and enhanced CO_2 concentrations in the Duke Forest Free Air Carbon Dioxide Enrichment experiment with LPJ simulations also show a high level of confidence in the model's process formulations (Hickler et al., 2003). However some other studies show that the CO_2 response in LPJ is overestimated (Cramer et al., 2004).

As discussed in the previous chapter (section 3.4), the model LPJmL does not account for nitrogen and other micro-nutrient dynamics. This would be especially important while dealing with abandoned crop lands of the tropics since we are simulating crop or natural vegetation growth on land which was abandoned because it became degraded and was unfit for food crops (Drechsel et al., 2001).

In this chapter, as discussed previously (section 3.4) , a couple of essential assumptions was done to simplify the analysis. We have assumed the LU to remain constant after a specific year. We have also computed and compared only primary energy, i.e. assumed 100% combustion efficiency, in order to keep a consistency among analysis done in different thesis chapters. We also have not accounted for additional emissions which would result from the different management measures. A quantification of effect of these assumptions on the potential of biofuel plantations to reduce [CO_2] goes beyond the given study. This could be explored in details in further studies especially in the near future when all sources of bioenergy especially lignocellulosic are commercially available.

The LU change will affect climate through biogeophysical effects. However, the climatic effect of small-scale LU changes will be small in comparison with natural climate variability. To get an estimate of biogeophysical effects of tropical LU changes, we analyze results of ESM experiments with extensively deforested tropics and interpret them for the reforestation case. This is a limitation of the experimental setup, as local-scale climate changes will not necessarily coincide with the changes on a large scale. However, we think that it is important to consider biogeophysical effects of LU change due to reforestation enhancement of moisture recycling. In this respect, even a qualitative interpretation of large-scale experiments adds a value to our study.

4.5 Conclusions

Comparing the carbon emissions saved through avoided burning of fossil fuels to the carbon sequestered by the re-growing natural vegetation on the tropical agricultural land abandoned after 1990, we find that lignocellulosic bioenergy grass plantations are most effective. The total carbon potentially saved by avoided burning of fossil fuels is more than an order of magnitude higher than total carbon sequestered by natural vegetation by the end of the 21st century. For the entire area of study, involving 35.9 million hectares, the bioenergy plantations potentially save from about 6 to 14 GtC while natural vegetation re-growth sequesters ~ 1.1 GtC by the end of the 21st century.

The mitigation potential of herbaceous lignocellulosic bioenergy grass species which represents *Miscanthus,* different switchgrass species or low-input high-diversity (LIHD) mixtures of native grassland perennials, is highest. This is also significant as such species have shown their ability to grow in unfavorable climatic and soil conditions, do not have significant management requirements and also do not compete with the land usage for food crops.

As the biogeophysical effects of small-scale LU changes cannot be quantified, it can only be concluded qualitatively that re-forestation of the topical abandoned croplands leads to an increased moisture recycling and a possible decrease in the near surface air temperature. The biogeophysical effects of tree plantations should be similar to that of forest regrowth. Thus, although the biophysical bioenergy potential of bioenergy trees is less than that of bioenergy grass, the plantation of bioenergy trees could potentially be a more effective mitigation measure as it has the potential of increasing the moisture recycling and possibly reducing the temperature.

Given the importance of the effect of accounting for nitrogen and phosphorous as well as considering different scenarios of future LUC, these elements should be considered in future studies to provide a more realistic estimation of the mitigation potential of abandoned crop lands in the near future. Moreover, as it is important to quantify the biogeophysical effects of such LUC, it is also important that future studies be carried out using a coupled model.

Appendix

Teble 4.1(appx): The annual surface energy balance averaged (as inverse) over land cells between 23°N and 23°S over the last 20 years of the MPI-ESM tropical deforestation experiment. Values of ΔRef are changes of biogeophysical parameters due to reforestation of the tropics from a completely deforested state. All fluxes are in Wm^{-2} and surface temperature in °C. SW = short-wave radiation; LW = long-wave radiation; LH = surface upwards latent heat flux; SH = surface upwards sensible heat flux; Temp = near surface air temperature.

Values	CTRL	ΔRef
Surface upwelling SW (proxy for albedo)	43.1	-11.6
net SW (↓ - ↑)	189	+3.6
net LW (↓ - ↑)	-68.8	+5.1
Net Radiation (SW + LW)	120.3	+8.7
LH	68.5	+9.7
SH	51.8	-1
Temp	24	+0.1

Chapter 5: Summary & Conclusion

Land Use and Land Cover Change (LULCC) emissions has contributed to a large fraction of the global anthropogenic emissions since the industrial revolution, thereby leading to the rise in [CO_2] and consequently climate change (Watson et al., 2000). On the other hand, several modeling studies found that the pure biogeophysical effect of historic LULCC was a global cooling. While the historic changes are mainly responsible for the state of the current climate, LULCC has the potential to be exploited to reduce the increase in [CO_2] by either de-carbonizing the energy system through utilizing bioenergy or by increasing the carbon stock of the terrestrial pools. In this thesis, I have thus investigated the role of bioenergy production in the terrestrial carbon cycle and energy balance using global vegetation and climate models.

5.1 In **chapter 2**, a purely academic study was performed to make a better estimation of the carbon cycle changes under large scale deforestation of the high latitudes. This is because, compared to a few observational studies, the biogeochemical response of such deforestation as computed in modeling studies by Bala et al. (2007) and Bathiany et al. (2010) was found to be an underestimation. Moreover, it was also investigated whether bioenergy plantations in the suitable parts of the deforested areas, due to fossil fuel substitution, was able to make up for the total carbon emitted as a result of such extensive LULCC. In addition, the pure biogeophysical effect of such LULCC was computed.

5.1.1 What are the total emissions for high latitude large-scale deforestation and how they compare with that of previous studies?

The total emissions, i.e. the sum of immediate emissions (from burning of above-ground biomass) and long term emissions (from emissions of litter and soil carbon pools) by the end of the 21st century for such large-scale LULCC, representing the 'slash and burn' method, were ~169 GtC for the most plausible scenario. This is much higher compared with Bala et al. (2007) and Bathiany et al. (2010) who found the same to be 80 GtC and 20 GtC respectively. This mismatch is caused by a combination of the difference in how 'deforestation' is simulated in the different studies and the different representation of the carbon cycle in the different models used in the different studies.

5.1.2 What are the biogeophysical effects of such deforestation?

Analyzing the purely biogeophysical effects of high latitude deforestation, in simulations with MPI-ESM, the global mean annual near surface air temperature was found to have decreased by 0.35°C. The regional cooling was stronger as the same temperature averaged over only the high latitude land area was found to have decreased by 1.9°C. This cooling was mainly a result of an increase in albedo, which lead the annual surface upwelling short wave radiation, averaged over the high latitude land areas to increase by 12.4 Wm^{-2}.

5.1.3 Are bioenergy plantations in the deforested areas able to make up for the carbon losses caused by the emissions?

If bioenergy was to be produced only in the deforested areas which were suitable for cropping, it saved carbon emissions through avoided combustion of fossil fuels, thereby reducing the carbon debt. However, by the end of the 21st century, and considering only the most plausible scenario, it was found that the carbon debt could not be neutralized. This is mainly because this scenario only involves about 14% of the total deforested area. As a result, considering the sum of only the biogeochemical effects of deforestation followed by bioenergy plantations, it was found that the net change of global mean surface temperature was an increase of 0.04 to 0.11°C.

5.2 Bioenergy cropping after deforestation would cause more damage to the climate than it would mitigate. Some fraction of agricultural land in the temperate and boreal region was abandoned in the recent past due to different reasons. Such an area was managed either by carrying out bioenergy plantations or by allowing this land to be restored to natural forests or grasslands through natural succession. This could act as an effective mitigation measure by saving carbon emissions through fossil fuel substitution or enhanced carbon sequestration. Moreover, such management would not cause any additional emissions from LULCC and would not affect the food security. Therefore in **chapter 3**, the mitigation potential of these two management options on temperate and boreal cropland abandoned between 1990 and 2005 was compared.

5.2.1 How much carbon is saved (from avoided emissions) from bioenergy plantations and how much carbon is sequestered by the re-growing natural vegetation?

Cumulatively at the end of the 21st century, the re-growth of natural vegetation on the abandoned croplands helped in the sequestration of ~1.6 $kgCm^{-2}$ while bioenergy plantations helped in saving from ~12.4 $kgCm^{-2}$ to ~25 $kgCm^{-2}$ through avoided usage of fossil fuels. The total area of the abandoned croplands of the temperate and boreal region is small and consequently the mitigation potential is also small. However, the mitigation potential is non-negligible, from up to 1.2% in 2010 to up to 0.4% at the end of the 21st century, of the global anthropogenic fossil fuel carbon emissions as projected by the SRES A2 scenario.

5.2.2 From the management options of bioenergy cropping or natural vegetation re-growth, which is the most effective mitigation measure for the temperate and boreal abandoned croplands?

Bioenergy plantations have proven to be more effective as the total carbon saved by the avoided burning of fossil fuels was more than an order of magnitude higher than the total carbon sequestered by natural vegetation by the end of the 21st century. Among the bioenergy options, bioenergy food crops were ignored as they being unsuited to nutrient deficit soils, additional management is needed to restore the soil quality to its pre-disturbed state. The mitigation potential of herbaceous lignocellulosic bioenergy grass, representing species like *Miscanthus* or different switchgrass species was found to be the highest. This is significant, especially since, such grass species have the ability to grow in unfavorable soil conditions.

5.3 The Tropical region has most of the world's forests and the tropical forests account for a large percentage of the terrestrial net primary productivity. Some fraction of the tropical agricultural land has been abandoned in the recent past mainly by uncontrolled uses such as overharvesting and degradation or damage to marginal land. Thus in **chapter 4**, in an attempt to determine which management measure is a better mitigation measure for the abandoned croplands of the tropics, the carbon emissions saved by the bioenergy plantations is compared with the amount of carbon sequestered by the natural re-growth of vegetation in the same area. The biogeophysical effect of the latter is also determined.

5.3.1 How much carbon is saved (from avoided emissions) from bioenergy plantations and how much carbon is sequestered by the re-growing natural vegetation?

Cumulatively by the end of the 21st century, the re-growth of natural vegetation on the abandoned tropical croplands helped in the sequestration of ~3.1 $kgCm^{-2}$ while bioenergy plantations helped in saving from ~16.4 $kgCm^{-2}$ to ~38.5 $kgCm^{-2}$ through avoided usage of fossil fuels. The total extent of the abandoned croplands of the tropical region is small and as a result, the mitigation potential is also small. However, the mitigation potential is non-negligible, from up to 2% in 2010 to up to 0.6% at the end of the 21st century, of the global anthropogenic fossil fuel carbon emissions as projected by the SRES A2 scenario.

5.3.2 From the above management measures, which is the most effective mitigation measure for the abandoned tropical croplands?

Similar to the results of chapter 3, the bioenergy plantations were found to be a more effective mitigation measure compared with re-growing natural vegetation as the total carbon saved by the avoided burning of fossil fuels was more than an order of magnitude higher than the total carbon sequestered by natural vegetation by the end of the 21st century. The mitigation potential of herbaceous lignocellulosic bioenergy grass was found to be the highest as the bioenergy from food crops were ignored. Among the bioenergy options, bioenergy food crops are unsuited to nutrient deficit soils. Since their mitigation potential is not significantly higher than that of the other options, the additional management is needed to restore the soil quality to its pre-disturbed state would not be worth the additional investment and emissions. Thus the mitigation potential of herbaceous lignocellulosic bioenergy grass was found to be the highest. This is significant, especially since, such grass species have the ability to grow in unfavorable soil conditions.

5.3.3 What is the biogeophysical effect of reforestation of the tropical abandoned croplands?

As the biogeophysical effects of small-scale LU changes cannot be quantified, it can only be concluded qualitatively that re-forestation of the tropical abandoned croplands leads to and increased moisture recycling and a possible decrease in the near surface air temperature.

5.4 To appreciate the effects of any mitigation option, all the simulations used the SRES A2 scenario as the reference scenario for the projections of climate and [CO_2] as this is the only scenario with no stabilization of [CO_2], i.e. the [CO_2] has an increasing trend even at the end of the 21st century.

5.4.1 What are the effects of the projected changes in the [CO2] and climate (according to the SRES A2 storyline) on the biophysical bioenergy potential and/or the biomass of natural vegetation?

In chapter 2, it was found that both climate change and increasing [CO_2] lead to increasing biophysical bioenergy potentials north of 45°N. The effect of changing climate was about twice as large as that of increasing [CO_2] and in combination, these two drivers showed an amplifying effect on the increase of biophysical bioenergy potentials. In chapters 3 & 4, it was found that the change of [CO_2] according to the SRES A2 scenario had by far the most dominating effect and resulted in the increase of biomass of the natural vegetation re-growing on the abandoned croplands. This was because of the fertilization effect. However, the change of climate (temperature and precipitation) according to the SRES A2 scenario causes the biomass to decrease, mainly because of draught stress.

5.5 Overall research question:

5.5.1 What is the role of bioenergy production in the terrestrial carbon cycle and energy balance?

Concluding the findings of this thesis and studying the role of bioenergy production in the terrestrial carbon cycle and energy balance, it can be said that due to the strong impact of the land's biosphere carbon cycle, bioenergy plantations on land covered by natural forest or grassland would not be an effective means to reduce the increase in [CO_2] as it would lead to a net carbon debt and a consequent increase in global mean near surface air temperature. Considering the scarcity of available land, an effective mitigation measure would be to manage croplands abandoned in the recent past, by allowing re-growth of natural vegetation or to carry out bioenergy plantations. Assuming high conversion efficiency of conversion from feedstock to final fuel, bioenergy plantations, especially that of lignocellulosic perennial grasses appears to be the most effective option.

Soil nutrients, projections of available land, as well as realistic efficiency of converting bioenergy feedstock to final fuel, should be considered in future studies to provide a more realistic assessment of the role of bioenergy production in the terrestrial carbon cycle and energy balance. Moreover, since any LULCC has its corresponding biogeophysical effects, their effect on the energy balance needs to be quantified.

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