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Modelling the effects of land use change on soil carbon on global scale

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Modelling the effects of land use change on soil carbon on global scale

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Abstract

Historical land-use changes (LUCs) have substantially altered the terrestrial carbon sink. This study focusses on assessing the effects of LUC on soil carbon and vegetation carbon turnover using a dynamic global vegetation model (DGVM). Observational datasets are used to assess how well the model represents the LUC effects.

First, an approach is developed for evaluating DGVMs against the existing observational meta-analyses of soil carbon changes for different LUCs. Using the DGVM JSBACH, idealized LUC simulations are performed whereby the entire land surface is covered by one vegetation type that then undergoes a LUC to another vegetation type. The grid cells that represent the climatic conditions of the meta-analyses are selected for the comparison of the mean simulated changes against the meta-analyses. The crop-to-forest conversion results in a soil carbon gain of 10% compared to a gain of 42% in the meta-analyses, while the forest-to-crop conversion results in a simulated loss of 15% compared to 40%. The model deviates from the meta-analyses for the crop-to-grass conversion, with the model simulating a loss while the meta-analyses indicate a gain. Excluding fire in grasslands in the model partly explains the deviation from the meta-analyses. Overall, accounting for crop harvesting substantially improves the model response to LUC.

The improved model is used to quantify the contribution of the changes in the quantity of litter inputs (input-driven) and the turnover of carbon in soils (turnover-driven) to historical changes in soil carbon. A factor separation analysis is applied to equilibrium simulations with the pre-industrial and present-day land use. On the regional level, the input-driven and turnover-driven changes vary depending on the dominant historical LUC type. A global loss of 54.0 Pg C is simulated over the industrial era: The input-driven and turnover-driven changes contribute a loss of 54.7 Pg C and 1.4 Pg C, respectively, while the synergistic effects between the two contribute a gain of 2.1 Pg C. Excluding crop and wood harvest substantially reduces the global losses through the input-driven changes. Thus less management of current ecosystems can reduce the soil carbon losses from past LUCs.

The vegetation carbon turnover time is an important parameter that determines the land-atmosphere CO_2 exchanges. Equilibrium simulations are performed to quantify the vegetation carbon turnover time of the present-day land use and a natural vegetation without land use. In line with a recent observation-based estimate, the turnover time of the natural vegetation is longer than the present-day land use by a factor of 1.82 in the tropical and 2.90 in the extratropical deforested regions. Although the turnover time of the present-day land use is shorter in all the regions with LUC, the vegetation's response time to an artificially induced CO_2 pulse is longer in the present-day land use in some regions. This analysis shows that the equilibrium turnover time is not a comprehensive indicator for the terrestrial biosphere's response to additional CO_2.

Zusammenfassung

Historische Landnutzungsänderungen haben die terrestrische Kohlenstoffsenke deutlich verändert. Diese Studie schätzt die Auswirkungen der Landnutzungsänderungen auf den Umsatz von Kohlenstoff in Böden und Vegetation mit Hilfe eines dynamischen globalen Vegetationsmodells (DGVM) ab. Beobachtungsdaten werden genutzt, um zu beurteilen, wie gut das Modell die Auswirkungen der Landnutzungsänderungen repräsentiert.

Zunächst wird ein Ansatz entwickelt, der die DGVMs gegenüber Metaanalysen aus Beobachtungsdaten für unterschiedliche Landnutzungsänderungen bewertet. Unter Nutzung des DGVM JSBACH werden idealisierte Simulationen durchgeführt, in denen die gesamte Landoberfläche mit einem Vegetationstyp bedeckt ist, der dann eine Landnutzungsänderung zu einem anderen Typ erfährt. Die Gitterzellen, die die klimatischen Bedingungen der Metaanalysen repräsentieren, werden für den Vergleich der mittleren simulierten Änderung mit den Metaanalysen ausgewählt. Die Umwandlung von Acker- in Waldfläche führt zu einem Anstieg des Bodenkohlenstoffs um 10% im Gegensatz zu einem Anstieg um 42% in den Metaanalysen, während die Umwandlung von Wald- in Ackerfläche eine Abnahme um 15% verglichen mit 40% Abnahme in den Metaanalysen bedeutet. Das Modell unterscheidet sich von den Metaanalysen für die Umwandlung von Acker- in Wiesenfläche, wobei das Modell eine Abnahme und die Metaanalysen eine Zunahme angeben. Ein Teil der Abweichung erklärt sich dadurch, dass Wiesenflächen im Modell nicht brennen können. Insgesamt verbessert sich die Reaktion des Modells auf Landnutzungsänderungen deutlich, wenn das Ernten der Ackerflächen einbezogen wird.

Das verbesserte Modell wird genutzt, um den Beitrag der Veränderungen beim Eintrag von Streu (Eintrags-bedingt) und beim Kohlenstoffumsatz im Boden (Umsatz-bedingt) gegenüber historischen Änderungen des Bodenkohlenstoffs abzuschätzen. Dazu wird eine Faktorenseparationsanalyse auf Gleichgewichtssimulationen mit vorindustrieller und gegenwärtiger Landnutzung angewendet. Auf regionaler Skala variieren die Eintrag-bedingten und Umsatz-bedingten Veränderungen in Abhängigkeit vom Typ der Landnutzungsänderung. Eine globale Abnahme von 54,0 Pg C wird für das Industriezeitalter simuliert. Die Eintrag- und Umsatz-bedingten Veränderungen tragen mit 54,7 bzw. 1,4 Pg C zur Abnahme des Bodenkohlenstoffs bei, wobei Synergieeffekte der beiden zu einer Zunahme von 2,1 Pg C führen. Wird das Ernten von Nutzpflanzen und Wald nicht berücksichtigt, verringert sich die globale Abnahme durch die Eintrag-bedingten Änderungen. Folglich kann ein geringerer Eingriff in heutige Ökosysteme den Verlust an Bodenkohlenstoff aus historischen Landnutzungsänderungen verringern.

Die Umsatzzeit des Vegetationskohlenstoffs bestimmt als ein wichtiger Parameter den CO_2-Austausch zwischen Land und Atmosphäre. Gleichgewichtssimulationen dienen dazu die Umsatzzeit des Vegetationskohlenstoffs unter heutiger

Landnutzung sowie unter natürlicher Vegetation ohne Landnutzung abzuschätzen. Übereinstimmend mit einer aktuellen beobachtungsbasierten Abschätzung ist die Umsatzzeit bei natürlicher Vegetation in den von Entwaldung betroffenen Tropen um einen Faktor 1,82 länger als unter heutiger Landnutzung, in den Extratropen ist sie sogar um einen Faktor 2,90 länger. Obwohl die Umsatzzeit unter heutiger Landnutzung in allen Regionen mit Landnutzungsänderung kürzer ist, ist die Reaktionszeit auf einen plätzlichen, künstlich erzeugten CO_2 Anstieg für die heutige Landnutzung in einigen Regionen länger. Diese Analyse zeigt, dass die Gleichgewichtsumsatzzeit des Kohlenstoffs kein allumfassender Indikator für die Reaktion der terrestrischen Biosphäre auf zusätzliches CO_2 darstellt.

Contents

Chapter 1

Introduction

In the last century, the global mean surface temperature has increased by about 0.85 °C (IPCC, 2013). This warming is associated with the increase in the green house gases concentrations in the atmosphere, mainly CO_2, with the present-day CO_2 concentrations exceeding the pre-industrial levels by about 40% (IPCC, 2013). The increase in the CO_2 concentrations is attributed to human activities of fossil fuel burning and land-use change (LUC). Not all CO_2 emissions by human activities have accumulated in the atmosphere: Of the 555 Pg C cumulative CO_2 emissions in the period between 1750 and 2011, less than half accumulated in the atmosphere (240 Pg C), with the remaining emissions taken up by the land and ocean (Ciais et al., 2013). However, LUC emissions have the largest uncertainties in the global carbon cycle (Ciais et al., 2013). As the terrestrial biosphere is not only a source but also a sink of carbon, atmospheric CO_2 concentrations affect the associated sink processes by enhancing photosynthesis in plants. Uncertainties in LUC emissions propagate in the accounting of carbon feedbacks between the atmosphere and the terrestrial biosphere. To improve future projections of the carbon cycle, and thus the climate, extensive research is still needed to understand how past LUCs have contributed in altering the terrestrial carbon sink.

The aim of this thesis is to gain a better understanding of how LUC contributes to changes in the soil carbon sink and the terrestrial carbon turnover. Before introducing the specific objectives of this study, the overall context is provided in detail by discussing (1) soils in the global carbon cycle, (2) LUC and land management effects on terrestrial carbon, and (3) the relevance of the turnover for carbon cycling.

1.1 Soils in the global carbon cycle

Soils are an important component of the global carbon cycle that contributes in regulating the atmospheric CO_2. Globally, the amount of carbon stored in soils is estimated to be about 1400 Pg C to a depth of 1 m and 2400 Pg C to a depth of 2 m (Batjes, 1996; Jobbágy and Jackson, 2001). For comparison, about 560 Pg C is stored in the vegetation biomass and about 760 Pg C is in the atmosphere. Therefore, the amount of carbon stored in soils is about three and four times as large as the amount present in the vegetation and atmosphere, respectively (Lal, 2004). In addition to carbon storage, soils are the fundamental foundation for our food security: They provide a medium for plant growth, which humans and animals depend on for their living. The decline in the quality of our soils, e.g. through carbon losses, affects different ecosystem services provided by soils, such as the provision of food production and the regulation of climate through CO_2 uptake.

The amount of carbon stored in soils is determined by the balance between the inputs of the photosynthetically derived organic matter from the plants and losses of organic carbon, through decomposition into the atmosphere, leaching and erosion (Jastrow et al., 2007). Sequestration, i.e. the process of capturing and long-term storage of atmospheric CO_2 (Sedjo and Sohngen, 2012), occurs when the inputs of carbon are larger than the outputs, while carbon losses occur when the outputs exceed the inputs. Photosynthesis and decomposition depend on climatic conditions, with decomposition being strongly influenced by edaphic factors such as the soil type and texture (Ontl and Schulte, 2012). In addition to the direct influence from environmental factors, the type of vegetation covering the Earth's surface largely determines the carbon inputs to the soil. Forest ecosystems tend to have the largest carbon inputs to the soil, often throughout the year, while the smallest inputs are found in croplands mainly during the growing seasons (Smith, 2007, 2008). The amount of soil carbon varies over time and spatially, across the different regions of the globe, depending on how the aforementioned factors change (e.g., Amundson, 2001; Scharlemann et al., 2014; Xia et al., 2010).

Given the large carbon storage potential, soils are considered to play an important role in climate change mitigation through decreasing the CO_2 emissions in the atmosphere. For example, in the recent 2015 Conference of Parties in Paris, the *"4 per 1000 Initiative: Soils for Food Security and Climate"* was launched with the aim of achieving an annual 0.4% increase in the global soil carbon content (Ademe, 2015; Minasny et al., 2017). Such an increase in soil carbon storage could potentially help limiting the average global temperature increase to the 2°C threshold (IPCC, 2014). Although a saturation of the soil carbon sink may limit its future sequestration potential (e.g., Sommer and Bossio, 2014), small positive changes in the current soil carbon sink still have a great potential to reduce the CO_2 emissions in the atmosphere (Paustian et al., 2016). However, carbon releases from soils contribute to increasing CO_2 concentrations in the atmosphere. Therefore, it is important to fully understand how different processes and forcing within the Earth system influence the evolution of the soil carbon sink.

Measuring changes in the amount of soil carbon is difficult because the carbon densities vary a lot spatially (Liski, 1995). Therefore, models are useful for quantifying and understanding changes in the soil carbon sink caused by external drivers. Since the 1980s, soil carbon models such as RothC, CENTURY and YASSO, have been widely used for understanding the dynamics of soil carbon in agricultural lands, grasslands and forests (Parton et al., 1988; Coleman and Jenkinson, 1996; Liski et al., 2005). These models are mainly applied at the local-scale or at regional levels, with the input-data, e.g. climate and soil properties, constrained based on the study region. The need to understand the effects of environmental changes on the terrestrial ecosystem led to the integration of soil carbon models in global vegetation models (GVMs). Consequently, GVMs have been used in understanding how climate change, CO_2 increase and LUC influence the terrestrial carbon balance (e.g., McGuire et al., 2001; Cramer et al., 2001; Eglin et al., 2010). Several GVMs can be coupled to General Circulation Models (GCMs), enabling the understanding of the climate-carbon cycle feedbacks (Friedlingstein et al., 2006; Arora et al., 2013). Despite the efforts made in understanding soil carbon dynamics, past and future changes of this sink remain a major source of uncertainty in the global carbon cycle and climate projections (Jones et al., 2003; Friedlingstein et al., 2003; Todd-Brown et al., 2013, 2014).

1.2 LUC and land management - definition and their effects on terrestrial carbon

Humans have drastically altered the land surface of the Earth, with about 30-50% of the land cover being transformed in different ways (Vitousek et al., 1997). One of the most visible forms of this transformation is *land-use change* (LUC), which denotes the human-induced change in the type of land use. Land use involves the use, management and modification of the land resources to fulfill different human needs. For example, croplands are cultivated, fertilized and harvested for food production while forests are harvested to obtain wood for constructing houses and producing furniture. Therefore, LUC broadly describes two things: the change in the type of land cover, e.g. forest to crop, and the change in the use and management of the land cover. While LUC always results in the replacement of land cover, land management practices lead to alterations in the terrestrial biosphere even without changes in the land cover type.

Extensive evidence exists on the human-induced alterations of the land cover. Statistics from the Food Agricultural Organization (FAO) show that about 10 million km^2 of forests, which is about 25% of the area covered by forests today, were deforested in the period between 1800 and 2010 (FAO, 2012). Furthermore, substantial grassland areas have been converted to croplands and pastures (Ramankutty et al., 2008). Studies show that the observed decline in the natural vegetation began even before the pre-industrial period (e.g., Pongratz et al., 2008). Although recent reforestation efforts may have reversed the trend in the temperate regions (e.g., Gold, 2003), FAO statistics indicate that an average of 0.084 million km^2 of forests are being deforested annually since 1990, with a cumulative loss of 3.1% of the global forest area between 1990 and 2015 (FAO, 2015). At present, there exists about 15 million km^2 of croplands and 34 million km^2 of pastures (Ramankutty et al., 2008; FAOSTAT, 2015). In addition to the expansion of agricultural and pasture land, 42%-58% of the ice-free land surface is managed by humans in different ways (Luyssaert et al., 2014). The most dominant forms of land management include; forestry, grazing and crop harvesting (Erb et al., 2016b). These large-scale modifications of the Earth's land cover, through LUC and land management, have a large influence on the terrestrial carbon cycle.

LUC influences the amount of carbon stored in the vegetation and soil. The expansion of agricultural lands results in the release of the carbon stored in the vegetation in forests and grasslands, which occurs mainly through burning. Compared to forests, croplands and pastures have less vegetation biomass; thus the clearing of forests results in a decline of the vegetation's carbon storage capacity (e.g., Pongratz et al., 2009), leading in turn to decreases in the organic matter inputs to soils. Furthermore, the different land management activities have direct impacts on terrestrial carbon. For example, tillage in undisturbed natural lands enhances decomposition, with studies showing that up to 30%-50% of soil carbon in these lands can be lost during the initial cultivation (e.g., Mann, 1986; Davidson and Ackerman, 1993). Any land management practice that contributes in the reduction of aboveground vegetation biomass results in a depletion of the organic matter inputs to the soils. Wood harvesting generally reduces the standing biomass in the vegetation. Much of cropland produces are removed for food and animal feeds and grazing reduces the aboveground biomass in the vegetation (references in Erb et al., 2016b). Recent studies demonstrate the importance of including land management processes in accounting for historical LUC emissions, because omitting these processes results in a substantial underestimation of human impacts on the Earth system (Stocker et al., 2014; Pugh et al., 2015; Arneth et al., 2017).

Modelling studies provide estimates of terrestrial carbon changes caused by historical LUC. Based on a compilation of these studies, historical LUC activities resulted in emissions of 1.5($\pm$0.9) Pg C/ yr in the 90s and 1.5($\pm$1.0) Pg C/ yr from 2000-2011 (Ciais et al., 2013). These emissions stem from direct releases of CO_2 from clearing and replacing vegetation and the indirect soil carbon losses, which continue for a long time after LUC. Cumulatively, the net CO_2 losses from the terrestrial ecosystems to the atmosphere from LUC amount to 180($\pm$80) Pg C in the period between 1750 and 2011 (Ciais et al., 2013). In the same period, terrestrial ecosystems that were not affected by LUC accumulated 160(±90) Pg C of the anthropogenic CO_2 emissions. One of the main factors contributing to the increased storage is the enhanced photosynthesis of plants at high CO_2 levels. However, as indicated by the 90% confidence intervals in the parenthesis, emissions of LUC are highly uncertain. One of the major sources of these uncertainties stems from the carbon fluxes from soils. Table 1.1 shows that model estimates of soil carbon changes from LUC are highly uncertain.

In order to improve future projections of terrestrial carbon changes, we need to tackle the current model uncertainties in the soil carbon changes from past LUCs. Two major aspects of research have to be addressed: First, the response of soil carbon to different LUCs in models needs to be evaluated using observations, and second, an understanding of how model processes influence soil carbon dynamics after LUC is required. Addressing these issues is a key aspect in narrowing down the uncertainties in the historical LUC emissions. The first two parts of the study presented here focus on these aspects (see section 1.4).

Table 1.1: Global changes in soil carbon simulated by different DGVMs.

Reference	Time period	Model Name	Soil carbon changes (Pg C)
Goll et al. (2015)	1750-2005	JSBACH	-17
Tian et al. (2015)	1901-2010	BIOME-BGC	-7.2
		CLM	-2
		DLEM	-10
		GTEC	-100
		ISAM	-60
		LPJ	-50
		ORCHIDEE	-15
		VISIT	-45
-	-	Model range	-2 to -100

1.3 The relevance of the turnover for carbon cycling

The *turnover time* of the terrestrial biosphere can be defined as the average time elapsed between the incorporation of carbon through photosynthesis and its release back to the atmosphere through respiratory or non-respiratory processes (Barrett, 2002). Mathematically, the turnover time is expressed as the ratio of the quantity of carbon in a given pool to the outgoing or incoming fluxes, assuming that the system is in steady state. From this mathematical formulation, we can infer that the longer the turnover time the larger the capacity of the terrestrial biosphere to sequester carbon is for a given carbon influx (Luo et al., 2003). The turnover time is normally estimated from the carbon densities and carbon fluxes (e.g., Carvalhais et al., 2014; Erb et al., 2016a). The terrestrial carbon turnover time is closely connected to climatic factors such as precipitation and temperature (Carvalhais et al., 2014). Due to the different amount of carbon stocks and carbon fluxes, vegetation and soils have different turnover times. Furthermore, the processes influencing the carbon dynamics in these two components act on different time scales.

The carbon uptake, allocation and respiration as well as natural disturbances act together in determining the turnover time of carbon in the terrestrial biosphere (Bloom et al., 2016). LUC and land management contribute in changing the turnover time through their direct influence on these factors. The replacement of natural forests with croplands, harvesting and grazing reduces the vegetation carbon stocks, which shortens the carbon turnover time (Erb et al., 2016a). Due to changes in the type of litter, the turnover rates of soil carbon are usually accelerated following the conversion of forests to croplands, with this acceleration further exacerbated by tillage in croplands (Mann, 1986; Davidson and Ackerman, 1993). The decline the soil carbon stocks and the increase of decomposition fluxes contribute in shortening the turnover time of soil carbon. Given the large-scale extent of LUC and land management (see section 1.2), we need to closely examine their effects on the terrestrial carbon turnover time. The last part of the present-study will address this aspect (see section 1.4)

1.4 Research objectives

The aim of this thesis is to gain a better understanding of how LUC contributes to changes in the soil carbon sink and the terrestrial carbon turnover. I approach this mainly from a modelling perspective, using the dynamic global vegetation model (DGVM) JSBACH, while complementing the results with observational datasets to assess if the model correctly represents the LUC effects. The focus of this study lies on the investigation of past effects of LUC. The specific objectives and the research questions for the individual chapters are presented below. A brief motivation is provided before outlining the research questions.

- **Provide a framework for evaluating DGVMs against the existing meta-analyses of soil carbon changes for different LUCs and apply the framework to evaluate JSBACH.**

As shown in section 1.2, soil carbon changes caused by historical LUC are highly uncertain. To reduce the uncertainties in soil carbon changes models have to be evaluated as reliable data sets become available (Luo et al., 2016). Local-scale field experiments provide the basis of our understanding on how LUC and management impacts on soil carbon dynamics (Smith et al., 2012a). In the recent years, dozens of these studies have been published in the literature either as single studies, for specific locations, or as a compilation of many local studies in the form of *"meta-analyses"* covering larger spatial scales (e.g., Don et al., 2011; Poeplau et al., 2011). These meta-analyses represent the changes in soil carbon associated with most of the LUC types that have occurred in the historical period. However, for the meta-analyses to be applied in model evaluation, we need a proper framework for model-data comparison.

In **chapter 2** a framework for evaluating DGVMs against meta-analyses is developed and applied to the DGVM JSBACH. The following research questions are investigated:

1. How can the available meta-analyses on changes in soil carbon due to different LUCs be used in evaluating DGVMs?
2. What does the model-data comparison reveal for the DGVM JSBACH?
3. What are the challenges involved in comparing DGVMs against the meta-analyses?

- **Quantify the contribution of changes in litter inputs and soil carbon turnover to the total soil carbon changes from historical LUC.**

A decline in the soil carbon sink can be attributed to two factors: (1) the decrease in the organic matter inputs to the soils and (2) the increase in the soil carbon turnover mainly through enhanced decomposition. Many past studies have quantified the soil carbon losses caused by historical LUC (Houghton, 2003b; Reick et al., 2010; Hansis et al., 2015; Tian et al., 2015). However, it is not known how the above factors contribute to these losses. While the effects of LUC and land management on soil carbon inputs are well known, their effects on the turnover of carbon are less understood. About 20-40% of the terrestrial net primary productivity is utilized by humans (Vitousek et al., 1986; Imhoff et al., 2004; Haberl et al., 2007). This decreases the vegetation biomass, leading to a decline in the organic matter inputs to the soils. If we want to increase our understanding of the sequestration potential of soils, we need a comprehensive assessment of the individual contributions of these two controls (input versus turnover) to historical soil carbon losses. However, the quantitative estimates of changes in soil carbon obtained through local-scale measurements and the meta-analyses are composed of the overall effects resulting from both the contribution of the turnover and the inputs. With the application of factor separation analysis models can be used for assessing the relative contribution of these controls to the total soil carbon changes.

In chapter 3, I use the DGVM JSBACH to quantify the contibution of both litter inputs and turnover changes to historical soil carbon changes caused by LUC. The following research questions are investigated:

1. How have the input-driven and turnover-driven controls contributed to the historical changes in soil carbon caused by LUC in simulations with the DGVM JSBACH?

2. How are the input-driven and turnover-driven controls influenced by land management through crop and wood harvesting?

- **Quantify the LUC-induced acceleration in the vegetation and soil carbon turnover time and assess the effect of this acceleration on the vegetation's response to additional CO_2.**

A recent observations-based study showed that the vegetation's carbon turnover time has accelerated due to the decline in natural vegetation and the current intensive management of the Earth's land cover (Erb et al., 2016a). However, as this study did not include soils, a comprehensive assessment of the total effects of LUC on the terrestrial carbon turnover time is still lacking. Given that the turnover time plays an important role in influencing the carbon sink (see section 1.3), an acceleration in the turnover time may change the transition time of carbon in the terrestrial biosphere. Therefore, in addition to quantifying the LUC-induced acceleration in the carbon turnover time, we also need to investigate the impact of this acceleration on the temporal development of carbon within the terrestrial biosphere.

In **chapter 4**, I apply the DGVM JSBACH to quantify the acceleration in the vegetation and soil carbon turnover time. In addition, I analyse the temporal development of carbon in two vegetation distributions differing in their equilibrium turnover time. The following research questions are investigated:

1. How strong is the LUC-induced acceleration in the soil and vegetation carbon turnover time in the DGVM JSBACH?

2. How does the turnover acceleration affect the vegetation's response to additional NPP resulting from an increase in CO_2 increase?

1.5 Formal remarks on the thesis structure

The next three chapters of my thesis are written in the style of scientific journal contributions. Thus they can be read independently of one another. Nevertheless, chapter 3 builds upon chapter 2 as DGVMs can only be useful for understanding the factors contributing to the historical changes in soil carbon after evaluating their simulated soil carbon response to LUC. Chapter 4 includes an assessment of the LUC effects on both the vegetation and soil carbon turnover, facilitating a comparison of the turnover effects in the two components. Chapter 2 has been published in the *Journal of Biogeosciences* (Nyawira et al., 2016) and chapter 3 is published in *Environmental Research Letters* (Nyawira et al., 2017). For consistency, these chapters are reproduced here with some minor editorial changes. Chapter 5 provides a summary of the major findings for my thesis and discusses the implications of these findings for terrestrial carbon modelling.

Chapter 2

Soil carbon response to land-use change: evaluation of a global vegetation model using meta-analyses[1]

2.1 Introduction

Global model estimates of land-use-related soil carbon changes rely on dynamic global vegetation models (DGVMs). To judge the reliability of DGVMs in simulating past and future changes of soil carbon, models have to be evaluated against observations. A range of meta-analyses on soil carbon changes following land-use change (LUC) has been published recently, aggregating local-scale measurements to spatial scales potentially applicable to DGVMs (e.g., Guo and Gifford, 2002). In this chapter, an approach for evaluating DGVMs against the observational data is developed.

A major driver of soil carbon changes in recent centuries has been LUC. For example, the replacement of natural vegetation with croplands usually leads to soil carbon loss while the reverse leads to a gain (Guo and Gifford, 2002). Unlike for vegetation, soil dynamics include slower processes ranging from decadal to centennial timescales; hence the carbon response to LUC lags the changes in vegetation carbon. Soil carbon changes due to LUC are caused by changes in soil carbon inputs and outputs when one vegetation type is replaced by another. Changes in soil carbon inputs stem from differences in litter quality and quantity, while the changes in outputs stem from

[1]**Sylvia S. Nyawira**, Julia E. M. S. Nabel, Axel Don, Victor Brovkin, and Julia Pongratz (2016): Soil carbon response to land-use change: evaluation of a global vegetation model using observational meta-analyses. Biogeosciences., **13**, 5661–5675.

alteration of soil decomposition processes that govern stabilisation of carbon in soils. The response of soil carbon to LUC depends on the local conditions, such as soil type, mineralogy and texture (Lugo et al., 1986) and on climate influences, such as temperature and soil moisture or precipitation (Marín-Spiotta and Sharma, 2013). Also, management practices can influence the soil carbon response; for example, Poeplau and Don (2015) showed that planting cover crops during winter and tilling them into the soil as additional carbon input can significantly enhance soil carbon on croplands. Due to the slow response of soils to LUC, soil carbon changes from past LUCs continue to have a long-term effect on the global carbon budget (Pongratz et al., 2009).

Despite the dependence of the soil carbon response to local conditions of soils, climate and management practices, regional and global syntheses of published data can be useful to aggregate local-scale measurements on soil carbon changes and estimate mean responses to different LUCs using a meta-analyses approach. Over the recent past, several of these meta-analyses have been published . An advantage of the meta-analyses is that they apply several quality checks to combine and aggregate the local-scale measurements. The meta-analyses provide estimates of the average magnitudes of relative and absolute changes and additionally the temporal response of soil carbon to LUC (Poeplau et al., 2011; Poeplau and Don, 2015). These analyses have also been used to understand the factors influencing the spatial and temporal variability of soil carbon changes following LUC. This has been done by correlating variables such as temperature, precipitation and clay content with the soil carbon changes (Don et al., 2011; Wei et al., 2014). However, the applicability of this observational data for global modeling has not been tested so far.

DGVMs are used to study the effects of LUC on soil carbon globally. They combine information on the past vegetation distribution, climate and LUC data and incorporate various processes to quantify global changes in terrestrial carbon stocks resulting from past LUCs (e.g. Pongratz et al., 2009; Stocker et al., 2011). In addition, by simulating climate and LUC scenarios following the RCPs, DGVMs are used to make future projections in terrestrial carbon stocks (e.g. Brovkin et al., 2013). However, global estimates of LUC carbon fluxes by different DGVMs show a large spread (Ciais et al., 2013). This spread has been attributed to several factors: the different climate used in driving the DGVMs (Anav et al., 2013), different modeling approaches of LUC (Houghton et al., 2012; Wilkenskjeld et al., 2014), inconsistent definition of land-use fluxes (Pongratz et al., 2014), parameterizations related to fluxes of land-use and land cover change (Brovkin et al., 2013; Goll et al., 2015) and land-management processes (Houghton et al., 2012). In a recent study, Tian et al. (2015) used the same model setup, with the same climate and LUC input data, to quantify global changes in soil carbon resulting from past LUCs across different DGVMs. They found that these changes differ widely across the models with some models showing almost no change and others showing a large decrease in soil carbon.

Until now, soil carbon changes resulting from different LUCs in DGVMs have not been compared to observational data compiled by the different meta-analyses. This is because an approach for comparing these changes to the meta-analyses is still lacking and many of the meta-analyses have only become available relatively recently. This chapter of my thesis aims at developing an approach that can be applied to any DGVM for evaluating the soil carbon changes for different LUCs against the meta-analyses. The applicability of the approach is tested using the standard version of the DGVM JSBACH. The causes of model discrepancies from the meta-analyses are identified using different sensitivity simulations. Further, I highlight the challenges involved in comparing simulated results to the meta-analyses and suggest what can be done to overcome these challenges.

2.2 Methods

2.2.1 Meta-analyses

This study uses results from the meta-analyses by Poeplau et al. (2011) in the temperate regions and Don et al. (2011) for the tropical regions including 95 and 385 published studies, respectively. The published studies include sites from different countries in the tropics and temperate regions. The site studies were conducted using two main experimental designs: paired plots comparing soil carbon between two adjacent sites with different land use types, and time series where the soil carbon of a particular site was monitored overtime after LUC. The paired plot approach is used to construct chronosequences comprising of plots with different ages after LUC that use one of the plots as the reference site. The paired plot based approach goes along with a higher methodological uncertainty in the data due to differences in the inherent soil properties such as texture between the plots, which affect the response of soil carbon to LUC. In contrast, the time series observational data are without such uncertainties, but very few time series are available to investigate the response of soil carbon to LUC. In calculating the soil carbon changes across the different sites, the reference site is always assumed to be in equilibrium.

The meta-analyses defined the following criteria for including the site studies: (1) climate conditions, age of the current land use, and the relevant site characteristics such as soil type, texture and land-use history had to be provided, (2) studies on organic and wetland soils were not included and (3) for paired plots the sites had to be adjacent to each other to reduce uncertainties due to the spatial variability of soil properties unrelated to the LUC (Don et al., 2011; Poeplau et al., 2011). Any studies that did not match any of the criteria were excluded in the compilation. The soil bulk densities were used to calculate the soil organic carbon. Mass correction was applied to account for changes in density with depth (Ellert and Bettany, 1995). In addition, Poeplau et al. (2011) used different variables, such as climate, time after LUC and the clay content, to derive carbon response functions (CRFs) describing the temporal response of soil carbon to LUC for the temperate regions. The response functions include general CRFs that account for only time after the LUC and specific CRFs that account for other site properties. Table 2.1 shows the LUCs represented in the two meta-analyses that are included in this study.

Table 2.1: Mean annual temperature (MAT) range, mean annual precipitation (MAP) range, mean sampling depths (± std) and the mean current land-use age for the local-scale observations in the meta-analyses. Note that the different equilibrium results presented below, e.g., for crop in the crop to forest LUC and the forest to crop LUC, are due to the different climate-criterion (precipitation and temperature) for the different LUCs.

Land-use change	MAT (°C)	MAP (mm)	Sampling depth (cm)	Age (years)
Crop to forest (temperate)	5.9–10.7	540–1020	39.53±24.8	40.28
Crop to grass (temperate)	6.7–11.2	440–1030	23.44±10.5	21.7
Forest to crop (temperate)	3.4–16.4	690–1320	28.48±13.5	50.21
Grass to crop (temperate)	1–12.7	150–960	27.11±11.1	39.69
Forest to crop (tropics)	15–27.5	570–3400	17.5±12.81	22.5
Forest to pasture (tropics)	18–28	570–4000	15.79±11.55	20.67

2.2.2 Carbon cycle model in JSBACH

The DGVM JSBACH (Raddatz et al., 2007; Reick et al., 2013), the land surface model of the Max Planck Insitute Earth System Model (Giorgetta et al., 2013), was applied in this study. Vegetation distribution in JSBACH is represented with 12 plant functional types (PFTs), of which 8 are natural types (4 forest types, 2 shrub types, 2 grass types (C3 and C4)), and 4 are anthropogenic types (C3 and C4 pastures and crops). The PFTs differ with respect to their phenology, albedo and photosynthetic parameters; photosynthesis is based on Farquhar et al. (1980) for C3 plants and Collatz et al. (1992) for C4 plants. The carbon cycle model in JSBACH describes the carbon allocation, the storage in the vegetation and soils, and losses through respiration and natural disturbances. For each PFT, the net primary production (NPP) is allocated to three vegetation carbon pools: the "green pool" containing living tissues, the "reserve pool" containing sugar and starches and the "wood pool" containing woody material. Each of these pools has different turnover rates, influenced by a background natural mortality and foliage losses due to seasonal and climatic influences. The carbon lost from the vegetation pools via turnover goes into the soils in form of litter where it is decomposed. Following LUC, a fraction of the vegetation carbon goes into litter and the other is released directly to the atmosphere. Additionally, carbon can be lost from the vegetation and soil through disturbances in the form of fire and windthrow.

Decomposition of litter in JSBACH is simulated by the YASSO model. YASSO is calibrated globally based on results from litter bag experiments (Tuomi et al., 2008, 2009, 2011) and has been evaluated on site to regional scale (Karhu et al., 2011; Thum et al., 2011; Lu et al., 2013). Decomposition of litter is distinguished in terms of the solubility of litter in four different compounds (acid, water, ethanol and non-soluble hydrolysable pools) and an additional slow decomposing humus pool. Each of these pools has a different decomposition rate derived from the litter bag experiments. The heterotrophic respiration depends on temperature based on a Gaussian model (Tuomi et al., 2008) and on precipitation based on an exponential function (Tuomi et al., 2009). For all PFTs non-woody litter has the same decomposition rates, while the decomposition of woody litter depends on the woody diameter. Additionally, litter is split into aboveground and belowground, where the aboveground litter burns while belowground litter does not. All the litter pools–aboveground are belowground–and the humus pool are summed up in obtaining the total soil carbon. YASSO shows a better correlation of present-day carbon stocks with the Harmonized World Soil Data Base compared to JSBACHs' previous soil model CBALANCE (Goll et al., 2015). YASSO has been shown to have a lower sensitivity to some uncertain model parameterizations such as the fraction of carbon lost to the atmosphere following LUC (Goll et al., 2015). A detailed description of the implementation of YASSO can be found in Thum et al. (2011) and in Goll et al. (2015).

2.2.3 Simulation setups

2.2.3.1 Idealized simulation approach

I performed idealized LUCs where the entire land surface was covered by one vegetation type, which was subsequently transformed to another type. The idealized simulations approach prevents interference of soil carbon changes that occur due to different types of LUCs occurring simultaneously in a grid cell or due to sequences of LUC over time. Such interferences occur in realistic LUC simulations. Here, most grid cells in the globe contain a mixture of different vegetation types and at a given year different LUCs may occur. For example, part of the forest in a grid cell may be converted to crop and at the same time part of the grass be converted to crop. Many DGVMs do not separate the soil carbon for the different PFTs and have one soil carbon pool for all the PFTs. Those that separate the soil carbon, e.g. JSBACH, typically add the soil carbon of the old PFT to the new PFT after LUC. Therefore, soil carbon change resulting from a specific LUC cannot be obtained using such realistic simulations. The idealized simulations approach used in this study ensures that starting with equilibrium soil carbon from one land use then changing to another land use, the resulting soil carbon change can be associated with the specific LUC.

Idealized land cover maps for four vegetation types; forest, crop, grass and pasture were created. In these cover maps the entire globe was covered by each of the four vegetation types. The regions where one of these vegetation types does not exist were masked out in our comparison of simulated results to the meta-analyses (see section 2.2.4). Each land cover map consisted of several PFTs: The forest land cover contained evergreen and broadleaf PFTs in the tropical and extratropical regions, while crop, grass and pasture land cover contained both C3 and C4 PFTs. The idealized land cover maps were created starting with a present day JSBACH land cover map obtained by remapping observed vegetation distribution into PFTs (see section A.1). In the grid cells where two PFTs belonging to the same vegetation type already existed, e.g., in a grid cell with both tropical deciduous and tropical evergreen from observed vegetation distribution, the cover fraction was scaled to the entire grid cells based on their relative distribution.

2.2.3.2 Standard simulation with JSBACH forcing

The carbon cycle model in JSBACH can be executed as part of the entire vegetation model or as a stand-alone model isolating the actual carbon cycle simulation from the simulation of other processes, such as photosynthesis and hydrological processes. In the stand-alone mode, the model is driven by net primary production (NPP), leaf area index (LAI), disturbances drivers, precipitation and 2 m air temperature together with the vegetation distribution. This setup has the advantage that the model can be run for centennial to millennial timescales at low computational costs.

To obtain the inputs for the carbon sub-model, idealized land-use simulations with JSBACH with each of the four created land cover maps (forest, crop, grass and pasture) were performed. In each of these simulations JSBACH was driven with observed climate from the climate research unit (CRU) for the years 2001 to 2010 (Harris et al., 2014). In a second step, the carbon sub-model was run using the NPP, LAI and the disturbances drivers obtained from the JSBACH simulations, together with precipitation and temperature from CRU, which are required as forcing for YASSO. The model was run until the soil carbon pools reached equilibrium for each of the four land covers. The total soil carbon in YASSO was considered to be in equilibrium when the relative change in soil carbon from one year to the next in the grid cell became less than 1%.

To perform the LUCs in Table 2.1, starting from the obtained equilibrium state for each land cover, I used the JSBACH land use transition matrices as described in

Reick et al. (2013). The transition matrix was modified to have only one LUC in all the grid cells in the entire globe at the first simulation year with no other LUC transitions during the rest of the simulation time. The distribution of PFTs for the target land cover map was taken from the idealized land cover maps described before, with the exception that the LUC transition to pasture assumed an equal distribution of C3 and C4 pastures (following the default JSBACH assumptions). These simulations represent the standard model version results.

2.2.3.3 Sensitivity simulation with observed NPP and LAI

Vegetation productivity as simulated by JSBACH has been shown to be higher as compared to observations (Anav et al., 2013; Todd-Brown et al., 2013). Additional simulations were performed where the NPP and LAI simulated by JSBACH was replaced with observations. This set of simulations served two purposes: to assess if the model bias in vegetation productivity has an effect on the soil carbon response to LUC and to obtain soil carbon response that is more representative of the observational data in the meta-analyses. In these simulations, I used gross primary production (GPP) obtained by extending flux net tower measurements using machine learning algorithms and LAI obtained from MODIS satellite (Tramontana et al., 2016). The global vegetation classification used for the GPP and LAI data is not the same as the PFTs classification used in DGVMs. The GPP and LAI was remapped into JSBACH PFTs; subsequently the NPP was derived from GPP (see section A.1). The model NPP and LAI was replaced with the remapped ones and the model was run to equilibrium for the different land cover maps and LUCs.

2.2.3.4 Sensitivity simulations including crop harvesting and excluding fire

To account for the influence of crop harvesting in the model, I introduced a crop harvesting scheme similar to what has been previously done in other DGVMs (Shevliakova et al., 2009; Bondeau et al., 2007; Stocker et al., 2011; Lindeskog et al., 2013). A harvest pool for the crops was introduced where the harvest decays to the atmosphere within a timescale of one year. This is in contrast to the earlier model version, where all material harvested from crops is transferred to the litter. In the grid cells with an explicit growing season, harvesting was done at the end of the growing season. In the grid cells without an explicit growing season, as occurs in the humid tropics, harvesting was done constantly throughout the year, imitating that each grid cell contains many individual fields that are harvested at different points in time. 50% of the harvest went into the harvest pool, while the rest went to the litter pool. The choice to transfer 50% to the litter was approximated from the average root to shoot ratio of several crop types (Extended data, Fig. 2, in Gray et al., 2014). The 50% accounts for root biomass, unharvestable parts of the stem biomass being left in the field and a potential return of carbon to soil in the form of manure.

Additional simulations were performed to test the sensitivity of the simulated soil carbon changes to fire. As discussed in section 2.4.2.2, in the standard setup of JSBACH fire affects natural grasslands but not pastures and croplands. The sensitivity simulations excluded fire on natural grasslands as well. Table 2.2 summarizes the simulations performed in this study and the names used to represent the respective simulations.

Table 2.2: A summary of the different simulations in this study.

Simulation name	NPP& LAI	Land-use change	Disturbances	Crop harvest
jsb_drvn	Simulated by JSBACH	crop to forest, forest to crop, crop to grass, grass to crop, forest to pasture	on	none
t16_drvn	Prescribed from observations	crop to forest, forest to crop, crop to grass, grass to crop	on	none
jsb_drvn_harv	Simulated by JSBACH	crop to forest, forest to crop, crop to grass, grass to crop	on	included
jsb_drvn_nofire	Simulated by JSBACH	crop to grass, grass to crop	off	none

2.2.4 Model-data comparison approach

The idealized simulations represent the soil carbon changes for the entire vegetated areas, including regions where LUC does not take place. Therefore, a criterion for selecting the model regions to consider in the comparison to the meta-analyses is needed. I selected the regions in the model based on two different criteria: climate and LUC applied independently. For the climate-criterion, the grid cells that fulfilled the precipitation and temperature range represented by the meta-analyses in Table 2.1 were selected. Previous studies found that the soil carbon response to LUC varies spatially due to many factors, among them precipitation and temperature (Don et al., 2011; Wei et al., 2014; Marín-Spiotta and Sharma, 2013). Therefore, the climate-criterion excluded grid cells with different climatic conditions from the meta-analyses, which have potentially different response to LUC. To assess if the regions obtained using the climate-criterion are representative of regions where the specific LUC has occured historically, I selected other regions using the differences between present-day and historical land cover in JSBACH. In these case, the grid cells where more than 10% of the specific vegetation type within the grid cell has undergone LUC were selected. The results shown in section 2.3 are averages over the climate-criterion-based regions. A comparison of the simulated changes for these two criteria is also included.

Two variables were used in comparing the simulated results to the meta-analyses; the relative and absolute soil carbon changes. The absolute soil carbon changes were calculated by subtracting the soil carbon of the previous land use from the soil carbon of the current land use. The relative changes were then calculated with respect to the previous land use. Additionally, I used the generalized CRFs derived from the meta-analyses in Poeplau et al. (2011) to compare the simulated transient response with the meta-analyses. In this case, only the CRFs with high model efficiency for the crop to grass and crop to forest LUCs were used.

The measurements for the individual observations contained in the meta-analyses are done at different ages following LUC. Therefore, the observations may not be in equilibrium for the current land use. To account for this, the simulated changes in soil carbon were sampled over the ages represented in the meta-analyses, which makes a direct comparison of the simulated and the observed soil carbon changes more appropriate. For this I used the age represented by each site in the meta-analyses to select the transient years in the simulations to include in averaging the soil carbon response. The soil carbon response was averaged over these years and spatially for the selected regions. This average represents the simulated soil carbon response over the different ages in the meta-analyses. In section 2.3.2, I show both the simulated equilibrium relative and absolute changes and the changes obtained by sampling over the ages represented by the meta-analyses.

2.3 Results

2.3.1 Soil carbon densities for previous and current land use

Before comparing the simulated changes in soil carbon against the meta-analyses in the next section, I present an assessment of the soil carbon densities prior to LUC. The mean soil carbon densities in the meta-analyses are compared to the soil carbon densities for different ecosystems used in bookkeeping models and compiled by the Intergovernmental Panel on Climate Change. For the temperate regions, the previous land use mean soil carbon of 14.7 kgC m^{-2} for the forests in the meta-analyses (Table 2.3) is slightly higher than the 13.4 kgC m^{-2} for the undisturbed forest in Houghton et al. (1983), but much higher than the 9.62 kgC m^{-2} in Watson et al. (2000). However, most carbon densities are lower than earlier estimates, such as for tropical forests: 11.7 kgC m^{-2} (Houghton et al., 1983) and 12.27 kgC m^{-2} (Watson et al., 2000); temperate grassland: 18.9 kgC m^{-2} (Houghton et al., 1983) and 23.6 kgC m^{-2} (Watson et al., 2000); and cropland 6-9 kgC m^{-2} (Houghton et al., 1983) and 8 kgC m^{-2} (Watson et al., 2000). A key reason for the lower carbon densities is the limited sampling of only the top-soil in the sites of the meta-analyses (Table 2.1), while the soil carbon densities for the different ecosystems in

Table 2.3: Mean simulated equilibrium soil carbon densities at the model depth (100 cm) and the mean carbon densities of the meta-analyses in kgC m^{-2} for previous and current land use in the different LUCs and simulations (±std). The meta-analyses soil carbon densities represent the mean over sites with different measuring depths.

Land-use change	meta-analyses		t16_drvn		jsb_drvn		jsb_drvn_harv	
	Previous	Current	Previous	Current	Previous	Current	Previous	Current
Crop to forest (temperate)	6.8±3.1	9.3±5.1	7.2±1.7	15.4±5.5	10.1±2.9	16.9±6.4	6.0±2.9	16.9±6.4
Crop to grass (temperate)	4.6±2.1	6.1±2.6	7.4±1.7	6.0±2.1	9.5±2.6	8.6±2.8	5.6±2.6	8.6±2.8
Forest to crop (temperate)	14.7±5.3	8.0±2.7	13.4±5.1	6.1±1.7	16.5±5.4	8.4±2.7	16.5±5.4	5.0±1.8
Grass to crop (temperate)	11.5±6.7	8.3±5.6	6.2±2.1	8.3±2.9	8.4±3.9	9.8±4.7	8.4±3.9	5.7±2.8
Forest to crop (tropics)	6.4±3.9	3.7±2.3	10.1±2.4	2.7±1.1	11.4±4.3	4.8±1.7	11.4±4.3	2.7±1.1
Forest to pasture (tropics)	3.7±2.8	3.9±2.6	-	-	11.4±4.1	5.8±1.8	11.4±4.1	5.8±1.8

Houghton et al. (1983) and Watson et al. (2000) are up to a depth of 1 m.

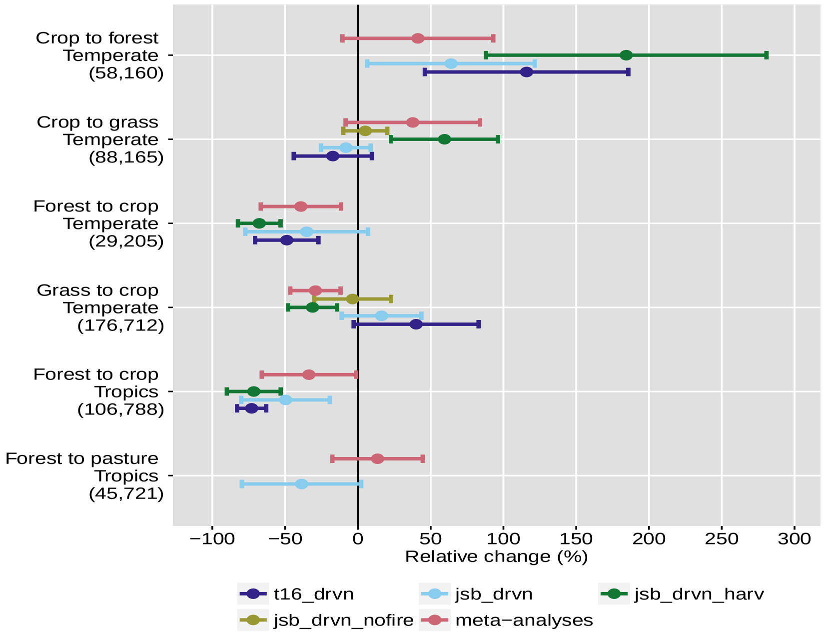
Table 2.4: Mean annual NPP for previous and current land use in kgC m^{-2} for the different LUCs and simulations (± std).

Land-use change	t16_drvn		jsb_drvn	
	Previous	Current	Previous	Current
Crop to forest (temperate)	0.42±0.10	0.73±0.24	0.58±0.15	0.90±0.34
Crop to grass (temperate)	0.43±0.09	0.41±0.14	0.57±0.15	0.63±0.17
Forest to crop (temperate)	0.77±0.26	0.44±0.12	1.04±0.34	0.58±0.14
Grass to crop (temperate)	0.32±0.11	0.34±0.12	0.48±0.24	0.44±0.23
Forest to crop (tropics)	1.21±0.28	0.35±0.10	1.42±0.60	0.69±0.22
Forest to pasture (tropics)	-	-	1.46±0.59	0.87±0.20

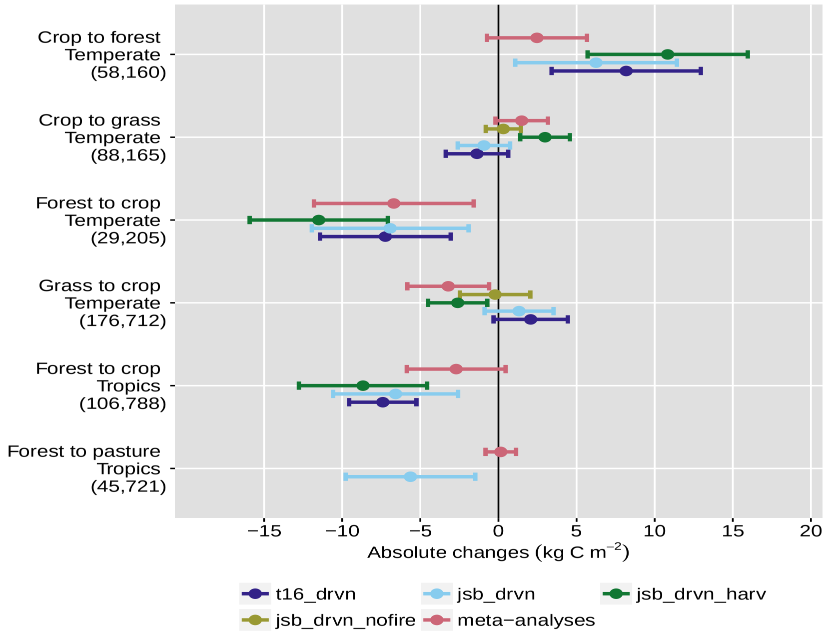
The soil carbon densities in Table 2.3 obtained at the model simulation depth are much higher compared to the meta-analyses. The lower carbon densities in the meta-analyses are again due to sampling only the top soils. Moreover, the model is in equilibrium for each of the considered land use while the local-scale measurements are done at different times. The average soil carbon densities for the previous land use in the jsb_drvn simulation are higher than in the t16_drvn simulation for all the LUCs (Table 2.3). The higher soil carbon densities result from the generally higher NPP in the jsb_drvn simulation compared to the t16_drvn simulation (Table 2.4), which in turn leads to higher litter fluxes (Table 2.5). Accounting for crop harvesting in the jsb_drvn_harv simulations decreases the litter fluxes (Table 2.5), which significantly decreases the equilibrium soil carbon densities. By explicitly accounting for crop harvest in the model the soil carbon densities for croplands decrease by about 16-24% for the considered regions.

Table 2.5: Mean annual equilibrium litter fluxes in kgC m^{-2} for previous and current land use for the different LUCs and simulations (± std).

Land-use change	t16_drvn		jsb_drvn		jsb_drvn_harv	
	Previous	Current	Previous	Current	Previous	Current
Crop to forest (temperate)	0.41±0.10	0.66±0.21	0.57±0.14	0.79±0.28	0.35±0.14	0.79±0.28
Crop to grass (temperate)	0.41±0.09	0.39±0.13	0.55±0.14	0.58±0.15	0.34±0.14	0.58±0.15
Forest to crop (temperate)	0.74±0.25	0.44±0.11	0.95±0.32	0.58±0.13	0.95±0.32	0.34±0.09
Grass to crop (temperate)	0.30±0.10	0.33±0.10	0.44±0.21	0.43±0.23	0.44±0.21	0.26±0.14
Forest to crop (tropics)	1.21±0.28	0.35±0.10	1.28±0.54	0.63±0.19	1.28±0.54	0.37±0.12
Forest to pasture (tropics)	-	-	1.31±0.53	0.78±0.16	1.31±0.53	0.78±0.16



(a) Mean equilibrium relative changes



(b) Mean equilibrium absolute changes

Figure 2.1: Mean simulated equilibrium relative (a) and absolute changes in soil carbon (b) compared to results from the meta-analyses. The first number in the parenthesis represents the number of studies in the meta-analyses and the second is the number of grid cells from the global simulation that fulfill the climate-criterion in the meta-analyses (regions in Fig. A1). The dots represent the mean changes and the bars represent the standard deviation.

2.3.2 Simulated changes in soil carbon for the different LUCs

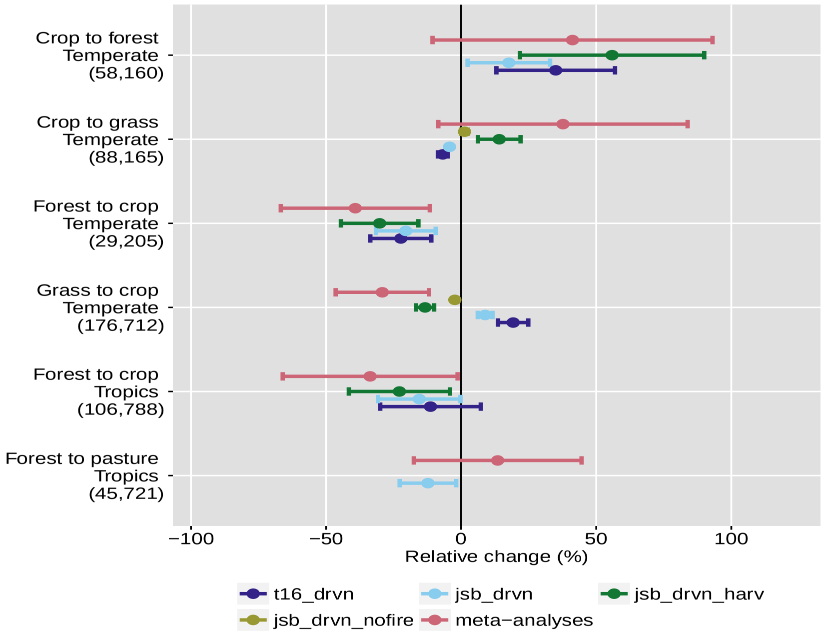
Figures 2.1 and 2.2 show an increase and decrease in soil carbon following conversion of crop to forest and forest to crop, respectively, for both the jsb_drvn and the t16_drvn simulations, consistent results from the meta-analyses. In the model this change stems from the higher average productivity in forests compared to croplands for both simulations (Table 2.4), which leads to higher litter fluxes (Table 2.5). In addition, woody material in forests decomposes slowly compared to leaf material from croplands. The conversion of crop to grass results in soil carbon decrease, while the reverse leads to a gain in both of these simulations, which is inconsistent with the meta-analyses (Figs. 2.1 and 2.2).

The reason for this deviation is related to litter fluxes or process other than soil decomposition leading to soil carbon losses, because of observational constraints on the other parts of the carbon cycle model: soil carbon decomposition rates in YASSO are calibrated against a wealth of measurements, and the simulations driven by observation based plant productivity (t16_drvn) result in the same deviation as the JSBACH-driven ones (jsb_drvn). The deviation may stem from an overestimate of cropland relative to grassland litter fluxes, or from an overestimate in the model of non-respiratory processes for grass. Although crop and grass have the same decomposition rates in YASSO, burning in grasslands leads to the loss of more litter carbon to the atmosphere and shorter turnover time (Table 2.6). This explains the simulated soil carbon decrease when croplands are replaced with grasslands. In the jsb_drvn_nofire simulation, switching off disturbances in grasslands leads to model agreement with the meta-analyses on the direction of soil carbon change (Figs. 2.1 and 2.2). The inclusion of crop harvesting in the model reduces the litter fluxes for crops (Table 2.5) and significantly increases the simulated soil carbon changes for the different LUCs (Figs. 2.1 and 2.2).

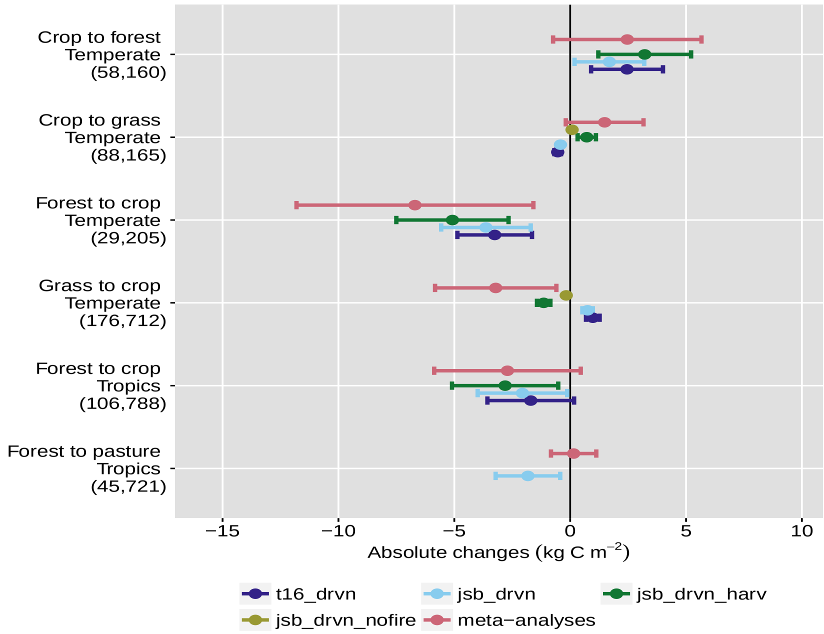
Table 2.6: Mean soil carbon turnover time (years) for the previous and current land use for the jsb_drvn simulation with and without disturbances.

Land-use change	Previous	Current
Crop to grass, with disturbances	17.1±4.5	15±2.6
Crop to grass, no disturbances	17.1±4.5	17.2±4.3
Grass to crop, with disturbances	21.9±8.3	28.7±14.9
Grass to crop, no disturbances	28.6±14.5	28.5±14.5

Although the simulated equilibrium relative and absolute changes for the conversion of temperate crop to forest and vice versa are larger than in the meta-analyses (Fig. 2.1), the current land use at the different sites in the meta-analyses may not



(a) Mean sampled ages relative changes



(b) Mean sampled ages absolute changes

Figure 2.2: Mean simulated relative (a) and absolute changes in soil carbon (b) over the sampled ages represented by the meta-analyses compared to results from the meta-analyses. The first number in the parenthesis represents the number of studies in the meta-analyses and the second is the number of grid cells fulfilling the climate-criterion in the meta-analyses. The dots represent the mean changes and the bars represent the standard deviation.

be in equilibrium. Sampling over the ages represented by the meta-analyses results in relative changes of about 10% for the jsb_drvn simulation and 25% for the t16_drvn simulation for the crop to forest conversion (Fig. 2.2a). These values are lower compared to the 40% relative changes in the considered meta-analyses and the 53% in Guo and Gifford (2002). For the forest to crop, the relative changes are about -15% for the jsb_drvn and t16_drvn simulations compared to the -42% in the meta-analyses (Fig 2.2a). In both of these simulations, the relative changes following the conversion of crop to grass and vice versa are relatively small (Fig. 2.2a). Despite meta-analyses showing an increase of about 8% for a tropical forest to pasture conversion (Guo and Gifford, 2002; Don et al., 2011), our model results indicate a decrease of about -15%. In addition, the absolute changes are smaller compared to the meta-analyses for all LUCs (Fig. 2.2b).

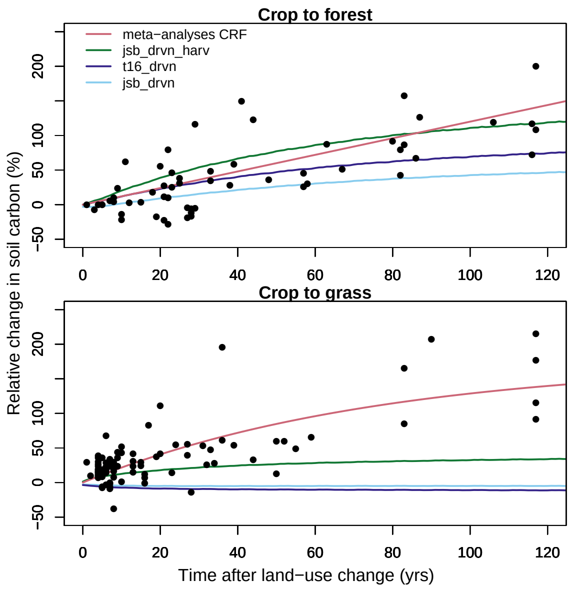
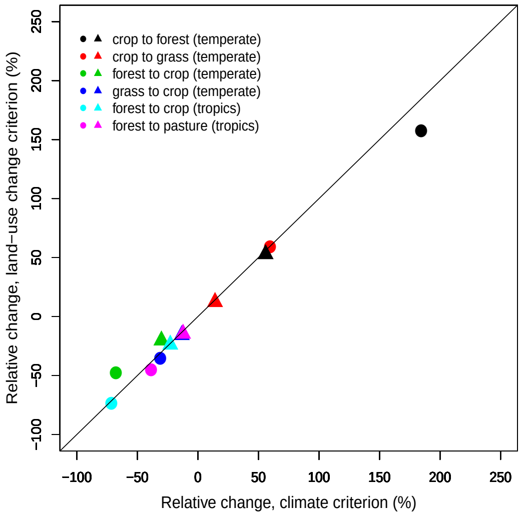
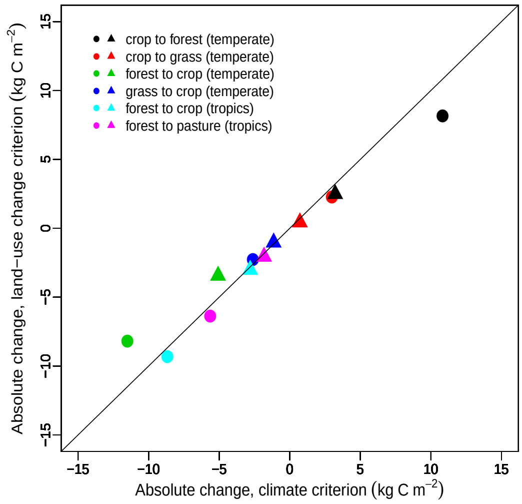


Figure 2.3: Mean simulated transient relative changes in soil carbon compared to the individual observations in the meta-analyses (black dots) and generalized carbon response functions (CRF) as in Poeplau et al. (2011) for the crop to grass and crop to forest LUCs.

Accounting for crop harvesting leads to larger relative and absolute changes in the model. The crop to forest LUC results in an increase of 42%, while the forest to crop results in a decrease of -22%. In line with the meta-analyses, the crop to grass LUC results in an increase of 13%, while the grass to crop results in a decrease of -6% (Fig. 2.2a). Although these changes are still often smaller than the meta-analyses, they are within the standard deviation represented in the meta-analyses for most of the LUCs (Fig. 2.2). Comparing the transient response with the generalized CRFs from Poeplau et al. (2011) and the individual observation points for the crop to grass and crop to forest LUCs, I find that accounting for crop harvesting leads to a stronger soil carbon response to afforestation in the model and a gain in soil carbon for the crop to grass conversion, in accordance with the meta-analyses (Fig. 2.3).



(a) Mean relative changes



(b) Mean absolute changes

Figure 2.4: Mean relative (a) and absolute (b) changes for the different land-use transitions with regions based on the climate (temperature and precipitation) criterion and based on where LUC has occured historically for the jsb_drvn_harv simulation. The triangles represent the mean changes over the sampled ages while the circles represent the mean equilibrium changes.

The climate-criterion (temperature and precipitation) used in the selection of the model grid cells for comparison with the meta-analyses resulted in small regions for the temperate zone. Selecting larger regions based on where the specific LUC has taken place historically, helps in judging if the soil carbon changes for the climate-criterion are representative of soil carbon changes in LUC regions. Averaging the soil carbon changes over regions where LUC took place historically results in the same direction of soil carbon changes as the climate criterion (Figs. A3 & A3), with slight differences in the magnitudes of the relative and absolute changes (Fig. 2.4).

2.4 Discussion

The above results show that the use of meta-analyses provides an opportunity for evaluating simulated soil carbon response to LUCs. In this section I discuss general issues related to the applicability of meta-analyses for DGVM evaluation, such as scale-related issues, explore the causes of model deviation from the observational data and identify the challenges involved in model-data comparison.

2.4.1 Application of meta-analyses for DGVM evaluation

DGVMs simulate soil carbon processes at large spatial scales and are widely used to provide soil carbon estimates relevant for the global carbon budget (Le Quéré et al., 2015). Reliability on these estimates depends on the ability of DGVMs to correctly represent present-day soil carbon changes from past LUCs. Site-level simulations are often used to evaluate DGVMs for CO_2 fluxes, such as net ecosystem exchange and terrestrial ecosystem respiration (e.g., Thum et al., 2011). While vegetation processes representing such variables are well represented in the models, soil processes that are important at the local scale, such as soil chemistry, are not represented in DGVMs. Although it may be impossible for a DGVM to capture the soil carbon response at an individual site, in particular if the site is not representative of a larger region, the model should be able to match average responses across observations covering a wide region. It is therefore possible to evaluate DGVMs at the scales they are meant for.

In the comparison the grid cells over which the response is averaged are chosen based on two independent criteria: the climate space covered by the meta-analyses and the regions where LUC has taken place historically. This selection helps in judging how robust the simulated results are and testing if the meta-analyses are indeed representative of regions where LUC has taken place. The results for the climate-criterion are qualitatively the same as those of the LUC-criterion (Figs. 2.1, 2.2, A2 and A3). Small differences occur for forest to crop and crop to forest in the temperate regions, where the LUC regions have smaller changes compared to the regions captured by the climate-criterion (Fig. 2.4). This suggests that the regions captured by the meta-analyses by Don et al. (2011) and Poeplau et al. (2011) are generally representative of regions where LUC has taken place historically, although the latter may not be representative of whole-ecosystem averages (see Pongratz et al., 2011). Although the site studies in the meta-analyses may have biases towards regions of similar soil and climatic conditions (Powers et al., 2011), the meta-analyses still show a large variability compared to the simulated results as indicated by the usually substantially larger standard deviation in the observational data (Fig. 2.2). This can be explained by the lack of DGVMs in representing the spatial heterogeneity of local soil and climate conditions and land-management practices.

Even though DGVMs provide land-use-related absolute soil carbon changes, in comparing the meta-analyses only relative changes are used. This is the preferred variable in the meta-analyses because spatial heterogeneity partly cancels in relative terms when two sites in close proximity are compared to each other, as done in paired-plots setups. Only relative changes allow for deriving robust carbon response functions (Poeplau et al., 2011). In the jsb_drvn_harv simulation, the equilibrium changes indicate a decrease in soil carbon of about 11 kgC m^{-2} and 3 kgC m^{-2} for forest to crop and grass to crop, respectively, in the temperate region. The decrease for forest to crop in the tropics is about 9 kgC m^{-2} (Fig. 2.1b). The reverse LUCs result in soil carbon increase of about the same magnitude. Because DGVMs are unaffected by small-scale spatial heterogeneity, their estimates of absolute changes are expected to be more robust than those of meta-analyses and therefore better representative for global C responses. After successful evaluation against relative changes, DGVMs can therefore be used to assess large-scale soil carbon changes in the absolute terms that are relevant for carbon budget estimates.

2.4.2 Causes of model deviation from meta-analyses

2.4.2.1 Accounting for crop harvesting

The importance of accounting for crop management practices, such as crop harvesting, irrigation and tillage, in DGVMs has been highlighted by recent studies (Levis et al., 2014; Pugh et al., 2015). In particular, Pugh et al. (2015) showed that the inclusion of tillage, grazing and crop harvesting in the LPJ-GUESS model increases the historical land-use carbon emissions. The increased emissions result from the reduced carbon inputs to the soil by removal of harvested material off-field and increased turnover rates via tillage. The results above show that lack of explicitly accounting for crop harvesting does not only lead to underestimation of soil carbon changes following the conversion of crop to forest and vice versa, but it also contributes to the wrong direction of change for the crop to grass LUC (Figs. 2.1 and 2.2). Figure 2.3 shows that accounting for crop harvesting in JSBACH improves the temporal response of soil carbon to the conversion of crop to grass and crop to forest. The removal of 50% crop biomass to the harvest pool –based on root to shoot ratios– is uncertain as it differs across crop types (Table 1.2 in Fageria, 2012); hence this value may not may not be representative of all the sites in the meta-analyses. Despite the uncertainty associated with the harvested crop biomass, accounting for crop harvesting significantly reduces the soil carbon for croplands (Table 2.3).

The model does not represent other crop management practices. For example, tillage in croplands leads to the exposure of mineral surfaces that are often inaccessible to decomposition causing more soil carbon loss (Post and Kwon, 2000). However, Pugh et al. (2015) showed that accounting for crop harvesting had larger effects on the historical carbon emissions compared to the inclusion of tillage. Moreover, fertilization can affect cropland soil carbon stocks by enhancing productivity and hence increasing soil carbon inputs, and compensating effects by enhancing decomposition by activating microbes (Russell et al., 2009). The carbon model used in this study simulates soil carbon based on the plant chemistry and climate. Recent studies have shown that the inclusion of microbial dynamics and priming processes in biogeochemical models can improve model agreement with observations (e.g., Wieder et al., 2013). As these processes are different across land-use types, the inclusion of such processes in future generation of DGVMs may lead to improved simulated soil carbon response to LUC.

2.4.2.2 Accounting for fire

DGVMs include process representation of vegetation fires to account for the annual emissions of carbon resulting from fires and to allow dynamical shifts in vegetation distribution. However, the choice of which vegetation type burns varies across different DGVMs. Earlier representations of fire in DGVMs accounted for burning only for natural vegetation types (e.g., Kloster et al., 2010; Reick et al., 2013), while recent studies included burning in pastures (e.g., Lasslop et al., 2014) and croplands (e.g., Li et al., 2013). Remote sensing data show that the burned area for different vegetation types varies across different regions. For example, Giglio et al. (2013) showed that while crops contribute to more than 50% of the burned area in Europe and Middle East, grasslands contribute to more than 50% of the burned area in Central Asia. The DGVM JSBACH accounts for burning only in natural vegetation types.

In the sensitivity simulations where grasslands are treated the same as croplands by neglecting burning in grasslands in the standard model simulation (jsb_drvn, which does not account for crop harvesting). The sensitivity simulations show a direction of change that is in accordance with the observational data for crop to grass and grass to crop (Figs. 2.1 and 2.2). In the simulations accounting for crop harvesting (jsb_drvn_harv), neglecting burning in grasslands would lead to even larger relative and absolute changes for the crop to grass and grass to crop LUCs. This shows that DGVMs assumptions on which vegetation types burn plays a major role on the soil carbon response to LUC. However, it remains unclear if the site studies included in the meta-analyses represent regularly burned regions or not. Establishing observational evidence for the sensitivity of soil carbon changes for a given land use towards frequency and intensity of fire events, similar to how meta-analyses show the sensitivity of responses to factors like precipitation, temperature or soil texture, would allow to evaluate the relevance of this process as currently represented in DGVMs.

2.4.2.3 Conversion of forests to managed grasslands

Results from the meta-analyses have shown that the conversion of forest to pasture in the tropics leads to negligible changes in the soil carbon and in some cases an increase (Guo and Gifford, 2002; Murty et al., 2002; Don et al., 2011). In the model the conversion of forest to pasture for the tropics leads to a decline in soil carbon comparable to that of converting forest to crop (Fig. 2.1). This is associated with larger NPP for forests compared to pastures, which leads to larger litter fluxes (Table 2.4 and 2.5). For most of the considered regions in the tropics, the larger simulated NPP for forests compared to pastures is consisted with other observations (Smith et al., 2012b). Murty et al. (2002) associated the observed increase in soil carbon following conversion of forest to pasture with low initial content of soil carbon, application of fertiliser and avoided grazing. Table 2.3 shows low previous land use soil carbon for forest to pasture compared to forest to crop in the meta-analyses. However, the model does not simulate low previous land use soil carbon for the forest to pasture transition in the considered regions (Table 2.3).

For the temperate regions, the conversion of grassland to forest increased soil carbon when the surface litter was included, while without surface litter a decrease in soil carbon was observed (Poeplau et al., 2011). In the comparison conversions between forest and grass in the temperate regions are not included. The smaller change for grass to crop as compared to forest to crop suggests, however, also here a simulated loss of carbon for the forest to grassland LUC. Schulze et al. (2010) in their review of the European carbon balance found that grasslands store more carbon compared to forests. They attribute this to the higher below-ground allocation for grasslands compared to forests, annual root turnover and possibly nitrogen fixation. JSBACH does not explicitly represent the potentially deep rooting of grasses, which likely contributes to the disagreement in sign of change for the tropical forest to pasture transition and the weaker simulated response for the temperate grass to crop transition. The latter may further be explained by the simulations not capturing the differences in productivity of grasslands compared to forests and cropland found across various eddy covariance sites in Europe (Schulze et al., 2010). Schulze et al. (2010) found generally larger NPP for grasslands and croplands, while the simulated results shows on average higher productivity for forests for the considered temperate regions (Table 2.4).

2.4.3 Challenges in model-data comparison

2.4.3.1 Sampling at different times following land-use change

The local-scale measurements constituting the meta-analyses are taken at different times after LUC; hence the current land use is often not in equilibrium. Yet often sites at different stages of disequilibrium are included in average responses, which have been subsequently interpreted in modeling studies as indication for the observation-based evidence of effects of historical LUC on equilibrium soil carbon stock changes (Pongratz et al., 2009; Reick et al., 2010; Stocker et al., 2011). Idealized simulations such as presented here can account for this transience in soil carbon response by sampling over the same ages as represented by the meta-analyses. Due to the larger availability of sites that have recently undergone LUC, averaging over all available sites of different ages in the meta-analyses has a strong bias towards smaller soil carbon changes than would be expected in equilibrium. This bias becomes apparent in the smaller relative and absolute changes compared to the equilibrium changes (Figs. 2.1 and 2.2). The bias amounts to about 20-40% of the equilibrium response that is captured by an average across the simulations accounting for crop harvest (Table 2.7). Therefore, parametrization and evaluation of DGVMs using meta-analyses needs to account for the transient state of the mean soil carbon changes for the different LUCs represented in the meta-analyses.

Table 2.7: The contribution of the mean absolute changes over the sampled ages to the equilibrium absolute changes for the jsbach_drvn_harv simulation.

Land-use change	Sampled age changes (kgC m^{-2})	Equilibrium changes (kgC m^{-2})	Contribution (%)
Crop to forest (temperate)	2.39	10.83	22
Crop to grass (temperate)	0.68	2.98	23
Forest to crop (temperate)	-3.77	-11.50	38
Grass to crop (temperate)	-0.50	-2.61	19
Forest to crop (tropics)	-1.45	-8.67	17
Forest to pasture (tropics)	-1.74	-5.63	31

2.4.3.2 Different soil sampling depths

Soil carbon models used in DGVMs typically simulate soil processes up to a depth of 1 m and are meant to capture the complete soil carbon stock changes after LUC. By contrast, some of the observations, in particular in the tropics, covered only a shallow sampling depth (Table 2.1). Analysis of the depth-dependence of observed soil carbon changes revealed that most of the change occurs in the top 30 cm (Poeplau and Don, 2013), in line with the fact that in most ecosystems the majority of soil carbon is stored in the upper layers with around 1520 Pg C, which is more than 56% of the total soil carbon globally, in the upper 1 m (Jobbágy and Jackson, 2000). For comparison of the relative and absolute of soil carbon changes at consistent depth, scaling of the site studies to the model depth can be applied (Yang et al., 2011; Deng et al., 2014). However, these scaling approaches used an equation calibrated across a wide range of ecosystems and are thus independent of the land use types. Hence, such as a scaling would only affect the comparison of the absolute changes, but not the relative changes.

Previous studies have shown that the amount of soil carbon varies with depth differently in different ecosystems. For example, Jobbágy and Jackson (2000) found that 42% of the total soil carbon in grasslands is stored in the upper 20 cm while for forests 50% of the carbon is in the upper 20 cm. Guo and Gifford (2002) argued that while forests have high above-ground inputs in the top layers, tree roots are less important sources of organic matter because much of the tree root systems lives for many years. On the other hand, the annual root turnover in grasslands contributes to larger soil carbon storage in deeper depths. Therefore also the changes of soil carbon vary with depth differently for different LUCs. Poeplau and Don (2013), using several local scale measurements, found that 91% of the total soil carbon change occurs in the upper 30 cm following afforestation, while 65% of the change occurs in the top soil following the conversion of crop to grass. In line with this, DGVMs may need to consider including vertically resolved soil profiles to represent the distribution of soil carbon with depth across different ecosystems, to represent that different types of LUCs act differently depending on the sampled depth and to be better comparable with meta-analyses. Conversely, to capture the full impacts of LUC on soil carbon as relevant for carbon budgeting and to allow a direct comparison to DGVMs, local-scale measurements need to consider a deeper sampling of the soil profile.

2.5 Summary of chapter 2

In this chapter, a framework for evaluating the simulated soil carbon changes for different LUCs was developed and applied to the DGVM JSBACH. The results show model agreement with the meta-analyses on the direction of changes in soil carbon for some LUCs. The model captures the gain and loss of soil carbon following afforestation and deforestation, respectively. However, for the conversion of crop to grass a loss is simulated, while the meta-analyses indicate a carbon gain. The results indicate that the response of soil carbon to the conversion of grass to crop and vice-versa is sensitive to fire in the model. Excluding fire in the model partly explains the model deviations from the meta-analyses for the grassland conversions. Accounting for crop harvesting substantially improves the carbon response to LUC. This comparison supports previous studies that found that the inclusion of crop harvesting is a crucial component in DGVMs to accurately represent soil carbon losses with agricultural expansion and historical land-use emissions (Stocker et al., 2011; Pugh et al., 2015).

A few challenges exist in comparing DGVMs to the meta-analyses. First, meta-analyses cover many observations where the current land use may not be in equilibrium; hence the mean relative changes in the meta-analyses represent a transient response. Idealized LUC simulations, as presented in this study, can account for this by sampling over the ages represented by the meta-analyses. Second, the meta-analyses include local-scale observations that are done at different sampling depths. Ultimately this challenge can be overcome only by deeper sampling in observational data or by DGVMs considering in the future including a vertically resolved soil profile.

Despite such challenges, this study shows that the use of meta-analyses on soil carbon changes following LUC offers the opportunity for evaluation and improvement of DGVMs. The framework developed for comparing simulated soil carbon changes against the meta-analyses is applicable to any DGVM. Extending this comparison to other DGVMs or to model intercomparison projects would not only provide an observational reference for validation, but also help investigate across a larger range of processes the key influences on models' sensitivity to LUC.

Chapter 3

Input-driven versus turnover-driven controls of simulated changes in soil carbon due to land-use change [1]

3.1 Introduction

Land-use change (LUC), for example, the transformation of natural vegetation to crops or pastures and the related land management practices, contributes substantially to changes in soil carbon. Analysis of local-scale measurements, which monitor the response of soil carbon to different LUCs, indicate that the magnitude and direction of the changes differ depending on the type of LUC (e.g., Don et al., 2011; Poeplau et al., 2011). Bookkeeping models and dynamic global vegetation models (DGVMs) that are used to quantify LUC effects on the terrestrial carbon estimate a global soil carbon loss ranging from 0 to 100 Pg C over the 20th century (e.g., Houghton, 2003a; Tian et al., 2015). The dominant effect of soil carbon losses by deforestation is counteracted to a smaller extent by recent reforestation efforts, which have led to soil carbon gain for some regions in the late 20th century (e.g., Houghton et al., 1999; Liski et al., 2002).

Changes in soil carbon are generally controlled by changes in the quantity of litter inputs from the vegetation to the soils (input-driven) and turnover of carbon in the soil, which is highly dependent on the quality of litter (turnover-driven). For example, replacing natural vegetation dominated by woody vegetation types with

[1] **Sylvia S. Nyawira**, Julia E. M. S. Nabel, Victor Brovkin, and Julia Pongratz (2017): Input-driven versus turnover-driven controls of simulated changes in soil carbon due to land-use change. Environmental Research Letters., **12**

pastures or croplands often leads to less biomass in the vegetation, which decreases the litter input. Furthermore, woody litter decomposes more slowly than non-woody litter; hence the turnover of litter and soil carbon is generally slower in forests compared to pastures or croplands. In addition to vegetation productivity and soil decomposition, there are processes that influence the litter fluxes to the soil and the carbon losses from the soil to the atmosphere. Natural disturbances via windthrow contribute to the transfer of vegetation biomass to the soils. In addition, vegetation fires, that occur naturally or are induced by humans, lead to carbon losses from both the vegetation and soil to the atmosphere. Previous studies have shown that the additional litter input associated with windthrow increases soil carbon (e.g., dos Santos et al., 2015), whereas forest fires tend to decrease soil carbon via losses in the litter carbon to the atmosphere (e.g., Liski et al., 1998). Therefore, these processes also contribute to the input-driven and turnover-driven changes in soil carbon.

Historical soil carbon losses not only result from anthropogenic changes in land cover, but also from land management: 42-58% of the ice-free land surface is managed to satisfy human needs without changing the type of land cover (e.g., forestry) (Luyssaert et al., 2014). About 8.18 Pg C yr^{-1}, which represents 12.5% of the global present-day net primary production (NPP), is removed by humans from the vegetation and used for food, timber and animal feeds (Haberl et al., 2007). Global human appropriation of the NPP has substantially increased, with studies estimating a doubling over the 20th century (Krausmann et al., 2013). As a result, less biomass is left in the vegetation today compared to the past leading to less litter input to the soil. Recent studies suggest a strong impact of this increased control on soil carbon for certain land management types. For example, Pugh et al. (2015) showed that accounting for crop harvesting enhances cumulative historical LUC emissions by about 15% due to reduced soil carbon input. Although the increased human control on the vegetation by land cover change and land management has generally resulted in less litter inputs, the impacts of human control on the turnover of carbon in the soil are less well understood.

The goal of this chapter is to show a model approach that can be used to isolate the contribution of the input-driven and the turnover-driven changes and their synergies to the total changes in soil carbon associated with LUC. A factor separation is applied to equilibrium simulations of present-day and pre-industrial land use, performed using the DGVM JSBACH. The asessment of the different controls provides for an improved understanding how LUC and land management, through crop and wood harvesting, have contributed to historical changes in soil carbon in JSBACH. Although the focus is on LUC, the approach can be applied to any equilibrium simulations to understand how different forcings contribute to changes in soil carbon via the input-driven and turnover-driven controls.

3.2 Methods

3.2.1 Model setup

The DGVM JSBACH with 12 plant functional types (PFTs) comprising natural vegetation (forests, shrubs and grasses), pastures and croplands (Reick et al., 2013) was applied in this study. Soil carbon dynamics in JSBACH are simulated by the YASSO model, which separates litter into four chemical pools (acid, water, ethanol and non-soluble hydrolyzable) with different decomposition rates that are independent of the PFTs. In addition, there is a slowly decomposing humus pool where a fraction of the decomposed products from the four chemical pools goes to. The parametrization of decomposition rates is based on litter bag experiments with a wide geographical coverage (Tuomi et al., 2009). The separation of the plant litter into the different chemical pools depends on the PFT, with the woody and non-woody litter decomposing differently. The decomposition rates depend on air temperature based on an optimum curve fitted using a Gaussian model (Tuomi et al., 2008), and on precipitation based on an exponential curve (Tuomi et al., 2009). The present-day soil carbon stocks simulated by YASSO within JSBACH show good agreement with the Harmonized World Soil Data Base for most regions (for details see Goll et al., 2015).

The model version applied in this study includes the crop harvesting scheme introduced in chapter 2 section 2.2.3; 50% of the aboveground biomass was removed from the field and stored in an anthropogenic food pool, which decays to the atmosphere within one year. The response of soil to LUC in this model version was extensively evaluated against local-scale observations compiled by different meta-analyses (Nyawira et al., 2016). Wood harvest was prescribed with maps from the Land-Use Harmonization project (Hurtt et al., 2011); 70% of the harvested material was stored into paper and construction pools, with the pools decaying to the atmosphere at different time scales Houghton et al. (1983). The rest of the material was left onsite where it decomposed with the YASSO decomposition rates. In the standard JSBACH, natural vegetation types are subject to disturbances in the form of fire, whilst crop and pasture areas are assumed not to be burned Reick et al. (2013). However, a recent study revealed that pasture-associated fires account for over 40% of the annual global burned areas Rabin et al. (2015). In line with this, the disturbances module was modified to include burning on pastures.

The carbon cycle model of JSBACH, which includes the vegetation carbon dynamics, natural disturbances, harvest and the YASSO soil carbon model, can be run independently of the rest of the model. This sub-model requires a set of drivers: net primary production (NPP), leaf area index (LAI) and environmental drivers for the disturbances module. These drivers were obtained by performing JSBACH simulations using the pre-industrial (1860) and present-day (2005) land cover maps. The two maps are based on crop and pasture fractions from the Land-Use Harmonization project Hurtt et al. (2011), and a potential vegetation map from Pongratz et al. (2008). Simulations with these two maps were driven by observed climate and CO_2 concentrations from the Climate Research Unit (CRU) for the years 2001 to 2010 Harris et al. (2014). Using the drivers obtained from JSBACH, and precipitation and temperature from CRU additionally required as forcing by YASSO, I performed two sets of simulations with each of the maps including or excluding land management through crop and wood harvesting. The simulations including land management are denoted as “LCM”, while those without management are denoted as “LCC”.

Table 3.1 summarizes the simulations in this study and their purpose. In the simulations with no harvest, the wood harvest maps were not prescribed and the crop harvest went directly to the litter pool. The carbon sub-model was run until all the carbon pools reached equilibrium. I considered the pools to be in equilibrium when the relative change in soil carbon from one year to the next became less than 1% in every grid cell. The total changes in soil carbon obtained in this study are expected to be higher than those from transient LUC simulations. The choice of equilibrium rather than transient simulations is important for quantifying the turnover of carbon in the soil. Koven et al. (2015) showed that in simulations with a changing climate the increase in the litter fluxes shifts the distribution of carbon initially to the faster soil carbon pools, from where the changes cascade down to the slower pools only with time, and thus decreases the inferred turnover rate even if the actual turnover rates of each pool are unaltered. A similar bias in the turnover of carbon can also be expected with transient LUC simulations, which would translate into biases in the isolated controls of changes in soil carbon (see section 3.2.2).

3.2.2 Factor separation approach

The change in soil carbon at a given time can be calculated by subtracting the incoming fluxes from the outgoing fluxes as in equation 3.1, where C_{soil} is the total carbon in the soil, $f_{veg \to soil}$ is the litter flux from the vegetation to the soil, and τ_{soil} is the soil carbon turnover. In equilibrium, the change in soil carbon with time is zero ($\frac{dC_{soil}}{dt} = 0$) and the incoming fluxes balance the outgoing fluxes, i.e. the litter input from the vegetation to soil equals the losses from the soil to the atmosphere due to soil respiration and fire fluxes ($f_{soil \to atmos}$). τ_{soil} can thus be calculated via the diagnosed incoming or outgoing fluxes (Eq. 3.2). τ_{soil} represents a property of the soil carbon dynamics that emerges from the decomposition rates of the YASSO pools, the distribution of litter into these pools according to the distribution of PFTs and the type of litter (woody versus non-woody). In addition, fire plays a role as it

Table 3.1: A summary of the model simulations in this study.

JSBACH forcing	Land cover	Acronymn	Crop harvest	Wood harvest	Fire	Purpose
Realistic vegetation distribution simulations						
CRU NCEP 2001–2010 climate. CO_2 concentration of 367ppmv	1860 2005	LCM_1860 LCM_2005	Removed to product pool	2005 and 1860 maps by Hurtt et al. (2011). Removed to product pool and litter	All PFTs except crop	Isolate land cover change & management effects
	1860 2005	LCC_1860 LCC_2005	Harvested to litter	None		Isolate only land cover change effects
Idealized global simulations[a]						
CRU NCEP 2001–2010 climate. CO_2 concentration of 367ppmv	forest crop grass/pasture		n/a Removed to product pool n/a	none n/a	All PFTs except crop	Assess global patterns for specific LUCs

[a] These simulations were performed with the entire globe covered by one vegetation type Nyawira et al. (2016)See details in. Using these simulations, we derive the controls for the global conversion of forest to crop, grass to crop, crop to forest and forest to pasture.

shortens the lifetime of carbon within the soil pools and adds carbon to the litter pools for the woody PFTs.

The differences in the turnover ($\Delta\tau$) and the litter fluxes (Δf) can be calculated by subtracting the turnover and litter fluxes of the pre-industrial from the present-day equilibrium. Combining these equations, and using the pre-industrial simulation as the reference, the total change in soil carbon between the two simulations can be expressed as in equation 3.3, further expressed as in equation 3.4. Canceling the first and last terms in equation 3.4, equation 3.5 represents the different controls of the soil carbon changes: the first term on the right hand side represents the input-driven change, the second term represents the turnover-driven change, and the third term is the synergy term. The synergy term represents the change in soil carbon associated with the turnover characteristics of the altered litter input (Δf), meaning e.g., for the case of higher litter input due to LUC, that the additional litter is distributed differently in the long- or short-lived decomposition pools as compared to the relative distribution of litter in the reference state. I calculated the controls for the changes between the simulations LCM_2005 and LCM_1860 and between the simulations LCC_2005 and LCC_1860. In addition, I also applied the factor separation to the idealized LUC simulations, described in chapter 2 section 2.2.3, and compared the results to the historical LUC simulations to assess how robust the spatial patterns are.

$$\frac{dC_{soil}}{dt} = f_{veg\rightarrow soil} - \frac{C_{soil}}{\tau_{soil}} \tag{3.1}$$

$$\tau_{soil} = \frac{C_{soil}}{f_{veg\rightarrow soil}} = \frac{C_{soil}}{f_{soil\rightarrow atmos}} \tag{3.2}$$

$$\Delta C_{soil} = \tau_{soil,2005} f_{veg\rightarrow soil,2005} - \tau_{soil,1860} f_{veg\rightarrow soil,1860} \tag{3.3}$$

$$\Delta C_{soil} = (\tau_{soil,1860} + \Delta\tau)(f_{veg\rightarrow soil,1860} + \Delta f) - \tau_{soil,1860} f_{veg\rightarrow soil,1860} \tag{3.4}$$

$$\Delta C_{soil} = \tau_{soil,1860}\Delta f + f_{veg\rightarrow soil,1860}\Delta\tau + \Delta f \Delta\tau \tag{3.5}$$

3.3 Results and Discussions

3.3.1 Global and regional patterns of the controls

Figure 3.1 shows that in most regions where LUC has occurred in the last 150 years the amount of carbon in soils has reduced. This is because in most regions pastures and croplands have increased at the expense of natural vegetation (Fig. B1). This largely reduces the litter inputs to the soils due to less vegetation biomass in croplands and pastures compared to forests and also due biomass removal via crop harvesting (Fig. 3.2 & Table 3.2). The LCM simulations result in a global loss of 54.0 Pg C. The input-driven and turnover-driven changes contribute to a loss of 54.7 Pg C and 1.4 Pg C, respectively, while the synergy effects contribute a gain of 2.1 Pg C. A larger contribution to the spatial pattern of the total changes stems from the input-driven changes, as seen from the similarity of the patterns between the input-driven and total changes (Fig. 3.1). In some regions the input-driven and turnover-driven changes contribute in opposite directions to the total change. For most regions the synergy contribution is small.

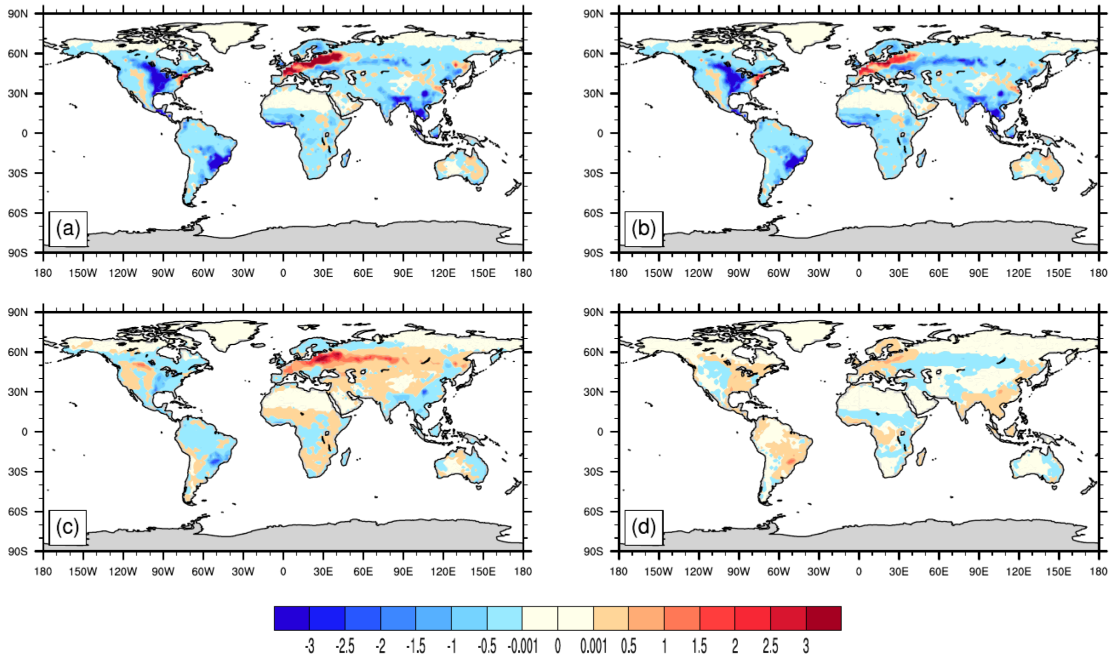


Figure 3.1: Global separated soil carbon changes in kg C m^{-2} for the LCM simulations (including land management). The controls are obtained using equation 3.5 and taking the LCM_1860 equilibrium as the reference. (a) Total soil carbon changes, (b) contribution of the input-driven changes, (c) contribution of the turnover-driven changes and (d) the synergy effects.

To understand the regional patterns of the input-driven and turnover-driven changes, the globe was divided into different regions based on the dominant LUC: afforestation, deforestation, and conversion of grasslands and pastures to croplands. The results show a gain in soil carbon in most regions where afforestation has taken place, e.g., Central Europe and the East coast of USA, which stems from both the input-driven and turnover-driven contribution (Fig. 3.1 & 3.3). For some grid cells, despite the increase in forest cover (Fig. B1), the input-driven changes result in soil carbon loss. These are grid cells where the productivity of forests is lower than that of pastures, because the climatic conditions in these regions are not favorable for forest growth. Despite the differences in the climatic conditions, the turnover-

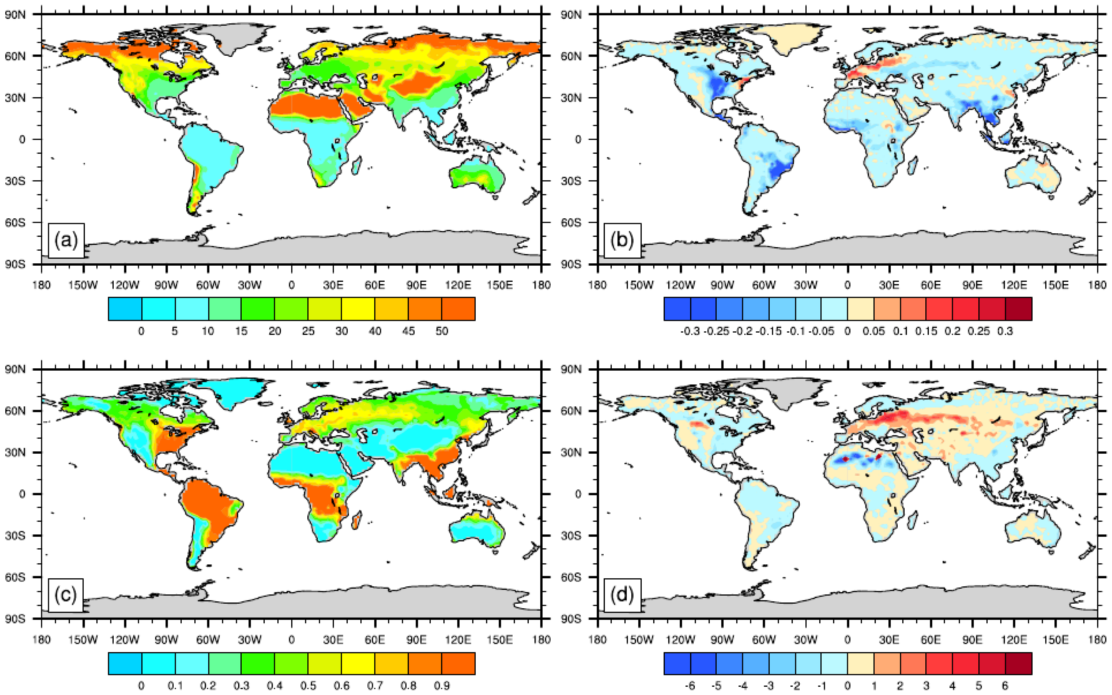


Figure 3.2: The different terms contributing to the input-driven, turnover-driven and the synergy soil carbon change for the LCM simulations (including land management). (a) Turnover time in years for the reference land cover map ($\tau_{soil,1860}$), (b) difference in the litter fluxes between the two land cover maps (Δf) in kg C m^{-2}. Multiplying these two terms gives the input-driven term in Figure 3.1. (c) Equilibrium litter fluxes to the soil for the reference land cover map in kg C m^{-2} ($f_{veg\rightarrow soil,1860}$), and (d) difference in the turnover times between the two land cover maps ($\Delta\tau$) in years. Multiplying these two terms gives the turnover-driven term in Figure 3.1.

Table 3.2: Global carbon fluxes in absolute values and relative to the simulated net primary production (NPP) for the simulation including land management (LCM simulations in Table 3.1).

	LCM_1860		LCM_2005	
	PgC yr^{-1}	%	PgC yr^{-1}	%
NPP	80.4	100	77.3	100
Crop harvest	1.6	2.0	3.6	4.7
Wood harvest	0.2	0.2	0.8	1.0
Vegetation fire and herbivory losses	6.6	8.2	6.1	7.9
Litter	72.0	89.6	66.8	86.4
Soil respiration	68.7	85.4	63.9	82.7
Soil fire losses	3.3	4.2	2.9	3.7

driven changes always result in a gain in soil carbon that stems from the slower decomposition of woody litter compared to non-woody litter (Fig. 3.3).

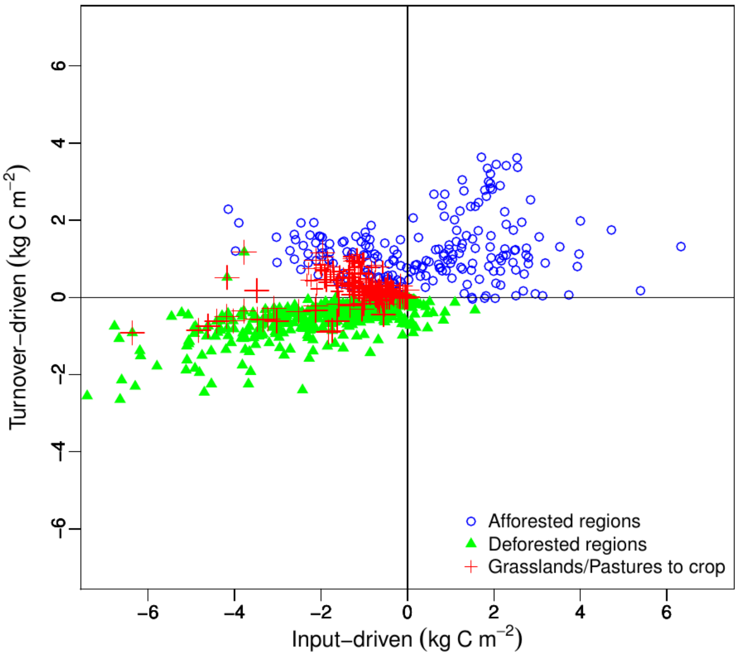


Figure 3.3: Grid cell relationship between the input-driven changes and turnover-driven changes in kg C m^{-2} for the LCM simulations. To select the grid cells I calculated the difference in the cover fractions between the present-day and pre-industrial and cover and set a threshold of 10% for the specific dominant LUC.

In the deforested regions, where pastures and croplands have increased at the expense of forests, e.g., central USA and some parts of South America and Asia, both the input-driven and turnover-driven changes contribute to losses in soil carbon (Fig. 3.1 & 3.3). The input-driven losses are partly due to the decrease in productivity, which decreases litter inputs when forests are replaced with pastures or croplands, and in addition due to crop harvesting.

In regions where pasture or grasslands have been converted to croplands, e.g., some parts of Africa, the input-driven changes contribute to soil carbon loss, whereas the turnover-driven changes contribute to a gain (Fig. 3.1 & 3.3). The input-driven loss in these regions is mostly due to crop harvesting as the simulated productivity of grasslands and pastures generally does not differ much from that of crops in JSBACH (Table 2.4 in chapter 2). The simulated turnover-driven gain in these regions mainly stems from the fire suppression on croplands (Andela and van der Werf, 2014), which results in a global decline of the carbon losses due to fire (Table 3.2). However, frequent fires may also lead to the conversion of burned biomass into organic matter that is richer in carbon and resistant to environmental degradation, which would lead to a slower turnover (Santín et al., 2015).

The DGVM JSBACH has been shown to provide LUC emissions that are within the range of other model estimates (Le Quéré et al., 2015). The global 54.0 Pg C soil carbon loss in our simulations lies in the middle of earlier estimates from a multitude of bookkeeping models and DGVMs, which span a large range from hardly any change to 105 Pg C (Houghton, 2003a; Reick et al., 2010; Hansis et al., 2015; Tian et al., 2015). However, the results in this study are not directly comparable to these estimates as we considered equilibrium states. The global present-day NPP of 77 Pg C in Table 3.2 is larger than in other model estimates, which range between 53-72 Pg C (Rafique et al., 2016). A comparison of the simulated NPP for the different PFTs reveals that JSBACH generally tends to be overproductive especially for forests (Fig. B3). While this may lead to biases in the simulated soil carbon for a given land-use distribution, biases in NPP often tend to cancel out when considering changes in soil carbon due to specific LUC (Nyawira et al., 2016). Although there are no global data sets for the soil carbon turnover, the terrestrial carbon turnover obtained from different Earth system models in deforested regions show good agreement with observational-derived estimates, with model discrepancies occurring mainly outside the centers of LUC in the permafrost and dryland regions (Carvalhais et al., 2014).

3.3.2 Spatial dependence of the controls on historical LUC

Vegetation productivity and decomposition rates vary depending on the climatic conditions; hence the input-driven and turnover-driven changes may vary across the climate zones. To assess if the results in figure 3.1 are representative of the global response for species LUC, I analyzed the controls for the idealized simulations of LUC. The idealized simulations represent the response if all the grid cells in the globe were covered by one vegetation type that is then transformed to another vegetation type. Wood harvest is not included in the idealized simulations, because the harvest data is only available for realistic vegetation distribution.

The direction of the input-driven and turnover-driven changes for most regions in the idealized simulations matches the results for the dominant LUCs over the historical period. Afforestation on croplands and pastures results in a turnover-driven gain almost everywhere on the globe (Fig. 3.4a & 3.4c), while deforestation results in a loss (not shown but its the opposite sign of Figure 3.4a & 3.4c), which is in agreement with the results in Figure 3.3. Exceptions occur in the dry and arid regions following a conversion of forest to cropland where fire suppression overcompensates for the effects of a shift from slowly decomposing woody to non-woody litter. However, these regions have marginal forest cover in reality and have thus not been subject to substantial historical deforestation (Fig. B1).

Similar to the grid cells with historical afforestation, the direction of the input-

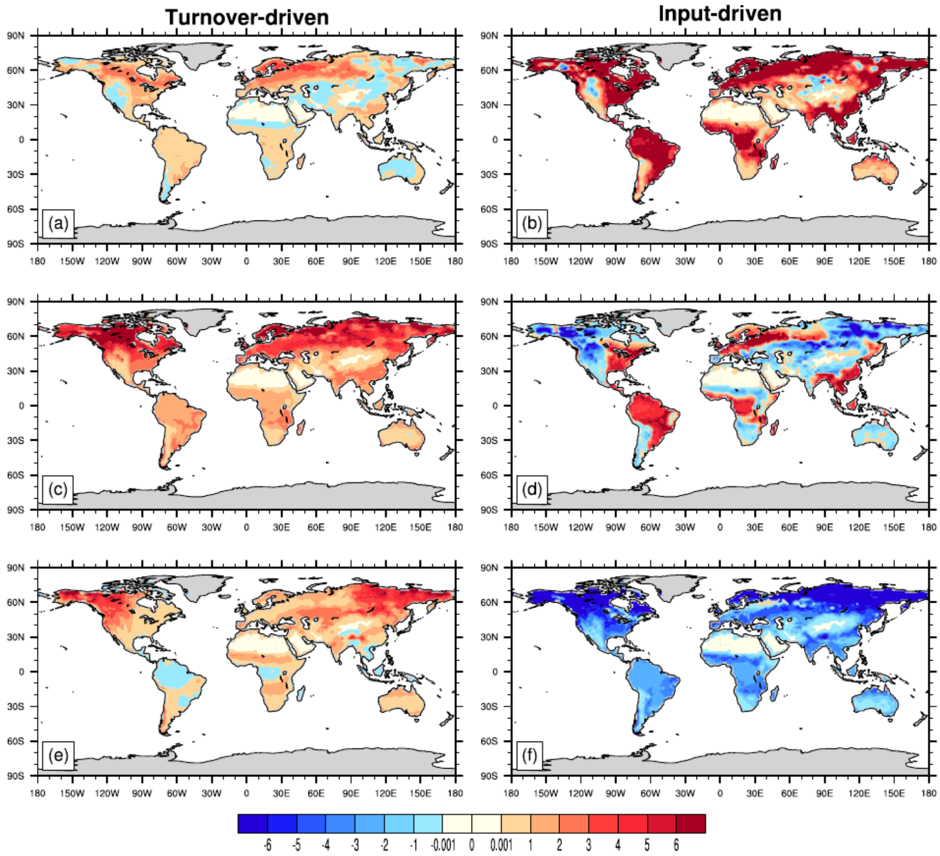


Figure 3.4: (a) & (b) The turnover-driven and input-driven changes for the conversion of croplands to forests, (c) & (d) turnover-driven and input-driven changes for the conversion of pastures to forests, (e) & (f) turnover-driven and input-driven changes for the conversion of grass to crop.

driven changes following the conversion of pasture to forests varies depending on the region, whereas except for the marginal regions afforestation on croplands results in an input-driven gain (Fig. 3.4d & 3.4d). The conversion of grasslands to croplands results in input-driven losses and turnover-driven gains in most regions where grasslands exist (Fig. 3.4e & 3.4f) . Overall, the results for the idealized simulations generally exhibit similar patterns as the regions considered in section 3.3.1; therefore, these analyses show that the simulated input-driven and turnover-driven changes for the dominant historical LUCs are qualitatively similar across different climate zones.

3.3.3 Contribution of land management

The factor separation was applied to the simulations excluding crop and wood harvesting for a comparison of the effects of land management on the controls with those of only the land cover change. The results show a global loss of 22.4 Pg C in the LCC simulations (compared to 54.0 Pg C in LCM simulations). The differences in the total changes between the LCC and LCM simulations stem mainly from the input-driven changes (Fig. 3.5).

Land management enhances the input-driven losses and decreases the gains almost everywhere in the globe, except for a few grid cells with afforestation where the input-driven gain is larger in the LCM simulations. The larger gain is due to the higher wood harvest intensity in 2005 compared to 1860, which amplifies the difference in the litter inputs in the LCM simulations, compared to the LCC simulations, as part of the harvest goes to litter (see section 3.2.1). Globally, the input-driven loss in the LCC simulations is 24.9 Pg C (compared to 54.7 Pg C in LCM simulations). The differences in the turnover-driven contribution between the LCM and LCC simulations are small. These differences are due to the different amount of woody litter through natural mortality when there is no harvest and due to the carbon losses through fire.

On average afforested regions exhibit larger soil carbon gain without wood harvest, while the deforested regions exhibit less losses due to larger litter fluxes in croplands (Fig. 3.6). In the regions with grasslands to croplands conversion, the turnover-driven gain associated with fire suppression outweighs the input-driven loss in the LCC simulations unlike in the LCM simulations. Hence in JSBACH, crop harvesting overcompensates for the fire suppression effects in these regions.

The fraction of the NPP exported through harvest influences the relative contribution of the controls. Haberl et al. (2007) estimate the NPP removed for food and timber, and forages consumed by livestock to be about 8.17 Pg C/yr. In the LCM_2005 simulation, the biomass removed from the vegetation for crop and wood harvest is 4.4 Pg C/yr (Table 3.2). Wood harvest contributes to about 0.97 Pg C/yr

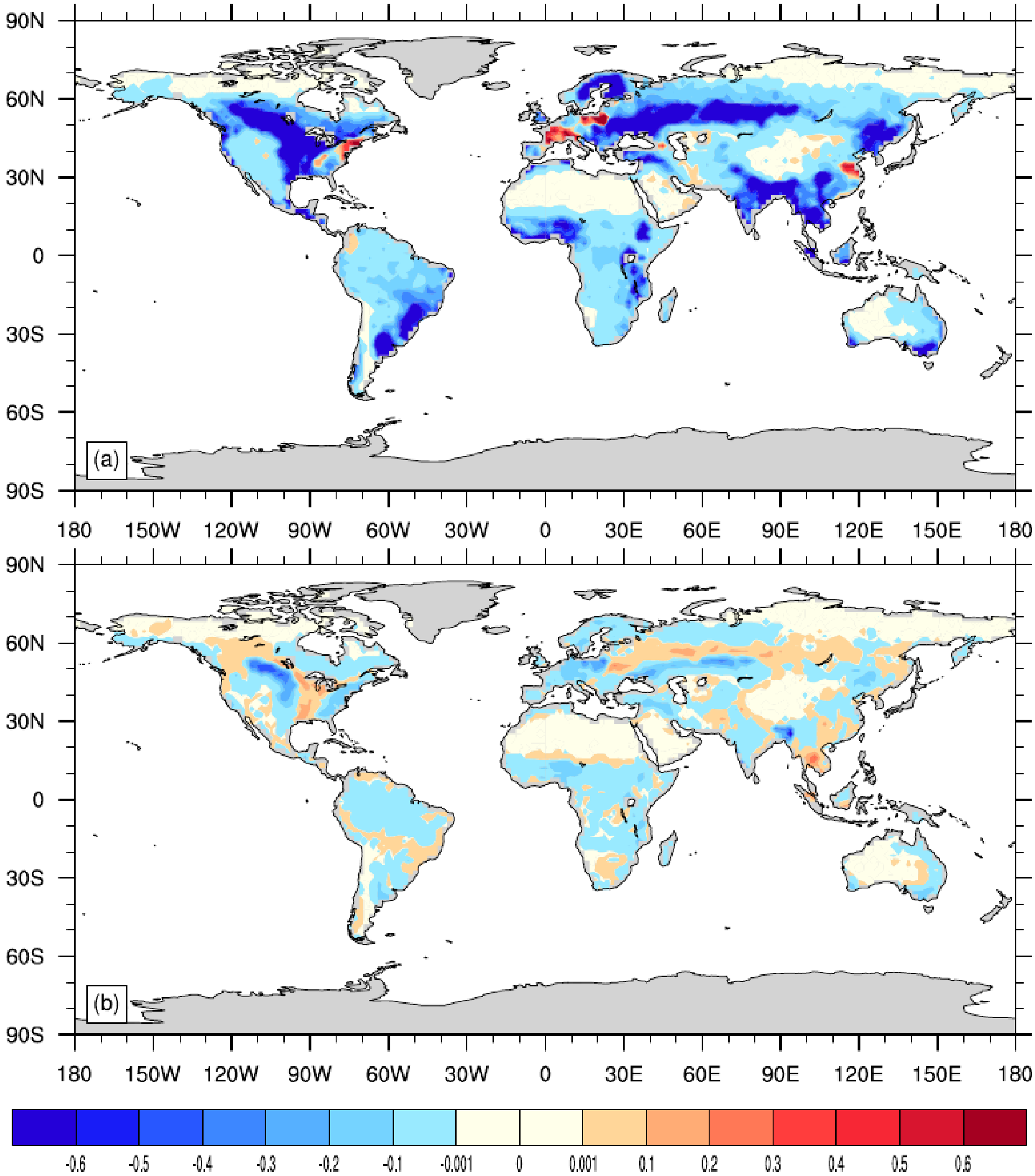


Figure 3.5: The difference in the (a) input-driven (b) and the turnover-driven changes in kg C m^{-2} between the LCM simulations and the LCC simulations. The differences are obtained by subtracting the input-driven and turnover-driven changes in Figure. 3.1 from those in Figure B2. For the input-driven changes, negative values indicate that the carbon losses are larger without land management in regions where natural vegetation is converted to croplands or pastures, wheres the gains are smaller in afforested regions.

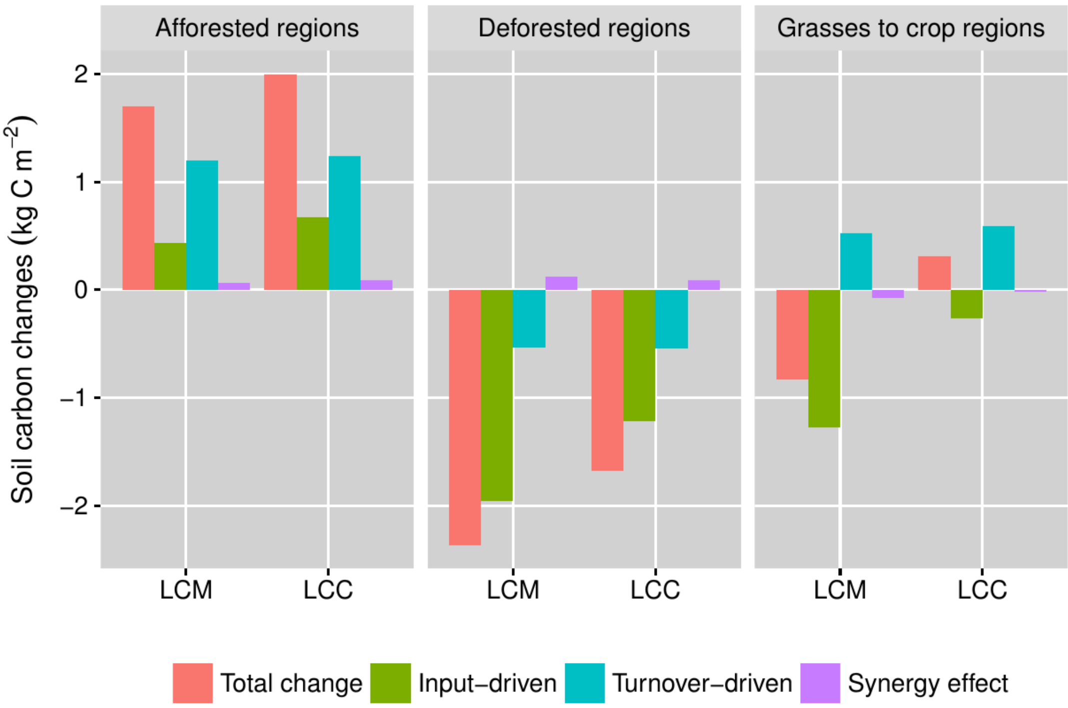


Figure 3.6: Mean total changes in soil carbon in kg C m^{-2} and the contributing input-driven, turnover-driven and synergy changes. LCM represents the changes between the LCM_2005 and LCM_1860 simulations (including land management), while LCC represents the changes between the LCC_2005 and LCC_1860 simulations (excluding land management). The “grasses to crop regions” also include regions where pastures have been converted to crop.

in the estimates by Haberl et al. (2007), while in the present-day simulation wood harvest amounts to about 0.8 Pg C/yr. Therefore, the larger difference between the simulated harvest and their estimate is likely due to the differences in the crop harvest or forages consumed by livestock that are not accounted for in the model. While the estimates by Haberl et al. (2007) are based on harvest data, in the model one constant parameter is applied for all the grid cells in the globe for the fraction of crop biomass that is harvested versus left on site. This parameter is quite uncertain and may vary depending on the crop type (Nyawira et al., 2016). Increasing the fraction of crop harvest would lead to larger global losses through the input-driven contribution.

Humans can manage soil carbon inputs through many ways, such as the choice of crop and tree species, fire management or residue management (see references in Erb et al., 2016b). By contrast, except for tillage and ploughing on croplands, the effects of management on soil carbon turnover are more indirect, and occur through processes in the soils that control decomposition; the turnover-driven effects are thus less directly manageable than those related to input. Current projections show a higher land management intensity for present-day compared to pre-industrial land use. Global human population is projected to rise in the future, with the rise expected to cause a scarcity of productive land (Lambin and Meyfroidt, 2011). As a result of this, land management on current ecosystems will most likely intensify to fulfill the increasing demand for food, shelter and livestock feeds. This will in turn decrease soil carbon inputs and enhance global soil carbon losses via the input-driven changes. With its substantial effects on the input-driven changes future LUC is likely to offset gains in soil carbon associated with climatic effects (Koven et al., 2015).

3.3.4 Model limitations and the implications of missing processes

The YASSO sub-model captures the first-order dependence of soil carbon dynamics based on temperature and precipitation, as these are the measurable variables for the litter-bag experiments used in the parametrization of the decomposition rates. YASSO has been shown to provide estimates of litter decomposition and soil carbon storage without biases across the different climatic conditions (Tuomi et al., 2009; Goll et al., 2015). However, second-order effects associated with changes in soil moisture and soil temperature following LUC are not captured. Overall, it should be noted that the turnover-driven changes estimated in this study are predominantly due to changes in the litter quality, but the PFT-dependent decomposition rates and fire effects additionally influence the simulated turnover.

In addition, land management practices other than crop and wood harvesting that influence the carbon turnover and the vegetation productivity are still missing in JSBACH. Tillage in croplands has been shown to increase historical carbon losses in other DGVMs due to the enhanced litter decomposition resulting from soil disturbances (Levis et al., 2014; Pugh et al., 2015). Although tillage amplifies the turnover-driven losses in these models, field observations still do not agree on its role in soil carbon cycling, with some studies showing that the adoption of no tillage does not significantly increase soil carbon stocks (e.g., Baker et al., 2007).

Furthermore, the DGVM JSBACH does not represent the increase in crop productivity associated with fertilizer and manure application. However, increased crop productivity may not necessarily translate to higher litter inputs to the soils as most of the NPP is removed by crop harvesting. In addition, some studies show that in some regions the application of nitrogen fertilizers enhances decomposition and this effect counteracts the effect of added litter inputs associated with enhanced productivity (e.g., Russell et al., 2009). As the relative share of the simulated input-driven and turnover-driven changes will be influenced by the inclusion of the missing processes, the results shown in this study may not represent the total LUC effects.

3.4 Summary of chapter 3

This study has demonstrated how the factor separation analysis can be used in assessing the relative contribution of the input-driven and turnover-driven controls on soil carbon changes after land-use change (LUC). On the global scale, both the input-driven and turnover-driven changes have contributed to the changes in soil carbon associated with LUCs over the industrial era, with the input-driven contribution being larger than the turnover-driven contribution in JSBACH. Crop and wood harvesting enhance historical soil carbon losses mainly through the input-driven changes. Thus, less management of current ecosystems is expected to reduce the committed soil carbon losses from past LUCs. Given that dynamic global vegetation models (DGVMs) differ widely in there representation of soil carbon dynamics, I encourage the application of this approach in other DGVMs and in model-intercomparison projects. This would facilitate a more robust quantification of the input-driven and turnover-driven changes and an assessment of the uncertainties associated with how different processes influence the controls.

Chapter 4

Accelerated turnover of terrestrial carbon due to land-use change

4.1 Introduction

The turnover time of carbon is an important quantity that determines the net CO_2 flux between the terrestrial biosphere and the atmosphere. Therefore, changes in the turnover of carbon are likely to have substantial effects on the carbon cycling in the terrestrial biosphere. Recent studies show that the response of the vegetation and soil to future changes in CO_2 and climate, simulated by different global models, is highly uncertain with the turnover changes contributing largely to this uncertainty (Friend et al., 2014). Despite the wide application of models in quantifying the terrestrial carbon changes, a comprehensive model-based analysis on the effects of land-use change (LUC) on the turnover of terrestrial carbon has so far been lacking. To understand terrestrial CO_2 exchanges, there is need to assess how the turnover of carbon changes with LUC.

LUC affects the turnover of carbon through its direct influence on the carbon stocks and the carbon fluxes in the terrestrial biosphere. In a recent study, Erb et al. (2016a) applied various data sets to assess the effects of land use on the turnover time of vegetation carbon. They found an acceleration in the vegetation carbon turnover time, with the turnover time of the present-day land use being half of that of the natural vegetation that would prevail in the absence of human interference. This acceleration is caused by two main factors. First, the replacement of natural vegetation with agricultural systems or pastures reduces the carbon stocks in the vegetation (e.g., Pongratz et al., 2009). Second, a substantial part of the net primary production (NPP) in plants is nowadays utilized by humans in different ways or consumed by livestock (Vitousek et al., 1986; Imhoff et al., 2004; Haberl et al., 2007), contributing to a further reduction in the vegetation carbon stocks. The observations-based estimate by Erb et al. (2016a) provide evidence that indeed land use has an effect on the vegetation carbon turnover time. However, due to the limited availability of reliable soil data, the effects of land use on the soil carbon turnover time have not been assessed. Since the processes in the terrestrial biosphere influence the vegetation and soil carbon dynamics in different ways, the effects of LUC on the carbon turnover time may differ between the vegetation and soils. Thus a comprehensive assessment of LUC effects on the carbon turnover time necessitates the inclusion of soils.

The amount of carbon stored in the vegetation is driven by the climate and CO_2. Interannual variations within the Earth system affect the vegetation carbon sink (e.g., Cao et al., 2005), mainly through influencing the carbon fluxes of net primary production (NPP) (Cao et al., 2004). Changes in the carbon turnover time can cause shifts in the distribution of carbon between pools and the carbon fluxes, which in turn affects the transition time of carbon within the terrestrial biosphere (Friend et al., 2014). Therefore, the observed acceleration in the vegetation carbon turnover time of the present-day land use will most likely affect the vegetation's response time to interannual variations.

In this chapter, I present an analysis of the effects of historical LUC on the turnover time of terrestrial carbon using equilibrium simulations of the present-day land use and a potential map with only natural vegetation. As a first step, the simulated acceleration in the vegetation carbon turnover time is compared to the observations-based estimate by Erb et al. (2016a). In a second step, the analysis is extended to soils to obtain the acceleration in the entire terrestrial carbon turnover time. In addition, sensitivity simulations excluding fire and harvest are used to assess the effects of these processes on the turnover acceleration. Lastly, I analyse the impact of the turnover acceleration on the vegetation's response time. For this, CO_2 pulses are applied to equilibrium states of the potential vegetation and present-day land use and the temporal development of carbon in these two vegetation distributions is analysed.

4.2 Methods

4.2.1 Simulations with present-day land use and potential vegetation

The dynamic global vegetation model (DGVM) JSBACH was used for all the simulations in this study. A detailed description of the carbon cycle model within JSBACH can be found in section 2.2.2 in chapter 2. Two sets of JSBACH simulations that differed in terms of the prescribed vegetation distribution were performed.

The first simulation was performed with a potential vegetation map consisting of only the natural plant functional types (PFTs), i.e. forests, shrubs and grasses (map details in Pongratz et al., 2008). The second simulation was performed using the present-day land use map (2005), consisting of both the natural PFTs as well as the anthropogenic PFTs (crops and pastures). This map was derived using the potential vegetation map in Pongratz et al. (2008) and the crop and pasture fractions from Hurtt et al. (2011). In both of these simulations, JSBACH was driven by present-day CO_2 concentrations (367 ppm) and 2001 to 2010 from the Climate Research Unit (CRU) reanalysis data (Harris et al., 2014). From these simulations the set of drivers required for running JSBACH's carbon cycle sub-model were obtained. These include; Net Primary Production (NPP), Leaf Area Index (LAI) and other environmental drivers for the disturbances module.

Using the obtained drivers the carbon-cycle model was run for both of the two land cover maps with different simulation settings (Table 4.1). In the standard simulation for the present-day land use, the crop harvesting scheme introduced in section 2.2.3 in chapter 2 was applied and the 2005 wood harvest map from Hurtt et al. (2011) was prescribed. Natural disturbances were switched on in the standard simulations, for both the present-day land use and potential vegetation, with windthrow only occurring on the woody PFTs and fire occurring on all natural PFTs and pastures but not on crops. The model was run until the vegetation and soil carbon pools were in equilibrium.

In addition to these two standard simulations, I performed sensitivity simulations that excluded fire or crop and wood harvest. Both harvesting and fire contribute in changing the life time of carbon in the vegetation and soil. Fire shortens the lifetime of carbon through the direct release of carbon from the vegetation and soil to the atmosphere, while harvesting transfers carbon from the vegetation to anthropogenic pools (paper and construction), which have different carbon life time. In addition, some part of the wood harvest is transferred to the litter where it decomposes with the YASSO decomposition rates. In the simulations with no harvest, the wood harvest map for the present-day land use simulation was not prescribed and the harvested biomass for the croplands went to the litter pool. These sensitivity simulations were used to assess the effect of these two processes on the carbon turnover. Table 4.1 summarizes the different simulations and the acronyms used in presenting the results.

4.2.2 Estimating the equilibrium turnover time and the acceleration factors

The turnover time for the vegetation, soil and the total terrestrial carbon was calculated using the respective carbon densities and fluxes. Equations 4.1, 4.2 & 4.3

Table 4.1: A Summary of the different simulations in this study.

Land cover map	Acronym	Crop & Wood harvest	Disturbances (fire)	Wood structural limits [a]
Potential vegetation	pot_std	n/a	on	standard & adjusted
	pot_nofire	n/a	off	standard
Present-day vegetation (2005)	prd_std	on	on	standard & adjusted
	prd_noharv	off	on	standard & adjusted
	prd_nofire	on	off	standard

[a] In JSBACH the amount of carbon in the wood pool is constrained using maximum carbon densities. The simulations with the adjusted structural limits were used to assess how this limits influence the response of the vegetation to additional CO_2 (see details in section 4.3.4).

show the equations applied in calculating the turnover of carbon for the soil (τ_{soil}), vegetation (τ_{veg}) and the terrestrial biosphere (τ_{eco}) for the simulations in table 4.1. C_{soil} is the total carbon in the soil pools, $f_{outgoing}$ are the outgoing carbon fluxes from the soil to the atmosphere, obtained by summing the soil respiration and the fire losses. C_{veg} is the total carbon in the vegetation pools and NPP is the net primary production. It should be noted that τ_{soil} can also be calculated using the litter fluxes, because in my simulations the soil carbon pools are in equilibrium and the total incoming litter fluxes are thus equal to the outgoing fluxes. The turnover time calculated using these equations can also be interpreted as the residence time of carbon in the vegetation, soil and the terrestrial biosphere (see Sierra et al., 2016).

$$\tau_{soil} = \frac{C_{soil}}{f_{outgoing}} \tag{4.1}$$

$$\tau_{veg} = \frac{C_{veg}}{NPP} \tag{4.2}$$

$$\tau_{eco} = \frac{C_{soil} + C_{veg}}{NPP} \tag{4.3}$$

To assess the effects of LUC on the carbon turnover time, acceleration factors were quantified by dividing the turnover time of the potential vegetation simulation with that of the present-day land use simulation. The acceleration factor indicates how long the equilibrium turnover time in the potential vegetation is compared to the present-day land use. The definition of the turnover acceleration used in this study allows for a direct comparison to the results by Erb et al. (2016a). Equations 4.4, 4.5 & 4.6 show how the acceleration factors were calculated: The terms on the right hand side of these equations are the equilibrium turnover times obtained from the simulations listed in Table 4.1. These factors were calculated separately for the vegetation, soil and the terrestrial carbon turnover time.

$$acc_{\tau\_std} = \frac{\tau_{pot\_std}}{\tau_{prd\_std}} \tag{4.4}$$

$$acc_{\tau\_noharv} = \frac{\tau_{pot\_std}}{\tau_{prd\_noharv}} \tag{4.5}$$

$$acc_{\tau\_nofire} = \frac{\tau_{pot\_nofire}}{\tau_{prd\_nofire}} \tag{4.6}$$

4.2.3 Simulations with artificially induced CO_2 pulses

The response of the potential vegetation and the present-day land use to CO_2 increase was analysed to assess the effect of the turnover time acceleration. This was achieved through an artificially induced one-year long CO_2 pulse in simulations with the potential vegetation and the present-day land use. To obtain the drivers for the carbon cycle sub-model for this one year, JSBACH simulations were performed with the potential vegetation and the present-day land use driven by 2001 CRU climate and the CO_2 concentration set to 450 ppm. Starting from the equilibrium states in Table 1.1, the carbon cycle model was run for each of the simulations for one year with the obtained drivers. In the subsequent years, the forcing with the present-day CO_2 concentration was repeated until the carbon pools were back in equilibrium. At high CO_2 levels the NPP is expected to increase mainly for forests, which have the C3 photosynthetic pathway, because rising CO_2 generally stimulates C3 photosynthesis more than C4 (Pearcy and Ehleringer, 1984; Lara and Andreo, 2011). Accordingly, the vegetation carbon storage increases within the one year of NPP increase and the additional carbon is expected to leave the vegetation after some time. The transient response of each of the simulations, including the sensitivity simulations, was analysed to assess the difference in the response to the additional carbon in the simulations with the two vegetation distributions.

4.2.4 Estimating the return time for the present-day land use and potential vegetation simulations

As the potential vegetation and the present-day land use have different turnover times, the time taken for the additional carbon to leave the vegetation in the simulations will be different. I introduced the return time as a timescale for quantifying the time taken for the added carbon to leave the vegetation. The return time depends not only on the initial turnover time of carbon, but also on the amount of additional carbon resulting from the NPP increase and how the added carbon is distributed in the different vegetation pools.

The NPP increase is expected to be higher in the potential vegetation compared to the present-day land use simulations, because the present-day land use includes more PFTs with the C4 photosynthetic mechanism, i.e. crops and pastures, which are less sensitive to CO_2 increase (Pearcy and Ehleringer, 1984; Lara and Andreo, 2011). As the goal is to assess the differences in the temporal response of the two vegetation distributions resulting from NPP uptake as well as the initial turnover time prior to the pulse, an approach is needed for isolating the latter effect. To do so, I normalized the change in the vegetation carbon with the additional NPP resulting from the CO_2 pulse (Eqn. 4.7). The normalization eliminates the differences in the amount of NPP uptake; thus the normalized carbon change shows the contribution of the initial turnover time.

To estimate the return time, I used a criterion based on the percentage of the normalized carbon change. The return time was estimated by counting the number of years it took for the percentage change to get below 10%. The results presented below are only for the vegetation, although the analysis was also conducted for the entire terrestrial biosphere. The normalization could not be done separately for the soils, because it is not possible to eliminate the differences in litter fluxes caused by differences in the additional NPP.

$$\Delta C_{veg,norm}(t) = \frac{\Delta C_{veg}(t)}{\Delta NPP} \tag{4.7}$$

4.3 Results

4.3.1 Comparison of the simulated turnover time of the vegetation carbon with observations-based estimates

I first compare the vegetation carbon turnover obtained from the simulations with the observations-based estimates by Erb et al. (2016a). As expected, and also in line with Erb et al. (2016a), the turnover time of the prd_std simulation is shorter than that of the pot_std simulation (Fig. 4.1a & Table C1). This is due to less woody biomass in the present-day land use compared to the potential vegetation, which is mainly caused by deforestation (Fig. C1a). Furthermore, wood harvest also contributes in shortening the life time of carbon in the prd_std simulation. There are notable differences between the model results and the observations-based estimates. In most of the regions the turnover time of the prd_std simulation is shorter than that in prd_erb16, while for all the regions the turnover of the pot_std simulation is shorter than in pot_erb16 (Fig. 4.1a). Excluding natural disturbances through fire results in a longer turnover time in both the potential vegetation and the present-day land use simulations (Fig. 4.1a & Table C1). Excluding crop and wood harvest results in a slightly longer turnover time for the present-day land use simulation in some regions.

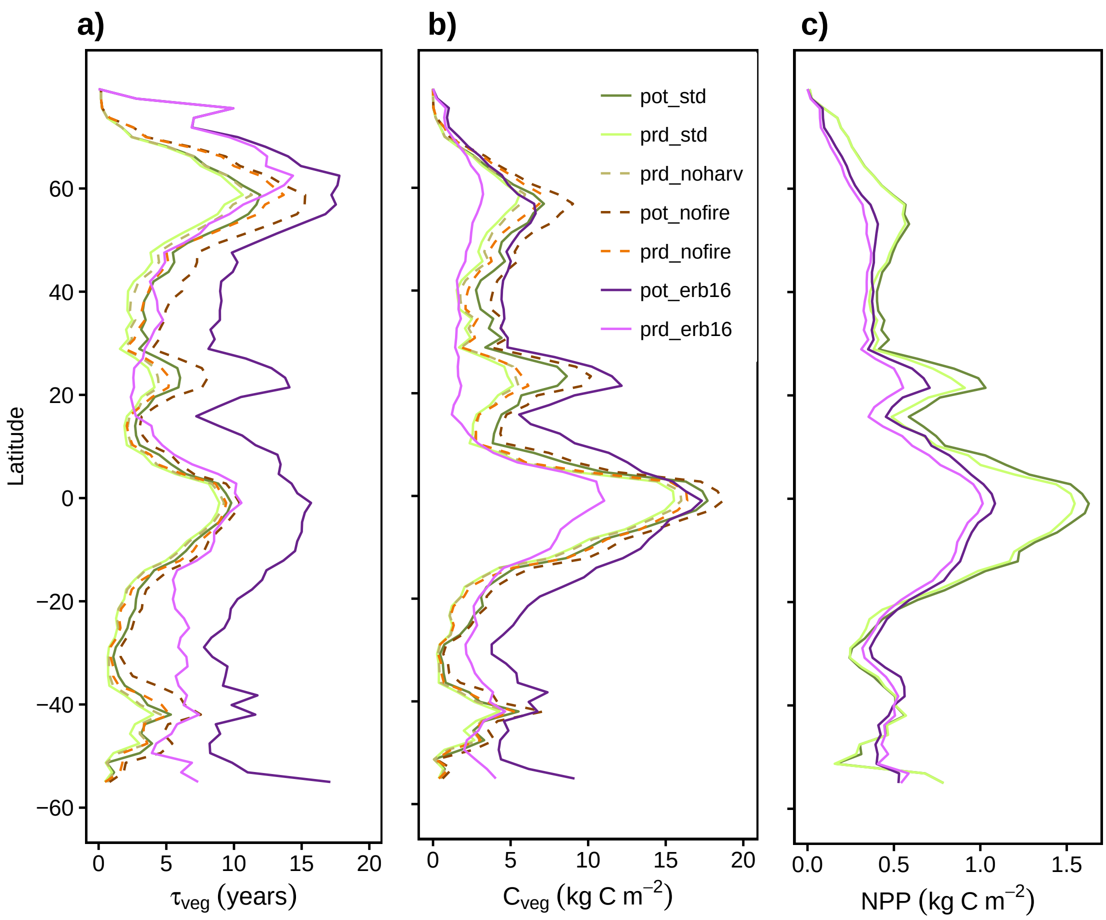


Figure 4.1: (a) The zonal means for the equilibrium vegetation carbon turnover times in the different simulations compared to the estimates by Erb et al. (2016a). The turnover times are calculated using equation 4.2. (b) Zonal means for the vegetation carbon densities. (c) Zonal means for the NPP. “pot” denotes the potential vegetation, while “prd” denotes the present-day land use. (see table 4.1 for the details of the simulations). pot_erb16 and prd_erb16 represents the turnover time of the potential vegetation and the present-day land use, respectively, in the estimates by Erb et al. (2016a).

To understand the discrepancies between the simulated vegetation carbon turnover and the data, I compared the vegetation carbon densities and the NPP with the estimates by Erb et al. (2016a). The NPP in both the potential vegetation and the present-day land use simulations is much larger than in these estimates (Figs. 4.1c & Table C1). The larger NPP translates into larger carbon densities for the present-day land use simulations compared to the observations-based estimates (Figs. 4.1b & Table C1). Despite the simulated NPP in the potential vegetation being larger than in the estimates by Erb et al. (2016a), the simulated carbon densities are smaller than in these estimates except for the inner tropics.

4.3.2 Simulated acceleration in the vegetation carbon turnover time

The global mean acceleration in the vegetation carbon turnover is about 17% less than in the observations-based estimate (1.89 in acc_{veg,τ_std} compared to 2.27 in acc_{veg,τ_erb16}) (Table 4.2). However, the difference in the acceleration is quite substantial on the regional level. Figure 4.2a & 4.2b show that compared to the estimate by Erb et al. (2016a), the simulated acceleration is small for most of the regions with LUC. The tropical deforested regions exhibit an acceleration of 1.82 compared to 2.90 in Erb et al. (2016a), while the extratropical deforested regions exhibit an acceleration of 2.51 compared to 3.97 (Table 4.2). The deforested regions in the extratropics show a larger acceleration compared to the tropics because of larger forest losses and a higher wood harvest intensity (Fig. C1). In some parts of Africa and South America there is hardly any simulated acceleration.

Table 4.2: The mean simulated acceleration in the vegetation carbon turnover time for the different model simulations compared to the observations-based estimates by Erb et al. (2016a). The acceleration factors were obtained by dividing the turnover time of the potential vegetation with that of the present-day land use. These values represent the factor by which the turnover time of the potential vegetation is longer than that of the present-day land use. See table C1 for the mean vegetation carbon turnover time for the individual simulations.

Acronym	Global	Tropics deforested	Extratropics deforested
acc_{veg,τ_erb16}	2.27	2.90	3.97
acc_{veg,τ_std}	1.89	1.82	2.51
acc_{veg,τ_noharv}	1.37	1.49	1.74
acc_{veg,τ_nofire}	2.09	2.00	2.70

The sensitivity simulations reveal that natural disturbances and harvest also influence the simulated acceleration. Excluding crop and wood harvest in the present-day land use simulation reduces the acceleration in some of the regions (compare

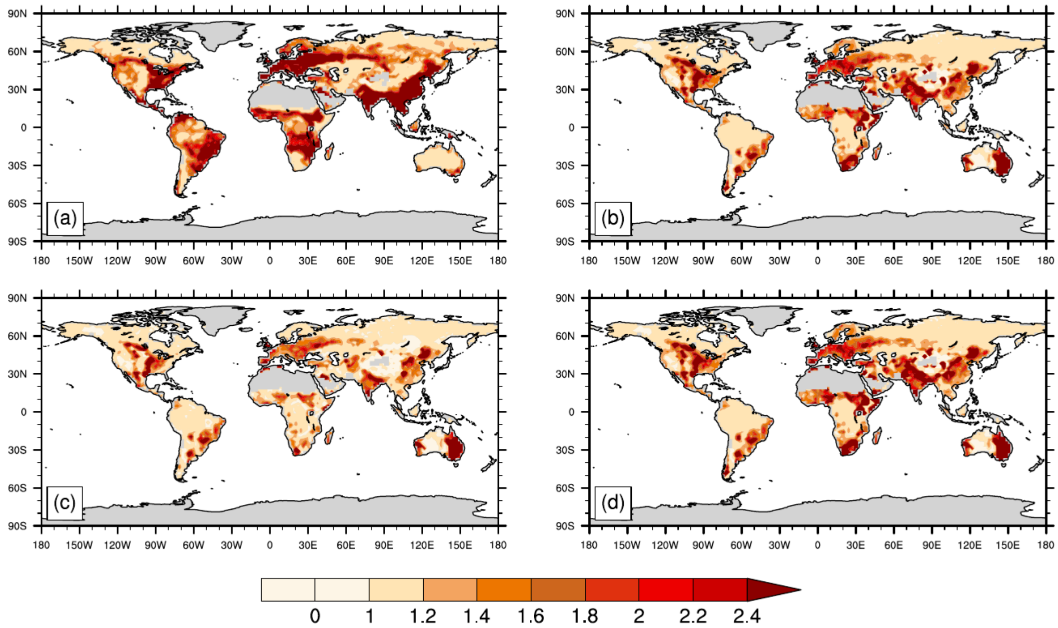


Figure 4.2: The simulated acceleration in the vegetation carbon turnover time for the different simulations compared to the observation-based estimate by Erb et al. (2016a). (a) The acceleration in Erb et al. (2016a) (acc_{veg,τ_erb16}), (b) the acceleration in the standard simulations (acc_{veg,τ_std}), (c) the acceleration when crop and wood harvest are excluded in the present-day land use (acc_{veg,τ_noharv}), and (d) the acceleration when fire is excluded in both the present-day land use and potential vegetation (acc_{veg,τ_nofire}). The equations used in calculating the acceleration factors are described in section 4.2.2. The values represent the factor by which the turnover time of vegetation carbon in the potential vegetation is longer than that of the present-day land use. Values above 1 indicate an acceleration, while values below 1 indicate a deceleration.

Fig 4.2b & 4.2c), with the global mean acceleration being about 30% less than that estimated when accounting for harvest (Table 4.2). On the contrary, excluding fire increases the turnover acceleration, with the turnover of the potential vegetation being twice that of the present-day land use (Table 4.2 & Fig 4.2d), although the acceleration is still smaller than in Erb et al. (2016a). This is mainly because fire results in more carbon losses in the potential vegetation, which has only natural ecosystems, compared to the present-day land use where croplands are not exposed to fire.

4.3.3 Simulated acceleration in the terrestrial carbon turnover time

While an acceleration in the vegetation carbon turnover is likely to affect the short-term exchange of CO_2 fluxes between the terrestrial biosphere and the atmosphere, an acceleration in the soils would have implications for the terrestrial carbon cycling on longer time scales. The simulations in this study allow for an extension of the analyses to the soils and thus to the entire terrestrial carbon.

Table 4.3: The mean simulated acceleration in the soil and terrestrial carbon turnover time for the different simulations. The acceleration factors were obtained by dividing the turnover time of the potential vegetation with that of the present-day land use. The values represent the factor by which the turnover time of the potential vegetation is longer than the present-day land use. See table C2 for the mean soil and total terrestrial carbon turnover time for the individual simulations.

Acronym	Global	Tropics deforested	Extratropics deforested
acc_{soil,τ_std}	1.01	1.05	1.05
acc_{soil,τ_noharv}	1.01	1.05	1.05
acc_{soil,τ_nofire}	1.03	1.06	1.07
acc_{eco,τ_std}	1.14	1.30	1.35
acc_{eco,τ_noharv}	1.05	1.17	1.16
acc_{eco,τ_nofire}	1.16	1.34	1.40

Figure 4.3a shows that the simulated acceleration in the soil carbon turnover time is quite small compared to the one in the vegetation. The global mean acceleration is 1.01, while the deforested regions in the tropics and extratropics show an acceleration of 1.05 (Table 4.3). The dry and arid regions in central Asia, Europe and some parts of Africa, show a deceleration (Fig. 4.3a & 4.2b). These are mainly regions where grasslands have been converted to croplands. In these regions, cropland expansion results in the decline of the soil carbon losses through fire, because croplands are not exposed to burning in my simulations. As a result, the soil carbon turnover time is longer for the present-day land use simulation compared to the potential vegetation

simulation (Table C2).

Excluding crop and wood harvesting has no effect on the soils (Table 4.3). Similar to the vegetation, a higher acceleration is found when fire is excluded in most of the regions. Due to the small acceleration in the soils, the total acceleration in the terrestrial carbon turnover time is also small (Fig. 4.3b & Table 4.3). Overall, these results show that accounting for the total terrestrial carbon results in a small turnover time acceleration in JSBACH.

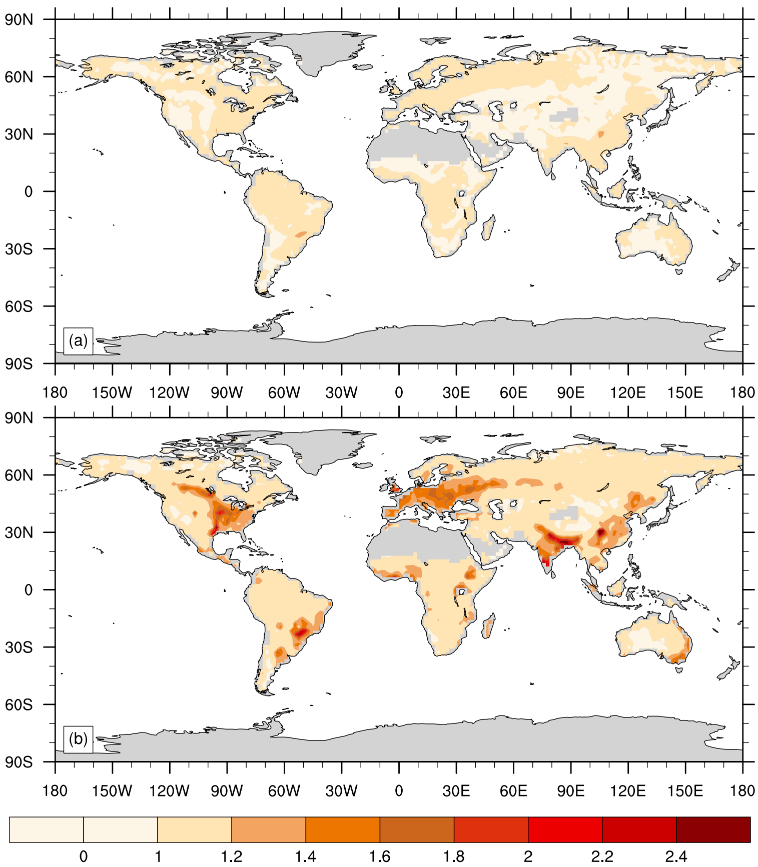


Figure 4.3: (a) The simulated acceleration in the soil carbon turnover time (acc_{soil,τ_std}), (b) the simulated acceleration in the total terrestrial carbon turnover time (acc_{eco,τ_std}). The values represent the factor by which the turnover time of the soil and the total terrestial carbon in the potential vegetation is longer than that of the present-day land use. Note that the turnover acceleration for the sensitivity simulations are not included here. Values above 1 indicate an acceleration, while values below 1 indicate a deceleration.

4.3.4 Comparison of the vegetation response to additional carbon

4.3.4.1 Global response

I compare the response of the potential vegetation and the present-day land use to the additional carbon resulting from the CO_2 pulse. As expected, the NPP increase caused by the CO_2 pulse results in more vegetation carbon uptake in the potential vegetation than in the present-day land use, because of larger forest areas (Fig. 4.4). Furthermore, the decline in the forest areas leads to a quicker loss of the additional carbon in the present-day land use compared to the potential vegetation, because less carbon is allocated in the long-lived wood pool (Fig. 4.2). Normalizing the change in vegetation carbon with the NPP increase from the pulse reduces the difference in the response between the potential vegetation and present-day land use simulations, with notable differences mainly in the deforested regions in the extratropics (Fig. 4.5). This shows that much of the difference in the response of the two vegetation distributions is due to the NPP uptake after the CO_2 increase, while a smaller difference is due to the initial turnover prior to the CO_2 pulse.

The global mean return time is 25 years in the potential vegetation simulation (pot_std) and 23 years for the present-day land use simulation (prd_std) (Table 4.4). For the extratropical deforested regions, the mean return time is 40 years and 32 years in the pot_std and prd_std simulation, respectively, while for the tropical deforested regions there is hardly any difference between the two simulations. Although excluding harvest resulted in a longer turnover time, the return times in the prd_std and prd_noharv simulations are almost the same. Similar to the turnover times, excluding fire results in a longer return time in both the potential vegetation and present-day land use simulations (Table 4.4). Overall, on average the carbon stays longer in the potential vegetation compared to the present-day land use.

Table 4.4: The mean return time in years averaged over the globe and the deforested regions in the tropics and the extratropics (± std).

Acronym	Global	Tropics deforested	Extratropics deforested
pot_std	25±27	40±24	40±28
prd_std	23±26	39±25	32±27
prd_noharv	23±26	38±25	32±27
pot_nofire	30±31	46±26	47±33
prd_nofire	28±31	42±26	38±33

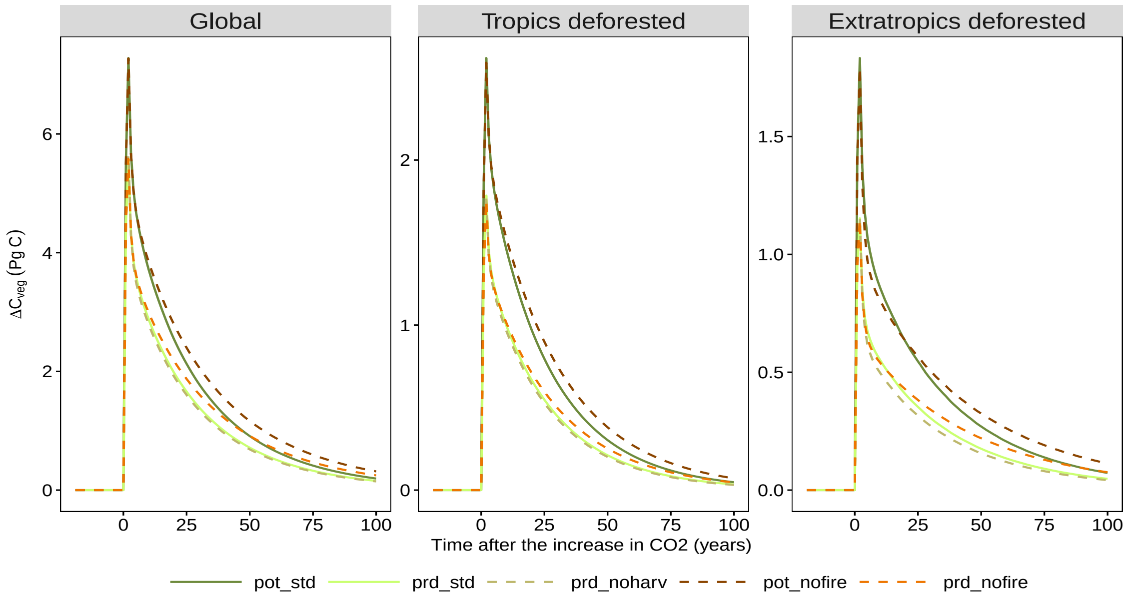


Figure 4.4: The temporal evolution of the additional carbon resulting from the CO_2 pulse summed over the entire globe, over the deforested regions in the tropics and over the deforested regions in the extratropics.

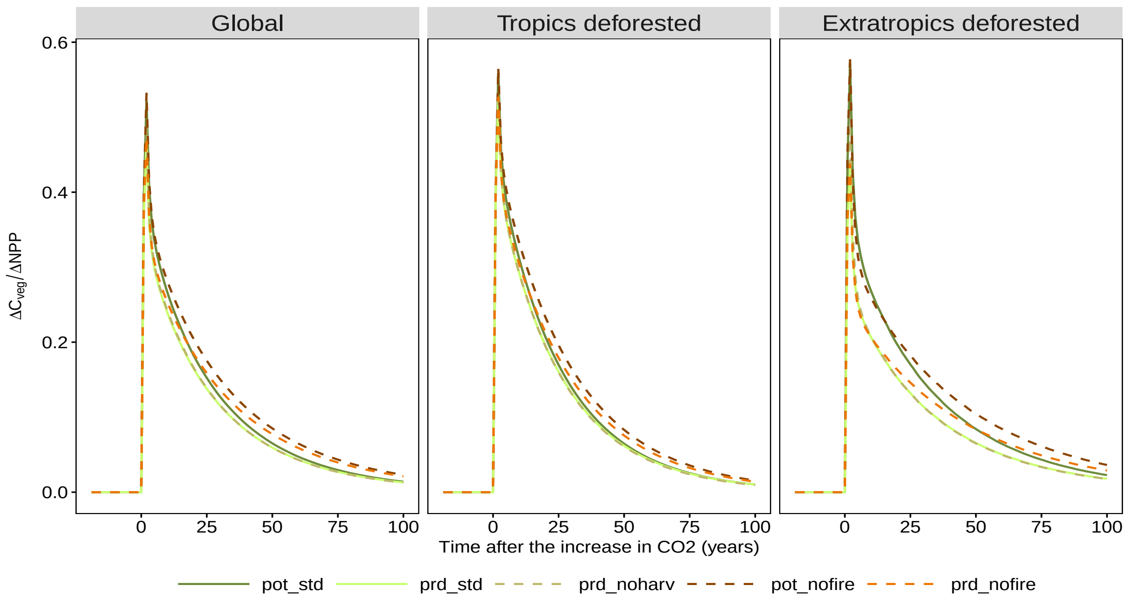


Figure 4.5: The normalized temporal evolution of the additional carbon resulting from the CO_2 pulse. The curves were obtained by summing the total additional carbon over the globe, deforested regions in the tropics and deforested regions in the extratropics at every time step and then dividing the spatial sum with the total added NPP over these regions.

4.3.4.2 Spatial patterns of the return time difference

Analysis of the spatial patterns reveal that the return time difference varies across the regions with LUC. The return time of the pot_std simulation is longer than that of the prd_std simulation in the deforested regions in Europe (Figure 4.6a). The return time difference in these regions is reduced when harvest is excluded in the present-day land use simulation, while the simulations with no fire exhibit generally similar patterns as the standard simulations (Figure 4.6). Despite the shorter turnover time in the deforested regions in the East Coast of the USA and East Asia for the present-day land use (Fig. 4.2), the return time in the prd_std simulation is longer than that in the pot_std simulation (Fig. 4.6a). There is hardly any difference in the return time in these regions when harvest is excluded in the present-day land use simulation (Fig. 4.6b). However, the longer return time for the prd_std simulation is still evident in the East Coast of the USA in the simulations with no fire (Fig. 4.6c). These results show that an acceleration in the carbon turnover time does not always lead to a quicker loss of additional carbon in JSBACH.

To understand these results, I analyzed the distribution of carbon in the pot_std, prd_std and prd_noharv simulations. Figure 4.7 shows that in the regions where the return time for the prd_std simulation is longer than that of the pot_std simulation (e.g., East USA), very little of the additional NPP ends up in the wood pool in the vegetation. By contrast, in regions where the return time for the pot_std simulation is longer than that of the prd_std simulation (e.g., Central Europe) much of the additional NPP is added to the wood pool. Excluding wood harvest also results in less carbon allocation to the wood pool in the prd_noharv simulation. This result can be explained by the carbon allocation scheme in JSBACH, whereby the carbon content of the wood pool is constrained using PFT-dependent structural limits. In equilibrium, the amount of carbon in the wood pool in the prd_std simulation is smaller than that in pot_std and prd_noharv simulations, because wood harvest decreases carbon in the vegetation pools. In the pot_std and prd_noharv simulations, the wood pool for extratropical PFTs is already at the maximum limit; hence much of the NPP resulting from the CO_2 pulse cannot be allocated to the wood pool. The additional carbon instead ends up in the short-lived non-woody pools or as excess NPP if the pools are full. As a result, the return time of the pot_std simulation is shorter than that of the prd_std simulation. Although not shown, this is also the case for the simulations with no fire in the East Coast of the USA. Thus, I conclude the distribution of the additional carbon explains the longer return time in the present-day land use compared to the potential vegetation.

To confirm this effect, I performed additional sensitivity simulations increasing the wood structural limits for the extratropical PFTs to levels close to those of the tropical PFTs (values in Table C3). The pot_std, prd_std and prd_noharv simulations were run again to equilibrium with the new structural limits followed by the simula-

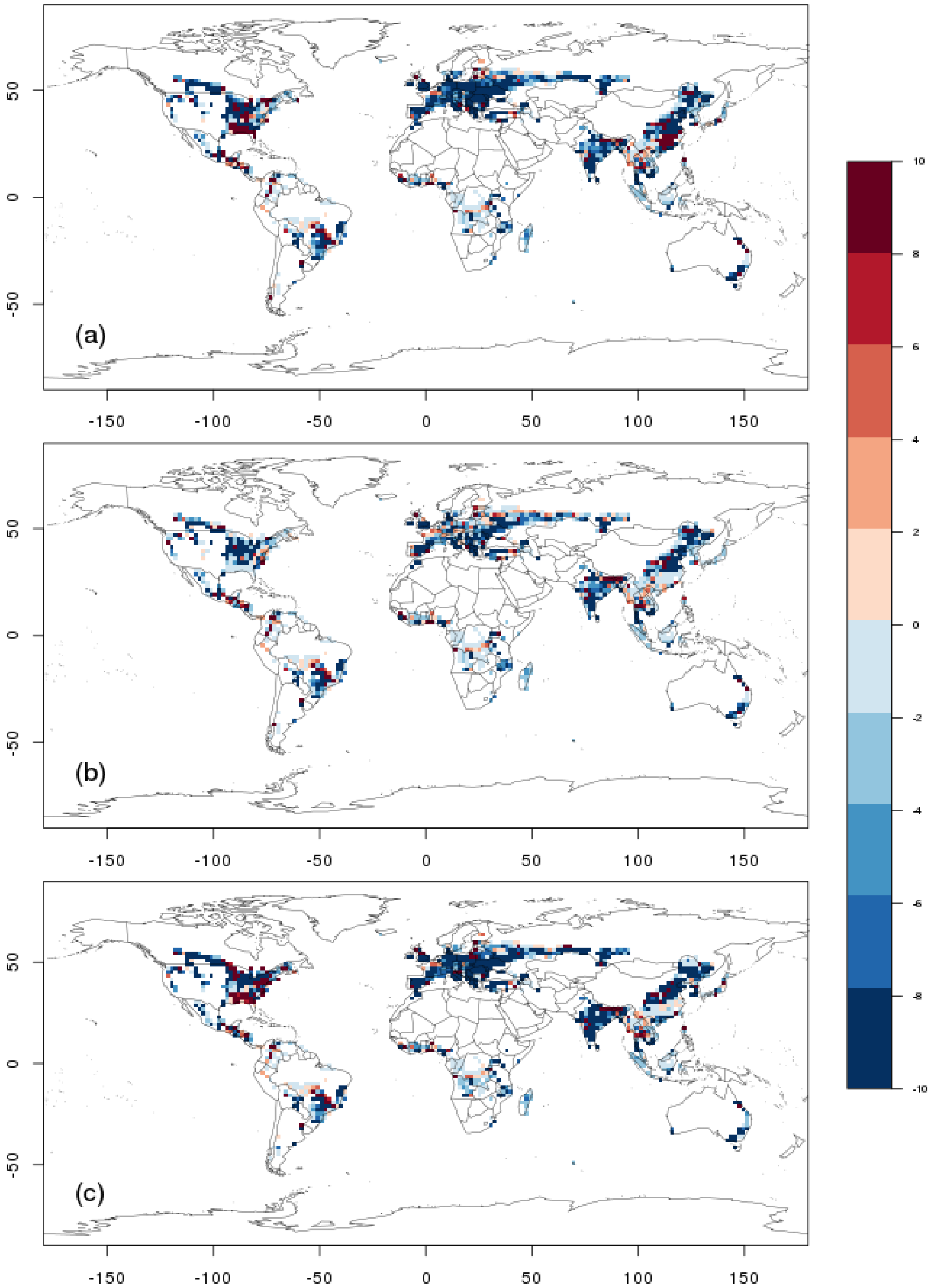


Figure 4.6: (a) The difference between the return time of the prd_std and pot_std simulations (prd_std-pot_std), (b) the difference between the return time of the prd_noharv and pot_std simulations (prd_noharv-pot_std), and (c) the difference between the return time of the prd_nofire and pot_nofire simulations (prd_nofire-pot_nofire). The values are only for the deforested regions. See section 4.2.4 for the details on how the return time was approximated.

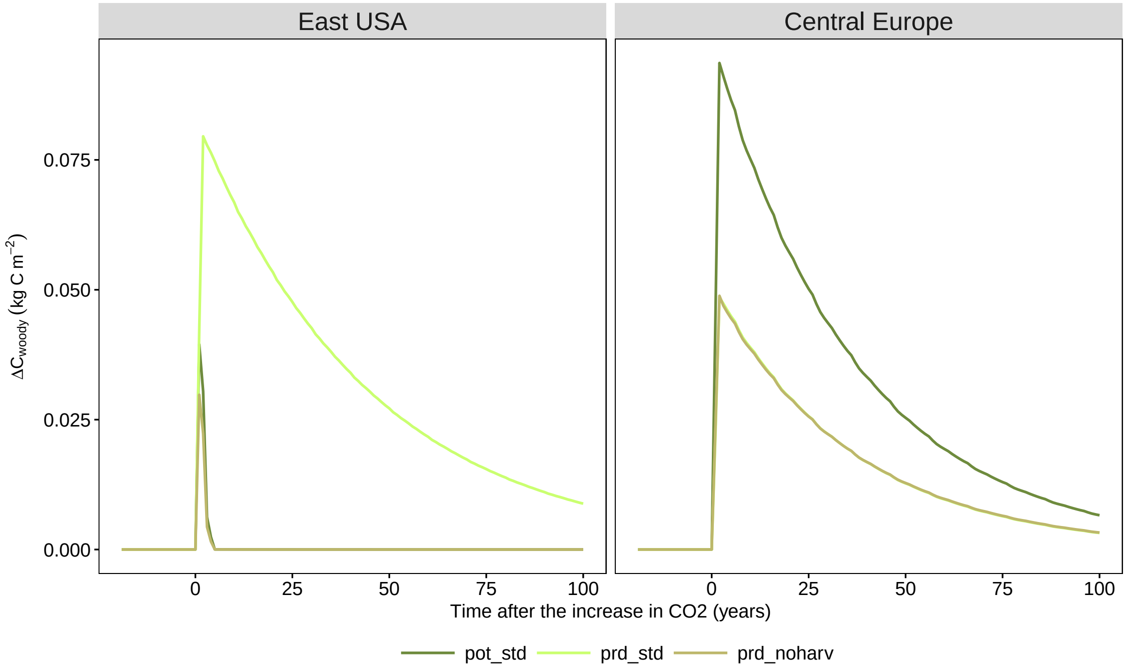


Figure 4.7: The temporal response of the added carbon in wood pool averaged over a selected region in the East Coast of the USA and Central Europe.

tions with the CO_2 pulse. The results show that by increasing the structural limits, the return time of the prd_std simulation is shorter than that of pot_std simulation in most of the regions (Fig. 4.8). In some of the regions the structural limits for the extratropical PFTs are still reached; thus the return time is still longer for the prd_std simulation.

4.4 Discussion

4.4.1 Uncertainties in the vegetation carbon turnover time acceleration

Compared to the estimate by Erb et al. (2016a), the turnover acceleration in the vegetation carbon turnover time is small (Fig. 4.2). Although this is always the case for all the regions with substantial LUC, the acceleration in the observation-based estimates spans a large range of uncertainty (Fig. 1 in Erb et al. (2016a)). This uncertainty is partly associated with the vegetation carbon densities used in estimating the turnover time. The carbon densities in the observation-based estimates are derived using the biome approach where a single value for a specific biome is extrapolated over large regions. Such an extrapolation does not account for the spatial variability in the vegetation productivity across the different climate

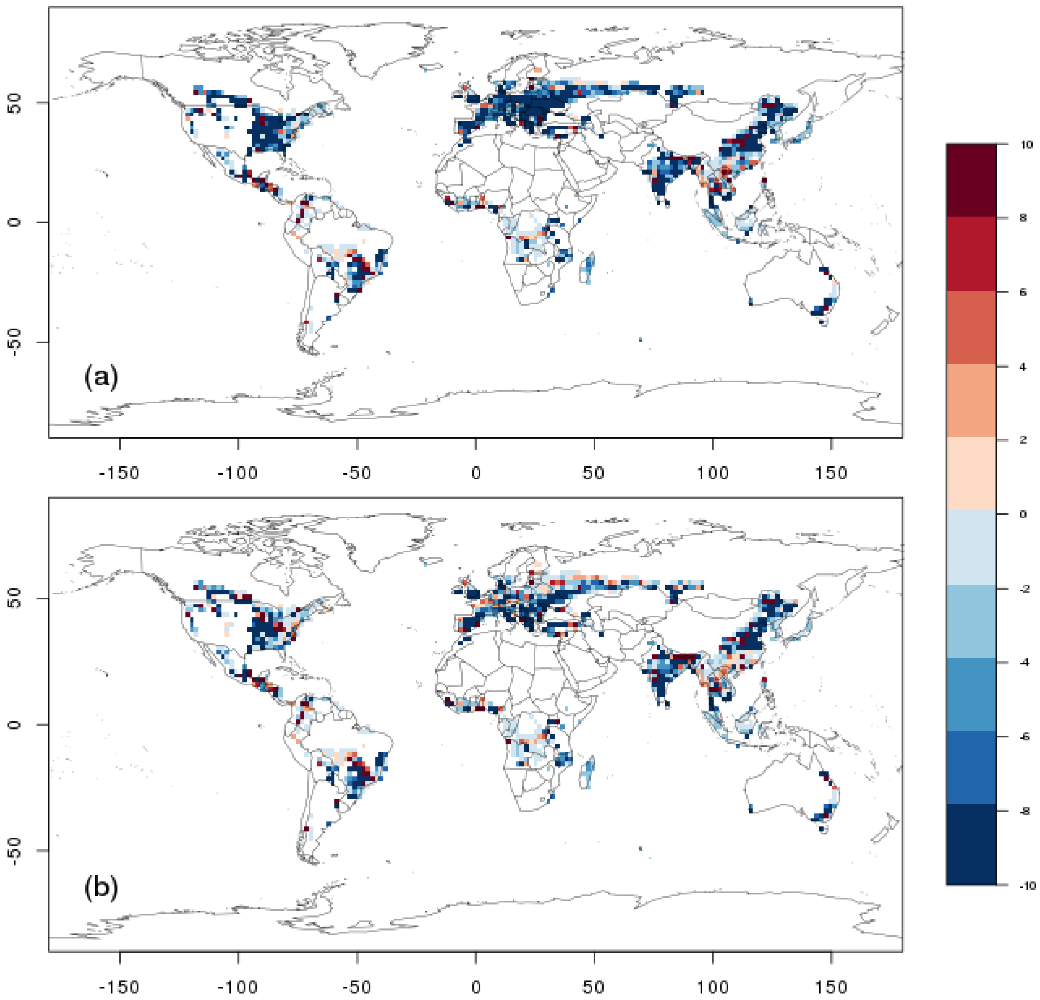


Figure 4.8: The difference between the return times of the present-day land use and the potential vegetation simulations with the adjusted JSBACH wood structural limits. (a) The difference between the return time of the prd_std and pot_std simulations (prd_std-pot_std) and (b) the difference between the return time of the prd_noharv and pot_std simulations (prd_noharv-pot_std). The values are only for the deforested regions. See section 4.2.4 for the details on how the return time was approximated.

zones. In addition, as demonstrated by the sensitivity simulations, excluding fire substantially increases the vegetation carbon densities (Fig. 4.1b & Table 4.3); thus extrapolating values obtained from undisturbed ecosystems will most likely lead to an overestimation of the carbon densities. This may explain why the turnover time for the potential vegetation in Erb et al. (2016a) is much longer than in the model estimate (Fig. 4.1), leading to a larger acceleration in the vegetation carbon turnover (Fig. 4.2).

The turnover time of the present-day land use is highly influenced by the carbon removed through different land management practices, such as crop and wood harvesting and grazing. An underestimation of the carbon removed by these processes would result in a longer turnover time for the present-day land use, which subsequently results in a smaller acceleration. A comparison of the amount of NPP removed via harvest in the model with observation-based estimates revealed that JSBACH tends to underestimate harvest in the present-day land use (Chapter 3). This underestimation stems from the prescribed wood harvest, the amount of carbon removed by grazing and in addition the uncertainty in the crop harvest parameters. Increasing the harvest intensity would result in a larger acceleration, because the turnover time of carbon in the present-day land use would be short. As more global observation-based estimates of land management processes become available, the parameters governing key processes such as grazing and crop harvest should be well constrained in DGVMs. This is important as land management is a key factor contributing to the acceleration in the carbon turnover time (Erb et al., 2016a).

4.4.2 Model limitations and uncertainty in the model structure

The results show that compared to the vegetationthe acceleration in the soil carbon turnover time is small (compare Fig 4.2 & 4.3). This is despite the difference in the decomposition rates of wood and non-woody litter. As the potential vegetation contains more forests, one would expect that the large amounts of woody litter to translate into longer turnover times in the potential vegetation. YASSO simulates decomposition based on air temperature and precipitation, which are the same for the present-day land use and potential vegetation in my simulations. Thus the small acceleration in the soil carbon turnover time could be due to the missing second-order effects of LUC on soil moisture and soil temperature in YASSO. Furthermore, soil disturbances exerted on cropland regions through tillage have an effect on turnover of carbon in the soils. Previous studies show that accounting for tillage leads to higher carbon losses following the conversion of natural vegetation to croplands, because of the enhanced litter decomposition in soils (Levis et al., 2014; Pugh et al., 2015). Thus the acceleration in the soil carbon turnover time in the regions with cropland expansion is most likely underestimated in my study.

One of the factors that influences the vegetation carbon turnover time is the NPP distribution in the short-lived versus long-lived pools. JSBACH uses PFT-dependent fractions to allocate carbon into the long-lived wood pool and the short-lived green and reserve pools. The amount of NPP that can be allocated into the wood pool is constrained with a PFT-dependent maximum carbon content, while the allocation to the green and reserve pools is constrained by the LAI and the maximum LAI, respectively. The results in this study show that the wood structural limits have an influence on how different vegetation distributions respond to additional CO_2 (Fig. 4.7). The response of plants to high CO_2 concentrations is still heavily researched with some studies showing that vegetation biomass saturates at high productivity values (Keeling and Phillips, 2007), while other studies show that plants may shift the allocation to the roots (Dieleman et al., 2012). However, the choice of one global parameter per PFT to represent the wood pool saturation does not capture the spatial variability of growth-limiting factors like nutrients and water availability (references in Poorter et al., 2011). Further analyses are still needed to assess the validity of the wood structural limits, as the carbon distribution in the vegetation is a key factor governing the turnover of carbon and the response to additional CO_2.

4.4.3 Implication for the terrestrial carbon cycle

The vegetation's carbon response to additional CO_2 is influenced by the NPP and the turnover time. Recent studies showed that models agree quite well on the NPP response to changes in the climate and CO_2, while the turnover response is highly uncertain (Friend et al., 2014; Koven et al., 2015). The analysis with the CO_2 pulses in different vegetation distributions contribute to our understanding of the role played by the NPP and turnover in influencing the vegetation carbon's response to additional CO_2. The results in this study show that eliminating the intrinsic differences in the NPP uptake substantially reduces the difference in the temporal response of the potential vegetation and present-day land use (compare Figs. 4.4 & 4.5). This suggests that the vegetation's response to high CO_2 is mostly governed by the NPP uptake, while the turnover plays a small.

The CO_2 pulse simulations show that the equilibrium turnover time, which is an ecosystem property that emerges from the multifaceted dynamics of carbon in different pools, may not always be indicative of the vegetation's response to additional CO_2. Although the equilibrium vegetation carbon turnover time is shorter in all the regions with LUC for the present-day land use (Fig. 4.2), the response to added carbon varies spatially across the different regions. Contrary to the expectation that the shorter turnover time of carbon in the present-day land use would translate to a faster carbon loss, the present-day land use exhibits a slower carbon loss compared to the potential vegetation in some regions (Fig. 4.6). This result suggests that in JSBACH managed forests may buffer the variability in CO_2 increase more than unmanaged forests, through the allocation of more carbon to the long-lived wood pool in some of the regions. This result could be in line with a recent observations-based study that showed a large biomass production efficiency in managed forests in the temperate regions (Campioli et al., 2015). Despite the application of idealized CO_2 pulses, the effect of the management simulated in these regions may also be expected with realistic CO_2 increase.

4.5 Summary of chapter 4

In this study, I quantified the acceleration in the terrestrial carbon turnover time caused by historical LUC. The acceleration in the vegetation is smaller than that estimated by Erb et al. (2016a) in most of the regions with substantial LUC. I find that on global average, the turnover time of the potential vegetation is longer than that of the present-day land use by a factor of 1.89 compared to 2.27 in Erb et al. (2016a). In the deforested regions in the extratropics the turnover time for the potential vegetation is longer by a factor of 2.51 compared to 3.97 in Erb et al. (2016a), while in the deforested regions in the tropics the turnover is longer by a factor of 1.82 compared to 2.90 in Erb et al. (2016a). The sensitivity simulations show that excluding crop and wood harvesting reduces the acceleration by about 30%; hence in line with Erb et al. (2016a) much of the simulated acceleration stems from the conversion of natural forests to agricultural lands. Furthermore, natural disturbances through fire influence the simulated acceleration with the exclusion of fire increasing the acceleration by about 10%. Extending the analyses to soils shows that the simulated acceleration in the soil carbon turnover time is quite small. In the deforested regions there is hardly any acceleration, while in regions where grasslands have been converted to croplands I find a deceleration in the turnover time that is caused by fire suppression on croplands. This result suggest the soil carbon turnover time in JSBACH is less sensitive to LUC. Due to the small acceleration in the soils, the acceleration in the entire terrestrial carbon turnover time is also quite small.

The idealized CO_2 pulse simulations show that the temporal response of the vegetation to additional carbon is mainly governed by the NPP uptake, while the turnover contribution is comparatively small. Despite the present-day land use exhibiting a shorter vegetation carbon turnover time than the potential vegetation in all the deforested regions, the difference in the return time after the CO_2 pulse differs across the regions. Consistent with the shorter turnover time, the return time in the deforested regions in central Europe is shorter in the present-day land use, while in the East Coast of the USA and Asia the return time is longer in the present-day land use. The latter effect is reduced when harvesting is excluded and the wood structural limits within the model are relaxed. This indicates that in the present-day land use an increase in CO_2 may lead to higher allocation of NPP to the long-lived wood pool, because wood harvest decreases the carbon in this pool. This finding may be consistent with a recent study showing a higher biomass production efficiency in managed compared to unmanaged forests (Campioli et al., 2015). However, an evaluation of the wood structural limits in JSBACH is needed to confirm the effect of more carbon allocation in managed compared to unmanaged forests.

The analysis of the temporal development of carbon in different vegetation distributions proved useful in understanding the role played by the turnover time in influencing the vegetation's response to additional CO_2. The presented results suggest that the equilibrium carbon turnover time may not be a clear indicator of the vegetation's response to CO_2 increase. Because DGVMs vary widely in their representation of carbon allocation, more studies are still needed to improve our understanding on the relevance of the equilibrium turnover time for vegetation carbon cycling.

Chapter 5

Conclusions and Outlook

The aim of this thesis was to provide an improved understanding of how LUC contributes to changes in the soil carbon sink and the terrestrial carbon turnover. This was achieved using simulations with the DGVM JSBACH and comparing the model results against observational datasets. In this concluding chapter, I revisit the research questions for the individual chapters highlighted at the beginning of the thesis. A summary of the findings for each question is provided. The implications of these results for terrestrial carbon modelling and recomendations for future work are provided at the end of this chapter.

5.1 Summary of findings

5.1.1 Development of a framework for evaluating DGVMs against the meta-analyses and applying it to JSBACH (Chapter 2)

- **How can the available meta-analyses on changes in soil carbon due to different LUCs be used in evaluating DGVMs?**
  This study developed a systematic framework for evaluating DGVMs against the meta-analyses. This included identifying a suitable simulation setup and choosing the criteria to be used for selecting the regions to be compared against the meta-analyses. I demonstrated that a comparison of the simulated relative and absolute changes in soil carbon against the meta-analyses can only be done using idealized LUC simulations. For selecting the regions for comparison of the model results against the meta-analyses two independent criteria were used: The first criterion was based on the climatic variables in the meta-analyses, while the second criterion was based on historical LUC. The DGVM JSBACH was evaluated using the established framework against the meta-

analyses by Don et al. (2011) and Poeplau et al. (2011). The comparison of the results from the two criteria showed that the meta-analyses are representative of the regions with historical LUC. The evaluation of the DGVM JSBACH against the meta-analyses demonstrates the applicability of the developed framework.

- **What does the model-data comparison reveal for the DGVM JSBACH?**
  The results show model agreement with the meta-analyses on the direction of soil carbon change for some LUCs, although the simulated magnitudes of change are smaller than in the meta-analyses. The conversion of crop to forest results in a relative change of 10% compared to 42% in the meta-analyses, while the conversion of forest to crop results in a change of -15% compared to -40%. However, the model and the meta-analyses disagree for the conversion of crop to grass and grass to crop. For the conversion of crop to grass the model simulates a loss of -4%, while the meta-analyses indicate and a gain of 38%. I showed that this deviation is partly due to fire, which contributes to soil carbon in losses in grasslands in the model. In addition, the lack of accounting for carbon removed through harvest in croplands contributes to the underestimation of changes in soil carbon for the considered LUCs. I therefore implemented an explicit crop harvesting scheme and showed that including crop harvest improves the response of soil carbon to LUC in JSBACH

- **What are the challenges involved in comparing DGVMs against the meta-analyses?**
  I identified two major challenges in comparing DGVMs against the meta-analyses: age and depth. The challenge with age is due to the differing times of when the local-scale measurements in the meta-analyses are taken after the LUC. The meta-analyses thus represent transient changes. My study shows that this challenge can be overcomed by age sampling in the idealized LUC simulations. The challenge with the depth is due to differing sampling depths in the local-scale measurements constituting the meta-analyses. While most DGVMs simulate soil carbon dynamics typically at 1 m depth, the local-scale measurements in the meta-analyses are done mainly at the top soil (0-30 cm depth). Although one solution could be scaling the soil carbon changes in the meta-analyses to model depths, the long-term solutions to this challenge are sampling at deeper depths in the local-scale measurements or including vertically resolved soil profiles in DGVMs.

5.1.2 Input-driven versus turnover-driven controls of changes in soil carbon due to LUC (Chapter 3)

- **How have the input-driven and turnover-driven controls contributed to the historical changes in soil carbon caused by LUC in simulations with the DGVM JSBACH?**
  I demonstrated how a factor separation analysis can be used to quantify the relative contribution of the input-driven and turnover-driven controls to the simulated total soil carbon changes caused by LUC. The analysis was applied to equilibrium simulations with the pre-industrial and present-day land use. This analysis shows that the turnover-driven changes contribute to a gain in soil carbon in afforested regions and a loss in deforested regions. The contribution of the input-driven changes varies depending on the vegetation productivity, with some grid cells exhibiting an input-driven gain following afforestation while others exhibit a loss. The regions where grasslands have been converted to croplands show an input-driven loss and a turnover-driven gain, which stems from the decrease in the fire-related carbon losses. Globally, I find a global loss of 54.0 Pg C: The input-driven and turnover-driven changes contribute to a loss of 54.7 Pg C and 1.4 Pg C, respectively, while the synergy effects of these two controls contribute a gain of 2.1 Pg C. Therefore, my study shows that historical soil carbon losses are dominated by the input-driven changes in JSBACH.

- **How are the two controls influenced by land management through crop and wood harvesting?**
  My study shows that crop and wood harvesting influence the changes in soil carbon mainly via the input-driven control, while their effect on the turnover-driven control is comparatively small. Harvesting reduces the soil carbon gain in the afforested regions and enhances the losses in regions with deforestation and where grasslands have been converted to croplands. On the global scale, excluding crop and wood harvest decreases the historical soil carbon losses from 54.0 Pg C to 22.4 Pg C, with the input-driven losses decreasing from 54.7 Pg C to 24.9 Pg C. This finding suggests that less management of current ecosystems can reduce soil carbon losses from historical LUCs.

5.1.3 Accelerated turnover of terrestrial carbon due to LUC (Chapter 4)

- **How strong is the LUC-induced acceleration in the terrestrial carbon turnover and how is it influenced by different processes in simulations with JSBACH?**

To assess how LUC has altered the turnover time of carbon in the terrestrial biosphere, the equilibrium turnover time of the present-day land use was compared to that of a potential vegetation with no land use. Acceleration factors were calculated by divided the turnover time of the potential vegetation with that of the present-day land use. The model results show that the vegetation carbon turnover time has accelerated due to LUC and harvesting. However, the simulated acceleration is smaller than in the observations-based estimates by Erb et al. (2016b). The results show that the deforested regions in the extratropics exhibit the strongest acceleration, with a simulated acceleration of 2.90 compared to 3.97 in Erb et al. (2016a). The acceleration for the deforested regions in the tropics is 1.82 compared to 2.51 in Erb et al. (2016a). About 70% of the simulated acceleration results from the historical conversion of natural forests to agricultural lands and pastures and only 30% is due to wood harvest. Compared to the vegetation, the acceleration in the soils is quite small, leading to a small acceleration in the entire terrestrial carbon turnover time.

- **How does the turnover acceleration affect the vegetation's response to additional NPP resulting from an increase in CO_2 increase?**
One-year long CO_2 pulses were applied to the equilibrium states of the present-day land use and the potential vegetation. The temporal development of carbon in the vegetation was analysed for the two vegetation distributions. The results show that the difference in the response of the potential vegetation and present-day land use mainly stems from the NPP uptake after the CO_2 increase, while the turnover plays a small role. Despite the present-day land use having a shorter equilibrium turnover time than the potential vegetation in all the regions with LUC, the difference in the return time after the CO_2 pulse differs across the regions. In central Europe, the return time to equilibrium after the CO_2 pulse is shorter in the present-day land use than in the potential vegetation, while in the East Coast of USA and some parts of Asia the return time is longer in the present-day land use. Using sensitivity simulations, I showed that this result is explained by the alleviated wood structural limits in harvested forests in the model, which leads to more NPP allocation in the wood pool in managed forests compared to unmanaged forests.

5.2 Implications for terrestrial carbon modelling

This study highlights the importance of comparing the simulated effects of LUC against observational datasets. By establishing a framework for model-data comparison, the DGVM JSBACH was evaluated using the observational meta-analyses on soil carbon changes for different LUCs. The evaluation has proven useful in identifying the causes of model deviation from meta-analyses. The introduced framework offers a consistent approach for comparing the simulated soil carbon changes for different LUCs among DGVMs. This framework can easily be extended to other models or to model-intercomparison projects to narrow down the uncertainties in the soil carbon changes from LUCs.

This study demonstrated the applicability of a factor separation analysis in assessing the relative contribution of the input-driven and turnover-driven controls to historical changes in soil carbon due to LUC. The results in this study indicate that the historical soil carbon losses are dominated by the input-driven control. Although the turnover-driven control plays a small role in influencing soil carbon changes, more studies are needed for a robust quantification of the contribution of these controls. The quantified input-driven and turnover-driven changes in this study provide a reference for future modelling studies. The results in this study show that fire enhances soil carbon losses, through accelerating the carbon turnover. Therefore, the simulated effects of fire on soil carbon should be re-assessed and calibrated when reliable observational datasets become available.

This study shows that the simulated LUC effects are substantially influenced by crop and wood harvesting. Accounting for these two processes enhances the simulated historical soil carbon losses from past LUCs. Furthermore, wood harvesting accelerates the vegetation carbon turnover time. Although JSBACH is still missing other key land management processes, my study demonstrates the importance of including these processes in DGVMs for comprehensive assessment of LUC effects.

5.3 Recommendations for future work

Evaluation of JSBACH's vegetation carbon pools.
The results in this study show that the allocation of carbon in the vegetation is a key factor influencing the response of the vegetation to additional CO_2 (Chapter 4). However, a comparison of the individual vegetation carbon pools, i.e green, wood and reserve pools, with observations is still lacking. Such a comparison would provide insights on whether the different parameters governing the carbon allocation into these pools are in line with what is observed. Forest free-air CO_2 experiments (FACE) provide datasets that have been widely used to evaluate the carbon distribution in forests in other models (e.g., De Kauwe et al., 2014; Negrón-Juárez et al., 2015). These data sets could in the future be used for evaluating the vegetation carbon pools in JSBACH with similar approaches as those introduced in the framework for soil carbon evaluation (Chapter 2). The results in this study show that ecosystem management through wood harvesting has an effect on the carbon distribution, whereby in some regions managed forests allocate more carbon to the wood pool than unmanaged forests (Chapter 4). This result can in the future be verified

by constraining the biomass production efficiency, i.e. the NPP to GPP ratio, for managed and unmanaged forests using the data results from Campioli et al. (2015).

Model developments with respect to land management.
This study mainly assessed the effects of LUC and land management through crop and wood harvesting on soil carbon. Other land management processes, such as tillage and fertilization, have not been accounted for. As discussed in the chapters in this study, these processes are likely to have an effect on the changes in soil carbon caused by LUC. Despite a few modelling studies accounting for some of these processes (Stocker et al., 2011; Levis et al., 2014; Pugh et al., 2015), our understanding on their influence on soil carbon dynamics remains limited. Including tillage and fertilization in future JSBACH developments will be useful to have a comprehensive assessment of the contribution of land management processes to changes in soil carbon. This would also be useful for assessing the robustness of the quantified input-driven and turnover-driven controls (Chapter 3).

The representation of wood harvest in the model is rather simplistic. In JSBACH, wood harvesting results in a daily removal of carbon from the different vegetation pools, while in reality harvesting often leads to the replacement of old forests with young forests. The carbon fluxes to the soil from wood harvest influence the temporal dynamics of soil carbon. Therefore, a realistic representation of wood harvest that accounts for different age classes in forests if likely to improve the temporal response of soil carbon.

The crop harvesting representation could also be improved in the future. I introduced a single parameter for estimating the amount of carbon removed through crop harvesting (Chapter 2). In reality the amount of vegetation biomass removed during harvest strongly depends on the crop type. This parameter should be re-assessed as global yield datasets become available.

A Supplementary information for chapter 2

A.1 Remapping of observational data into JSBACH PFTs

A remapping was done to create the observation-based NPP and LAI forcing for JSBACH (t16_drvn simulations in chapter 2). I used the global maps of LAI that are derived from the MODIS satellite and the gross primary production (GPP) derived by extending flux net tower measurements using machine learning algorithms (Tramontana et al., 2016). The data applied was for the period between 2001 to 2010. Vegetation classification for the GPP and LAI is based on the International Geosphere Biosphere Programme (IGBP), while JSBACH uses PFTs to represent the global vegetation distribution.

Using the classification rules by Pongratz et al. (2008) and Poulter et al. (2011), I remapped the cover fraction map used in deriving the GPP and LAI data into JSBACH PFTs (see cover fraction map description in Friedl et al., 2010, Table. 1). Since the remapping classification rules did not include pastures, the cover fractions for the pastures were taken from JSBACH's cover fractions and reduced from the remapped grasses cover fractions. I used the remapped cover fraction map for remapping the GPP and LAI. For every grid cell where there is a cover fraction value for a given PFT, there needed to be a GPP and LAI value. Each PFT in JSBACH had an observation vegetation type it can be linked to directly. In such cases, the GPP and LAI of the PFT was taken directly from the observation classification. Grasses and pastures were assumed to have the same GPP within every grid cell. For the grid cells, with a cover fraction but no GPP and LAI, the GPP and LAI values were taken from the closest neighboring cells. An assumption was made that the productivity of, for example, a deciduous forest in an area with forests alone is the same as that of a forest in a savanna. Unlike for GPP, there are no observations for autotrophic respiration, which makes it difficult to obtain NPP from the GPP. I calculated annual GPP to NPP ratios for each PFT from a simulation where JSBACH was driven by CRU climate. In this case, I assumed that the model biases in GPP and autotrophic respiration, both dependent on productivity, largely cancel. These ratios were used to scale the remapped GPP to NPP.

For the idealized simulations, I scaled the remapped cover fractions proportionally to create the idealized cover fraction maps for forest, crop, grass and pasture. The relative distributions of the different PFTs belonging to one vegetation type are kept at the relative distribution obtained from the remapped cover fraction map. The NPP and LAI values were also extended to the entire vegetated area, using the nearest neighbour approach. Most of the grid cells where the values are assigned using this approach are masked out in the comparison of the simulated soil carbon changes against the meta-analyses (see chapter 2 section 2.2.4).

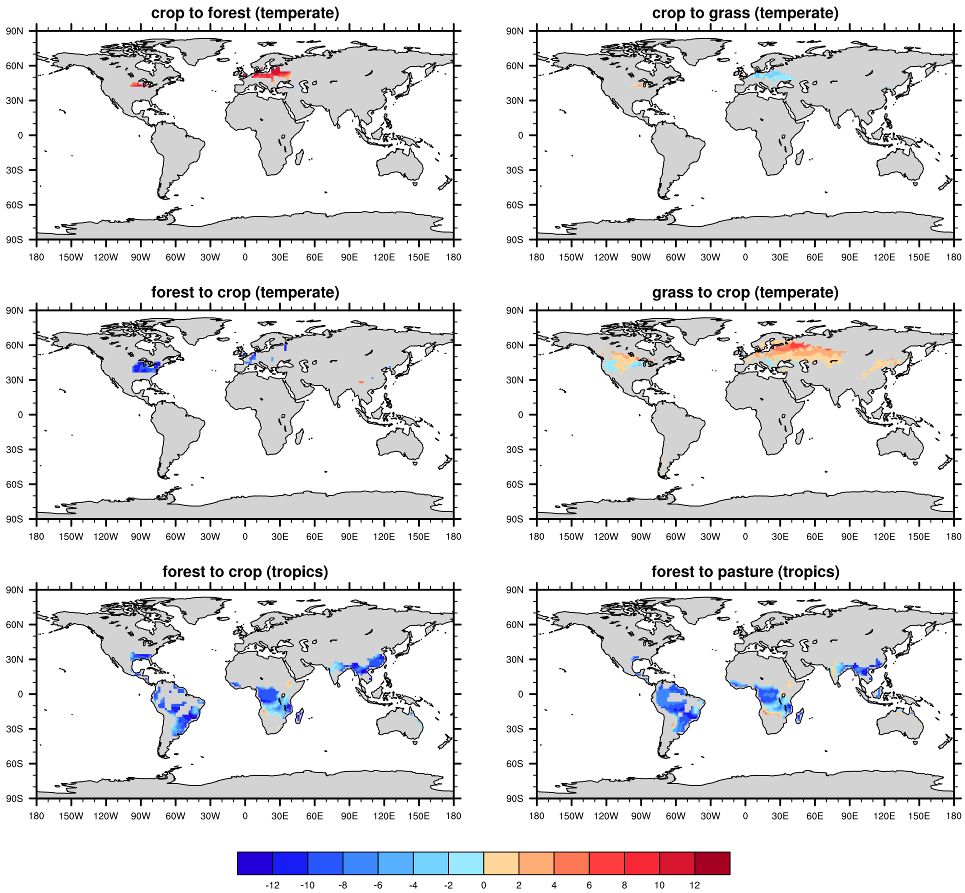
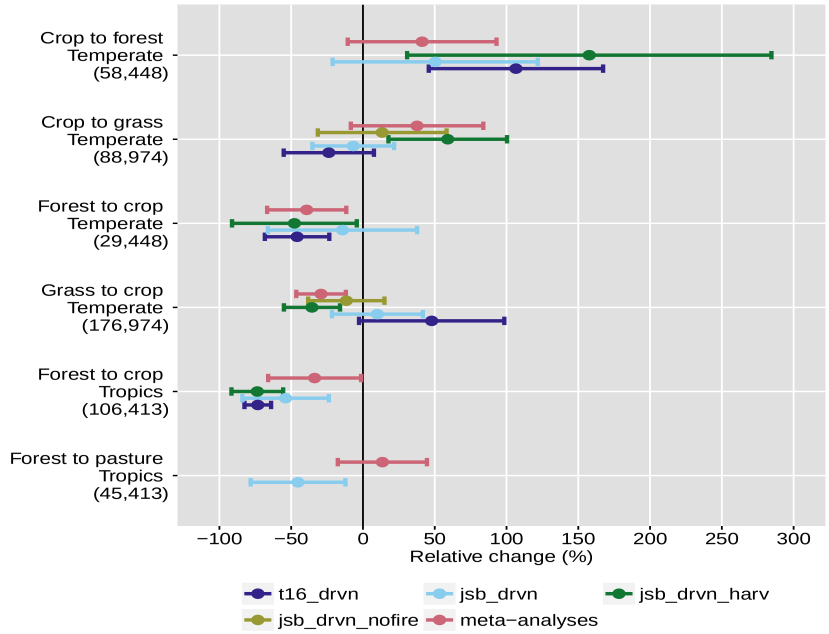
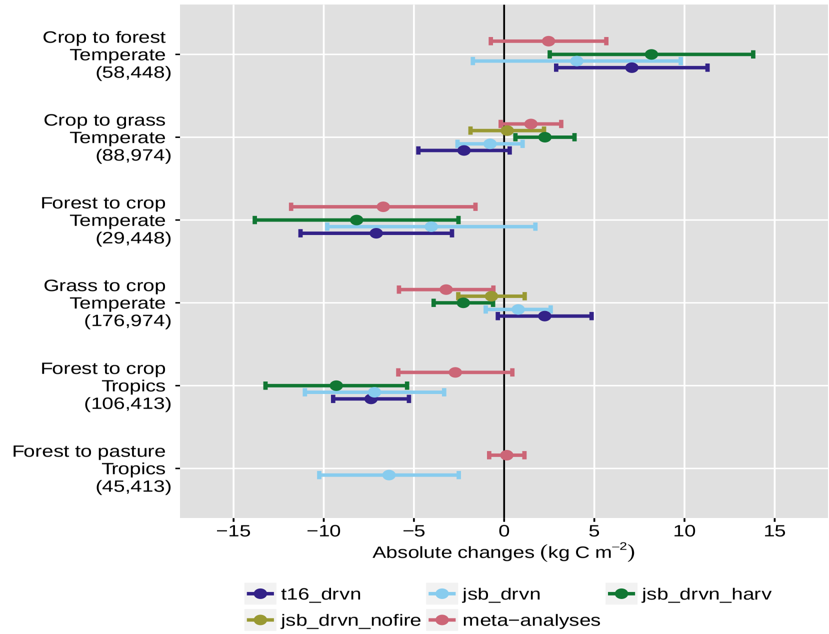


Figure A1: Equilibrium absolute changes in soil carbon in kgC m^{-2} for the different land-use changes in the jsbach_drvn simulation. The regions are based on the climate criterion, i.e. the precipitation and temperature range in the meta-analyses.

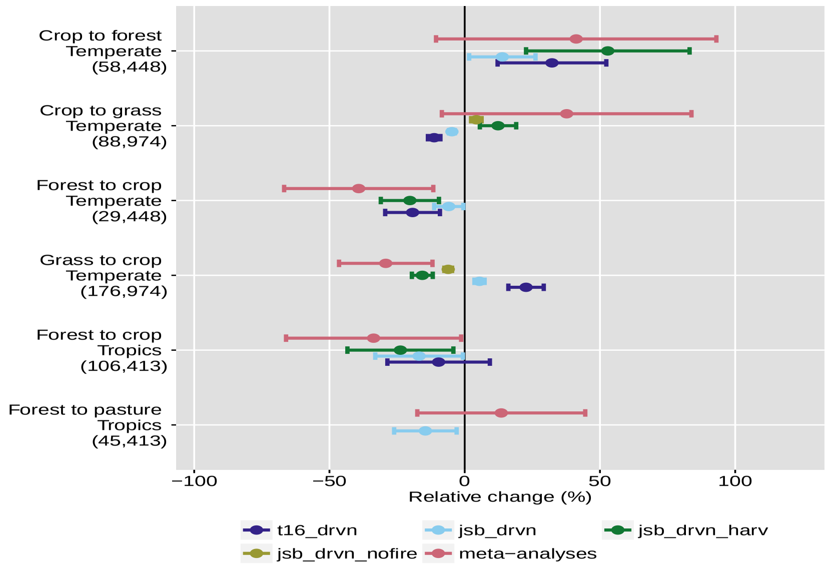


(a) Mean equilibrium relative changes

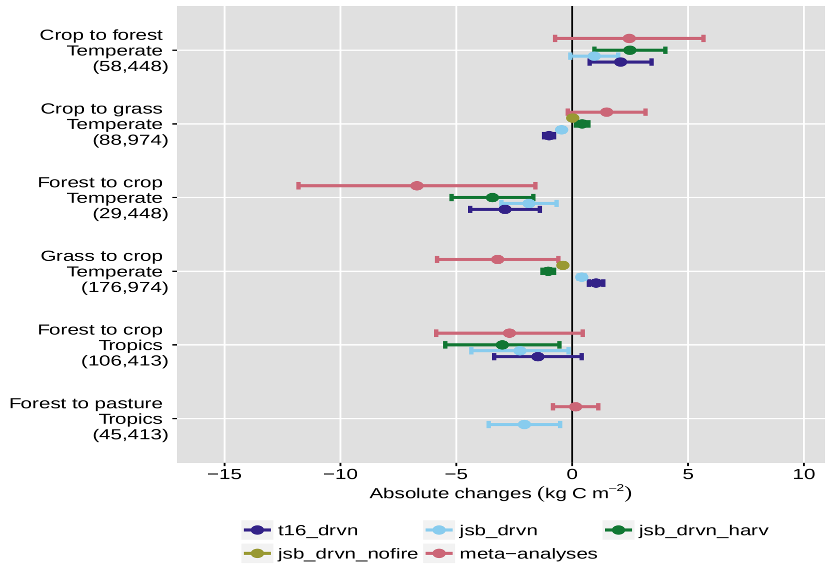


(b) Mean equilibrium absolute changes

Figure A2: Mean simulated equilibrium relative and absolute changes in soil carbon for the regions selected based on where land use change has taken place historically compared to the mean changes in the meta-analyses. The first number in the parenthesis represents the number of sites in the meta-analyses and the second is the number of grid cells that have undergone the specific land-use change historically. The bars represent the standard deviation.



(a) Mean sampled ages relative changes



(b) Mean sampled ages absolute changes

Figure A3: Mean simulated relative and absolute changes in soil carbon over the sampled ages represented by the meta-analyses compared to the mean changes for the meta-analyses. The first number in the parenthesis represents the number of studies in the meta-analyses and the second is the number of grid cells from the global simulation that have undergone the specific land-use change historically. The dots represent the mean changes and the bars represent the standard deviation.

B Supplementary figures for chapter 3

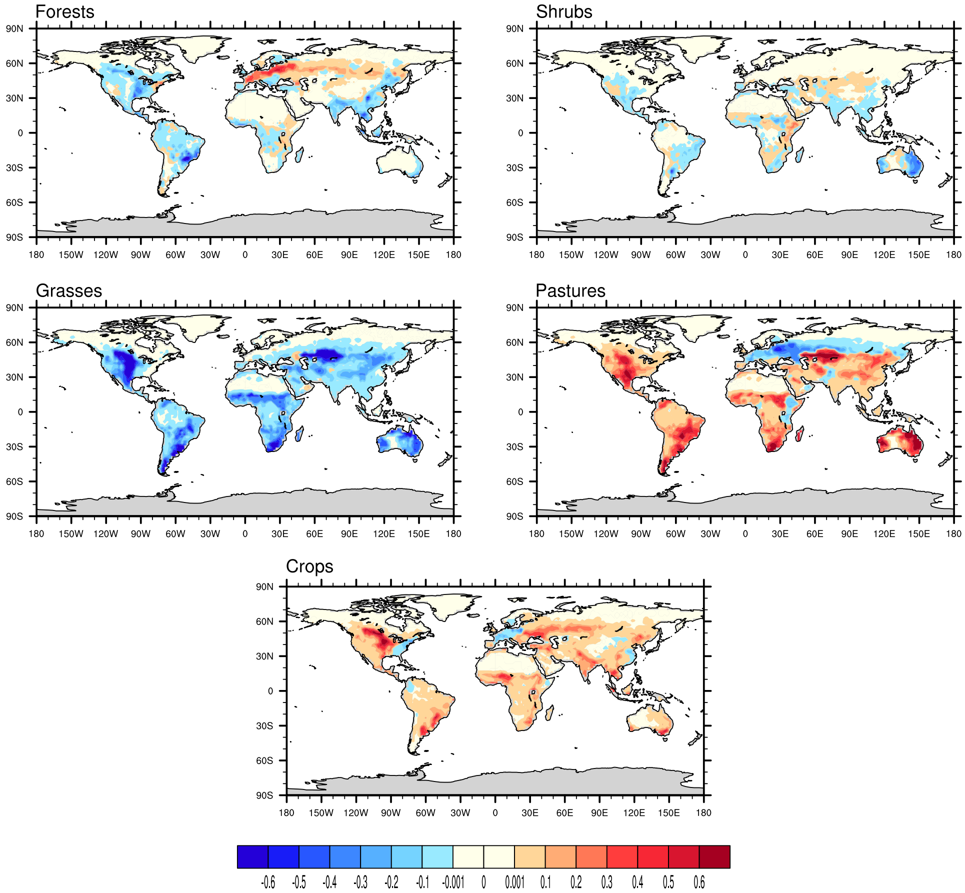


Figure B1: Differences between the applied present day (2005) and pre-industrial (1860) land cover maps. The difference represents the fraction of the grid cell that has increased or decreased in present-day compared to pre-industrial land cover

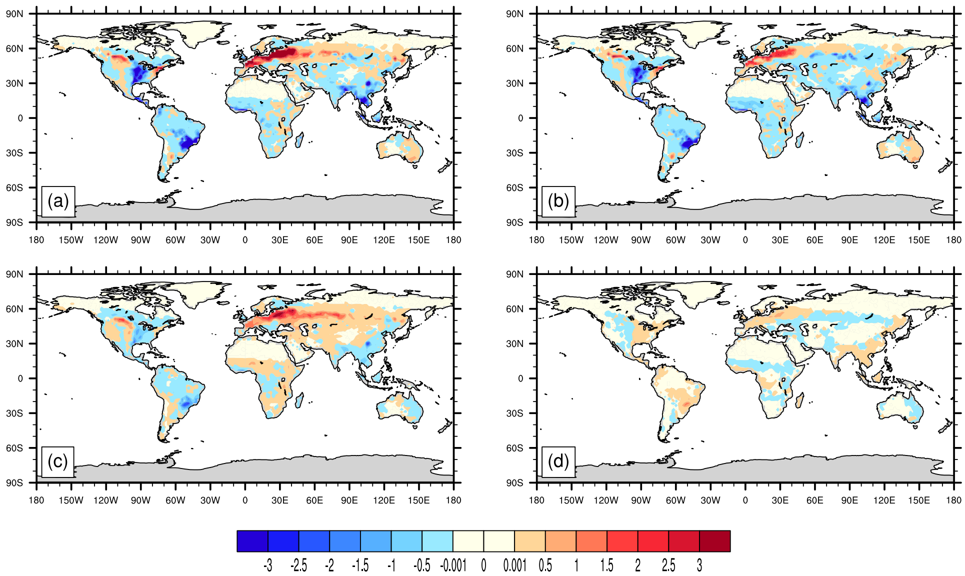
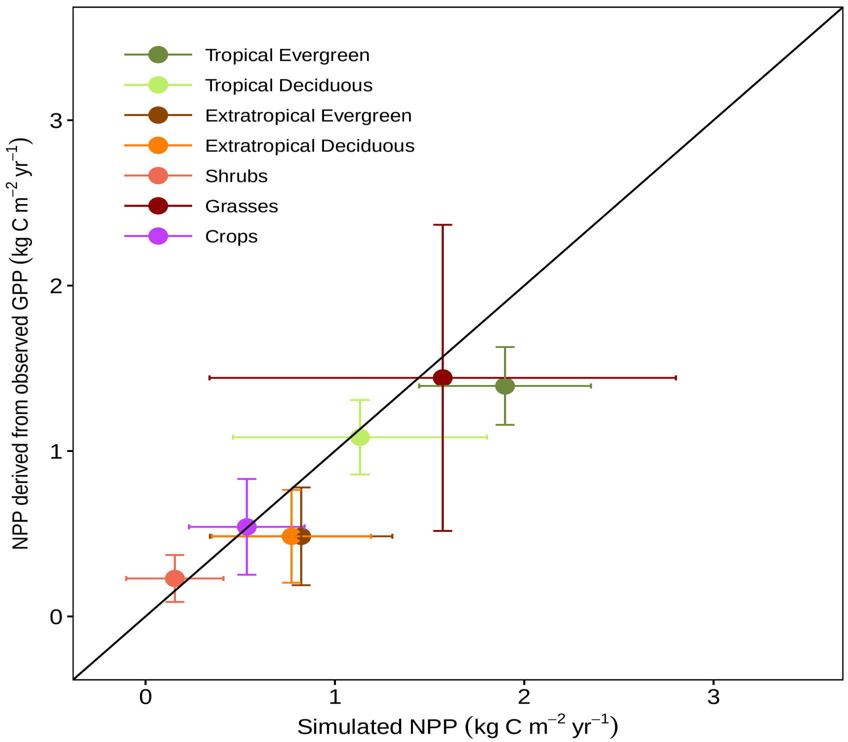
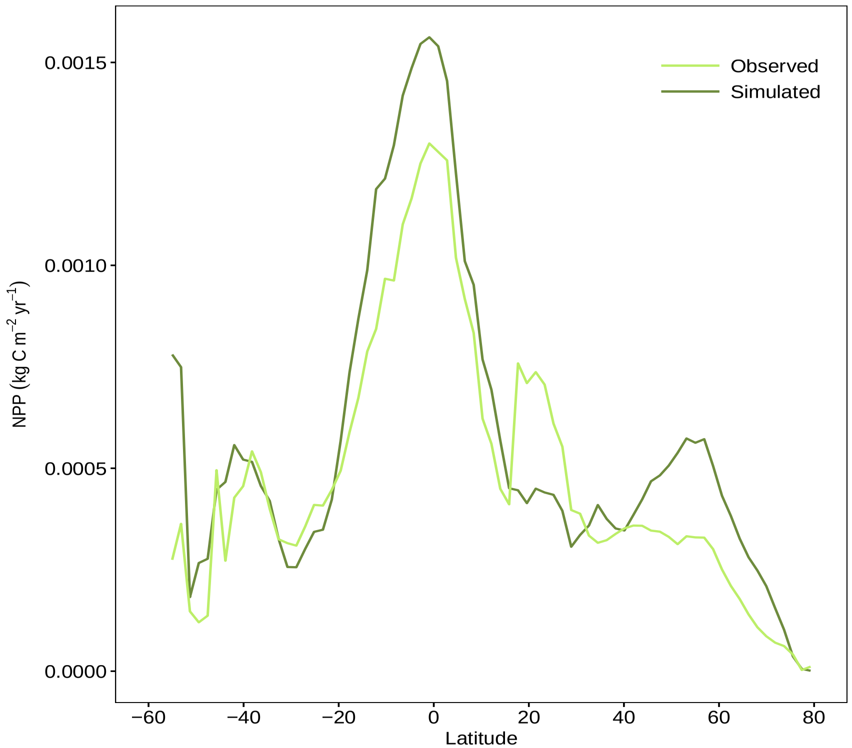


Figure B2: Global separated soil carbon changes in kg C m^{-2} for the LCC simulations (excluding land management). The controls are obtained using equation 4 and taking the LCC_1860 equilibrium as the reference. (a) Total soil carbon changes, (b) contribution of the input-driven changes, (c) contribution of the turnover-driven changes and (d) contribution of the synergy effects. Compare to Fig. 1 for results including land management.



(a) NPP for different PFTs



(b) Land zonal mean NPP

Figure B3: (a) Comparison of the NPP simulated by JSBACH with the NPP derived from observations of gross primary production (GPP). The dot represents the mean, the horizontal error bar represents the spatial standard deviation for the model and the vertical error bar shows the spatial standard deviation for the observations. The mean was taken over the grid boxes where the PFT existed in the observations. (b) The global zonal mean NPP for all the PFT types in the model and for all the vegetation types in the observations. The zonal mean was obtained by weighting the NPP with the cover fraction for every PFT and vegetation type. The NPP was obtained from the GPP by assuming 50% is lost through autotrophic respiration. The GPP data is described in Tramontana et al. (2016). The remapping of the biomes in the observations to JSBACH PFTs can be found in section A.1.

C Appendix of chapter 4

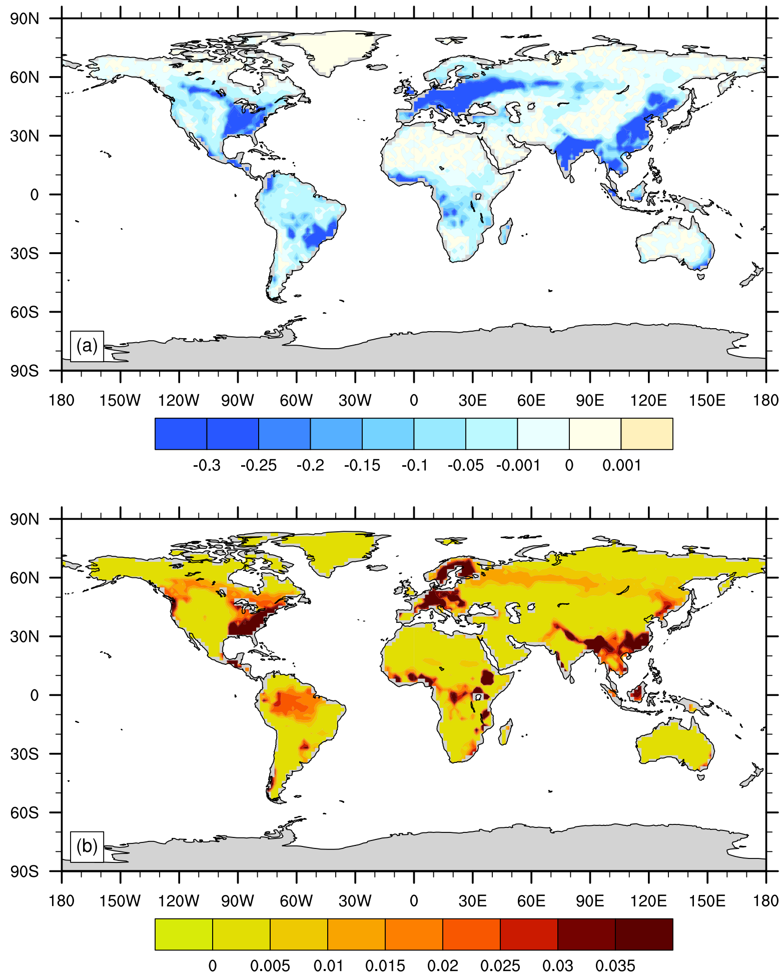


Figure C1: (a) The difference between the potential vegetation and the present-day land use forest cover fractions and (b) The prescribed wood harvest map for the present-day land use.

Table C1: The mean vegetation carbon densities (C_{veg}) and NPP in kgC m^{-2} and the turnover of the vegetation carbon (τ_{veg}) in years for the different simulations compared to the observations-based estimates by Erb et al. (2016a). The values represent the means over the entire globe and over the deforested regions in the tropics and extratropics regions.

	Acronymn	Global			Tropics deforested			Extratropics deforested		
		C_{veg}	NPP	τ_{veg}	C_{veg}	NPP	τ_{veg}	C_{veg}	NPP	τ_{veg}
Model simulations	pot_std	5.05±6.90	0.61±0.60	5.50±5.18	12.23±7.11	1.38±0.50	7.94±3.04	8.44±5.75	0.79±0.39	9.45±4.20
	prd_std	3.80±5.68	0.57±0.55	4.38±4.58	8.11±6.04	1.20±0.42	5.79±3.14	4.93±4.01	0.73±0.32	5.87±3.60
	prd_noharv	4.02±5.87	0.56±0.55	4.70±4.81	8.52±6.13	1.19±0.43	6.16±3.13	5.45±4.35	0.72±0.31	6.61±3.88
	pot_nofire	5.85±7.35	0.61±0.60	7.01±6.10	13.61±6.88	1.37±0.50	9.35±2.61	10.19±5.81	0.79±0.39	12.42±3.94
	prd_nofire	4.39±6.05	0.58±0.55	5.52±5.43	8.98±6.13	1.20±0.42	6.65±3.06	6.01±4.32	0.73±0.31	7.66±3.97
Data by Erb et al. (2016a)	pot_erb16	7.19±5.94	0.51±0.33	11.85±6.15	14.75±3.73	0.94±0.17	15.52±2.53	8.76±3.24	0.55±0.12	15.55±4.54
	prd_erb16	3.29±3.39	0.45±0.31	6.80±4.67	4.79±3.32	0.79±0.19	5.49±2.93	2.55±1.45	0.48±0.12	5.19±2.81

Table C2: Global mean turnover times of the soil and total terrestrial carbon for the different simulations. The values represent the means over the entire globe and over the deforested regions in the tropics and extratropics. The descriptions for the different simulations can be found in Table 4.1.

Acronym	τ_{soil} (years)			τ_{eco} (years)		
	Global	Tropics deforested	Extratropics deforested	Global	Tropics deforested	Extratropics deforested
pot_std	31.75	9.11	20.82	36.12	16.23	29.58
prd_std	31.64	8.68	19.87	34.04	12.98	22.73
prd_noharv	31.65	8.69	19.86	35.30	14.09	25.80
pot_nofire	39.76	9.90	23.71	45.75	18.55	35.58
prd_nofire	39.27	9.29	22.23	42.79	14.43	26.71

Table C3: The standard and adjusted maximum carbon contents for the woody plant functional types (PFTs) in JSBACH. The units are mol (C)/ m^2 canopy.

PFT	Standard limits [a]	Ajusted limits
Tropical evergreen forests	2997.25	2997.25
Tropical deciduous forests	2997.25	2997.25
Extratropical evergreen forests	1998.2	2500.2
Extratropical deciduous forests	1498.6	2500.2
Rain green shrubs	582.8	582.8
Deciduous shrubs	416.2	416.2

[a] The standard structural limits are for the model version applied in the current study. The limits for the extratropical forests have been revised in the CMIP6 model version.

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Acronyms

LUC	Land-Use Change
FAO	Food Agricultural Organization
GVM	Global Vegetation Model
DGVM	Dynamic Global Vegetation Model
ESM	Earth System Model
GCM	General Circulation Model
RCP	Representative Concentration Pathways
IPCC	Intergovermental Panel on Climate Change
CMIP5	5th phase of the Coupled Climate-carbon cycle Model intercomparison project
CMIP6	6th phase of the Coupled Climate-carbon cycle Model intercomparison project
PFT	Plant Functional Type
CRF	Carbon Response Function
GPP	Gross Primary Production
NPP	Net Primary Production
LAI	Leaf Area Index
MAT	Mean Annual Temperature
MAP	Mean Annual Precipitation
MODIS	Moderate Resolution Imaging Spectroradiometer
CRU	Climate Research Unit

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Eidesstattliche Versicherung

Declaration on Oath

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertationsschrift selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

I hereby declare, on oath, that I have written the present dissertation by myself and have not used other than the acknowledged resources and aids.

Hamburg, den 01. August 2017 ____

Sylvia Sarah Nyawira