GEO 511 Master thesis

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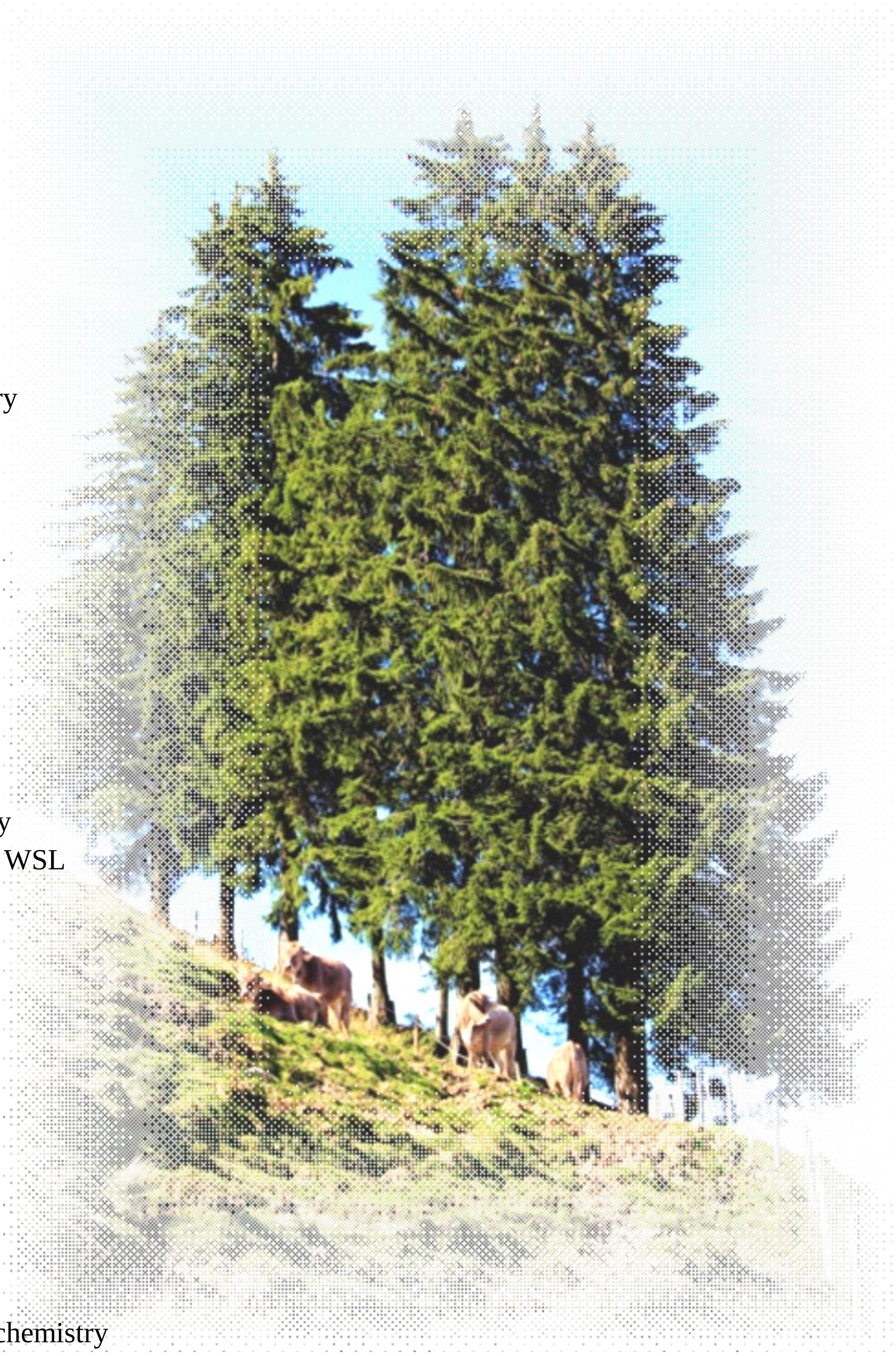
# Modeling the Effects of Climate and Land Use Change on Soil and Vegetation Carbon Dynamics in Switzerland with CoupModel



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# Abstract

Since the mid-20th century, reforestation has been taking place in Western Europe, North America and China. At the same time, the climate has been changing, bringing about increases in global mean surface temperature and changes in precipitation patterns. However, the effects of these changes on vegetation and especially soil, the largest active terrestrial reservoir of carbon, are still uncertain. Therefore, it is important to determine to which extent the changes in land use, precipitation, and air temperature affect the C dynamics of soil and vegetation in the future. Modeling these changes with a soil-plant-atmosphere system model could therefore increase our understanding about the state of future soils and ecosystems.

The aim of this modeling study was to explore how changes in land use and climate affect the C dynamics of soil and vegetation in Jaunpass, located in the Swiss Alps. In particular, the goal was to determine if the changes in soil and vegetation C dynamics due to afforestation reported by a space-for-time study in Jaunpass could be reproduced by long term simulations, and if climate change could affect the C cycling of this site considerably in the future. The coupled heat and mass transfer model CoupModel was used for land use change simulations (years 1960 – 2010) and climate change simulations (years 2010 – 2100) with three different climate scenarios (CLM, RCA, and REGCM3).

Afforestation considerably increased the C stocks of soil and vegetation, which is in agreement with the field study, but the temporal scale of the changes was different. When compared to the simulations with current climate, forest C stocks (soil and vegetation) were negatively affected by climate change already after 40 years of simulation, whereas no real change was found in grassland C stocks. The model in general overestimated the root and soil C stocks, whereas the aboveground C stocks were underestimated in the long term. Moreover, the effects of afforestation on the soil temperature could not be reproduced by the model. Thus, the reported changes in vegetation and soil C stocks after land use change could be only partly reproduced by soil-plant-atmosphere system modeling in this study. These results demonstrate that using this kind of a modeling approach could increase our understanding about the changes taking place in the soil-plant-atmosphere system of alpine regions due to climate change and afforestation, but the model parameters need to be carefully adjusted for the study site and purpose.

*Keywords:* land use change, climate change, soil organic carbon, carbon balance, plant-soil-atmosphere system modeling, CoupModel

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# 1 Introduction and Aim

Ecosystems have been changing more rapidly and extensively in the past 50 years than in any comparable period of time in human history, mainly due to human influence (World Resources Institute, 2005). Since the mid-20th century, deforestation has been generally taking place in the tropics, whereas reforestation is mainly occurring in Western Europe, North America and China due to land abandonment and afforestation efforts (IPCC, 2013). These kinds of changes in land use affect the ecosystem properties and processes. A good example of this is the loss of soil organic carbon (SOC) as a result of the conversion of natural ecosystems into managed ecosystems for food or timber production (IPCC, 2013). SOC is not only relevant to soil structure and fertility, but also to the atmospheric levels of $CO_2$; in the global C cycle, soil is the largest active terrestrial reservoir (Rumpel & Kögel-Knabner, 2010), being estimated to equal the sum of the atmospheric and biotic C pools (1400Pg; Hiederer and Köchy, 2011). Therefore, a change of just 10% in the SOC pool would be equivalent to 30 years of anthropogenic emissions and could drastically affect the concentrations of atmospheric $CO_2$ (Stockmann et al., 2013). Currently, land use change (LUC) is globally causing $CO_2$ emissions that are second only to those from fossil fuel combustion (Power, 2010). As a result, it is important to find out what kind of changes are taking place in C dynamics of the soil-plant system under land use change. In particular, the effects of afforestation are important to look for as afforestation is happening in many countries throughout Europe.

LUC leads to a different soil environment, which in turn affects microbial growth and decomposition processes. Therefore, there are diverse effects of LUC on the terrestrial C cycle. For example, a meta-analysis was performed that found LUC from pasture to forest reduced soil C stocks by 10% (Guo & Gifford, 2002). Another modeling study found a similar effect using carbon response functions where 75% of all observations showed SOC losses even 100 years after LUC, with a decline in SOC of -7 ± 23% (Poeplau et al. 2011). These kind of changes in SOC could be even larger at high altitudes as relatively high amounts of labile soil organic matter are stored in the alpine soils as a result of suppressed decomposition under unfavorable climatic conditions (Hagedorn et al., 2010a; Hiltbrunner et al., 2013). However, the total soil C stocks were only moderately affected by afforestation in a space-for-time study in Jaunpass, Switzerland, whereas decreased soil organic matter quality and less favorable microclimatic conditions resulted in lower soil respiration rates (Hiltbrunner et al., 2013). Therefore, the effects of LUC on SOC are uncertain and depend on many factors such as land use history, climate conditions, and soil properties.

Another factor affecting the global C cycle is the climate. Globally, the last decade alone has been the warmest since sufficient measurement started in the 19th century, producing record-breaking heat waves in many parts of the world (Coumou et al., 2013). The increase in global mean surface temperature will very likely bring about more frequent and intense extreme precipitation events (IPCC, 2013). These changes could affect the C cycle in many ways, as increased temperature generally leads to longer growing seasons and increased vegetation growth, which then leads to increased C storage (Schaphoff et al., 2006), as well as increased rates of decomposition of soil organic matter (Conant et al., 2011; Davidson & Janssens, 2006). Furthermore, higher rainfall is associated with a larger SOC pool (Jenny, 1980), whereas droughts can either increase or decrease the C sequestration by the suppression of soil respiration or decrease of plant productivity and C input to the soil (Heimann & Reichstein, 2008). Due to all of these possible changes in the C cycle, it is important to find out to which extent the changes in land use, precipitation, and air temperature affect the C dynamics of soil and vegetation in the future. Therefore, modeling these changes with a soil-plant-atmosphere system model could increase the understanding about the state of future soils and ecosystems.

This master thesis is part of the NRP68 SNF project “soil as resource”, Key aspect 1: Carbon and Soil Organic Matter (SOM). The part “The effect of climate and land use change on soil carbon in Swiss soils” of NRP68 examines the vulnerability of soils rich in organic matter to changes in climate and land use change and aims to identify the most endangered soils and take suitable protective measures (NRP68, 2015). For this master project, data from the space-for-time studies conducted by Hiltbrunner et al. (2013, 2012) in Jaunpass was used in order to model the C dynamics after LUC and in different climate scenarios. For this purpose, the coupled heat and mass transfer model CoupModel was used. CoupModel is mainly used to quantify and increase the understanding of basic hydrological and biological processes in the soil-plant-atmosphere system (CoupModel, 2014). Until now, it has not been used for modeling the effects of LUC and climate change on the C balance of the soil-plant-atmosphere system. However, it has all the model characteristics needed for this kind of a study. Since CoupModel can be used for modeling the entire soil-plant-atmosphere system, it can increase the understanding of the processes occurring in the soil and vegetation after LUC. Thus, using this model can be a good tool for investigating the effects of climate and LUC on the C dynamics.

Instead of collecting long-term data, space-for-time studies make use of sites that have a different stand age. The method requires homogeneous landscapes in order to minimize the effect of other factors that might contribute to the results. This inevitably brings about a challenge, as space is not time. Therefore, it is unknown how the results would differ if there was long term data available, or how future changes in climate would affect these processes. This is why modeling is required; it not only offers a way to construct past and future changes within the landscape, but also helps to identify the relevant factors contributing to the results. The aim of this modeling study was to determine how changes in land use and climate affect the C dynamics of soil and vegetation in Jaunpass, Switzerland. For this study, the following research questions were addressed:

- Can the changes in soil and vegetation C stocks after land use change be reproduced by soil-plant-atmosphere system modeling?
- What is the temporal scale of the changes in soil and vegetation C stocks after land use change?
- Can soil-plant-atmosphere system modeling be used for assessing the future changes in the soil and vegetation C stocks by using climate scenarios?
- How do the changes in temperature and precipitation affect soil and vegetation C dynamics in the future?
- What is the importance of land use change compared with climate change in terms of soil and vegetation C stocks?

It was hypothesized that the land use change from grassland to forest increases the C stocks of soil and vegetation and that the temporal scale of these changes is similar in the simulations and the measured data. In addition, it was hypothesized that the changes in temperature and precipitation have a negative effect on soil and vegetation C stocks in the future and that land use change has a larger impact than climate change on the C stocks of the plant-soil system.

In the second part of this thesis (Section 2), the relevant literature of C cycle affected by land use and climate change is reviewed. The chapter also includes a section of literature on modeling the terrestrial C cycle (Section 2.4). In the third chapter, the methods, data and model structure are described. The results are presented in chapter four. A discussion is provided in chapter five and conclusions are drawn in chapter six.

# 2 Literature Review

## 2.1 Terrestrial Carbon Cycle

The carbon cycle can be conceptualized as a three-compartment system including terrestrial, oceanic and atmospheric pools (Dawson & Smith, 2007). The terrestrial pool consists of the C stored in the soil and in the vegetation. C enters the terrestrial biosphere mainly through photosynthesis in the form of carbon dioxide ($CO_2$), but C can also be derived into the soils either from parent materials by bicarbonate weathering of silicate minerals or from the atmosphere as wet, occult or dry deposition (Dawson & Smith, 2007). C is lost from the terrestrial ecosystems mainly as $CO_2$, the most important processes being the respiration of autotrophs (plants and photosynthetic bacteria) and heterotrophs (fungi, animals and some bacteria), although C can also be lost as volatile organic compounds, methane, or dissolved C (Heimann & Reichstein, 2008). Therefore, the amount of C stored in the system (commonly referred to as “C stocks”) depends on the balance between the C inputs and C outputs (“fluxes”). The spatial and temporal fluctuations between the in- and outflows of C in the ecosystems are mainly caused by climate and LUC, which can determine whether the ecosystem is a source or a sink of C (Dawson & Smith, 2007; Smith et al., 2008). Other possible fluctuations can be related to species composition, soil type, and season (Smith et al., 2008), since they all affect the C balance of the ecosystem by inducing changes in the net primary production.

Within the global C cycle, the soil is the largest active terrestrial C reservoir (Rumpel & Kögel-Knabner, 2010). Globally, soils have been estimated to store from 1220 Pg (1Pg = $10^{15}$g) to the most recent estimates of about 2000 Pg in the uppermost meter (Kögel-Knabner & Amelung, 2014). In the soil, C is stored in soil organic matter (SOM) as a complex mixture of materials derived from plant litter as well as faunal and microbial biomass, including particulate organics, humus, charcoal, living biomass and fine plant roots (Stockmann et al., 2013; Kögel-Knabner & Amelung, 2014). SOM contains about 58% elemental C, soil organic carbon (SOC) (Stockmann et al., 2013). The amount of C stored in the soil at a given time depends on the balance between the C input by root and litter deposition and the release of C by decomposition (Jandl et al., 2007). In general, the concentration and dynamics of SOC are highest in the topsoil (0-30cm), whereas the subsoil C stocks (30-80cm) generally have slower turnover rates and a higher degree of stabilization (Poeplau & Don, 2013). The rate of decomposition is mainly controlled by moisture and temperature through their effects on microbial activity, but litter quality and soil microbial community composition also play an important role (Stockmann et al., 2013). If site factors such as excess soil moisture or low temperature inhibit soil respiration, C can accumulate in the soil (Jandl et al., 2007).

For example, in boreal and high altitude forests the annual decomposition rate is limited by the short growing season (Jandl et al., 2007). Similarly, SOC stocks generally increase as mean annual temperature decreases (Post et al., 1982; Figure 1).

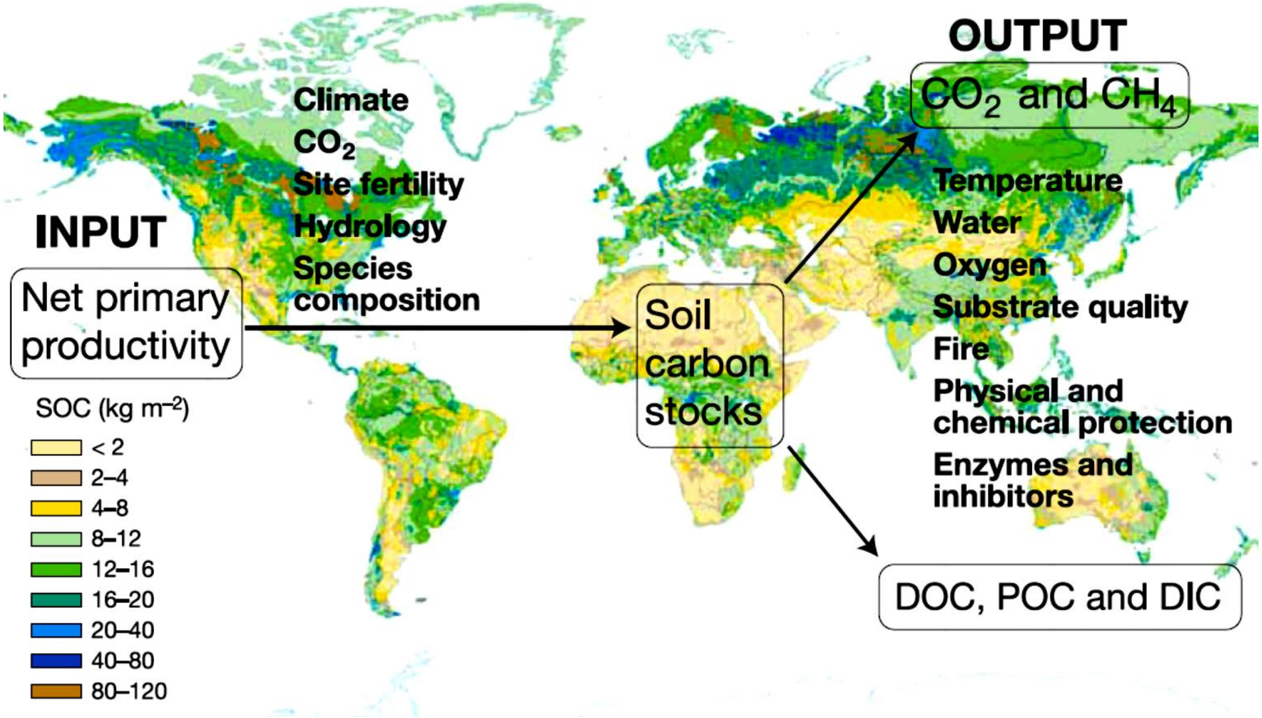

Figure 1. Diagram of factors controlling the main inputs and outputs of soil C, superimposed over a global map of SOC stocks. While $CO_2$ is the main product of decomposition in soil, $CH_4$, dissolved organic carbon (DOC), particulate organic carbon (POC) in water, and dissolved inorganic carbon (DIC) are also significant exports from some soils. Source: Davidson & Janssens, 2006.

SOC can be divided into different pools according to the decomposition rate (fast, slow and very slow/passive/inert), biological stability (labile, stabile, refractory and inert), and turnover time (short, long, very long) (Stockmann et al., 2013). For example, fresh plant litter and root exudates usually have a turnover time of years, whereas the turnover time of physically or chemically stabilized organic matter can range from centuries to millennia (Trumbore, 2009). However, the turnover time of SOM depends not only on the chemical quality of the C compounds, but also site conditions, soil properties (clay content, pH, nutrient status, moisture) (Jandl et al., 2007) and accessibility of the microbial community to the SOM (Dawson & Smith, 2007). In conclusion, SOM dynamics are now generally considered to be controlled more by physicochemical and biological influences from the surrounding environment that reduce the rate of decomposition than by the intrinsic properties of the organic matter itself (Schmidt et al., 2011; Stockmann et al., 2013). This helps to explain why even easily decomposable substances can be incompletely decomposed in the soil (Stockmann et al., 2013).

## 2.2 Effects of Land Use Change on Soil and Vegetation Carbon Dynamics

LUC modifies the characteristics of vegetation, including its color, seasonal growth and C content (Foley et al., 2005; IPCC, 2013). This also has implications for the C dynamics of the soil beneath the vegetation. Each soil has a carbon-carrying capacity that depends on the nature of vegetation, precipitation, and temperature, and results from a balance between inflows and outflows to the SOC pool (Guo & Gifford, 2002). LUC disturbs this balance until a new equilibrium is eventually reached in the new ecosystem. During this process, soil may act as a C sink or source according to the ratio between inflows and outflows (Guo & Gifford, 2002). Subsoil SOC stocks have been found to be less sensitive to LUC than topsoil SOC stocks, but they are generally also affected due to the changes in SOC allocation into the subsoil, DOC leaching, bioturbation and access of roots (Guo & Gifford, 2002; Poeplau & Don, 2013; Poeplau et al., 2011).

Whether the SOC stocks ever achieve the level prior to LUC is uncertain, and depends not only on land use history, climate conditions, soil properties, and ecosystem productivity, but also on tree species and management intensity (Guo & Gifford, 2002; Hiltbrunner et al., 2013; Poeplau et al., 2011). Land use history is an especially important source of complexity as it influences the initial nature and size of SOC pools (Post & Kwon., 2000). A meta-analysis of 74 publications indicates that whenever one of the LUCs decreases the SOC stocks, the reverse process usually increased the SOC stocks and vice versa (Guo & Gifford, 2002). SOC stocks were found to decline after LUC from pasture to plantation (-10%), native forest to plantation (-13%), native forest to crop (-42%), and pasture to crop (-59%). On the other hand, SOC stocks increased after LUC from native forest to pasture (+8%), crop to pasture (+19%), crop to plantation (+18%), and crop to secondary forest (+53%) (Guo & Gifford, 2002; Figure 2). Since the process of SOC sequestration is reversible, the LUC leading to increased C stocks in either the soil or in the vegetation must be continued indefinitely to maintain the increased stock of SOC (Freibauer et al., 2004). Furthermore, the increases in SOC may be limited over time as the maximum C storage is attained, which may occur as quickly as 10 or 100 years (Dawson & Smith, 2007). The accumulation of SOC is generally a slow and continuous process after the establishment of afforestation of cropland, whereas the land use from grassland or forest to agricultural land usually causes rapid SOC losses (Poeplau et al., 2011).

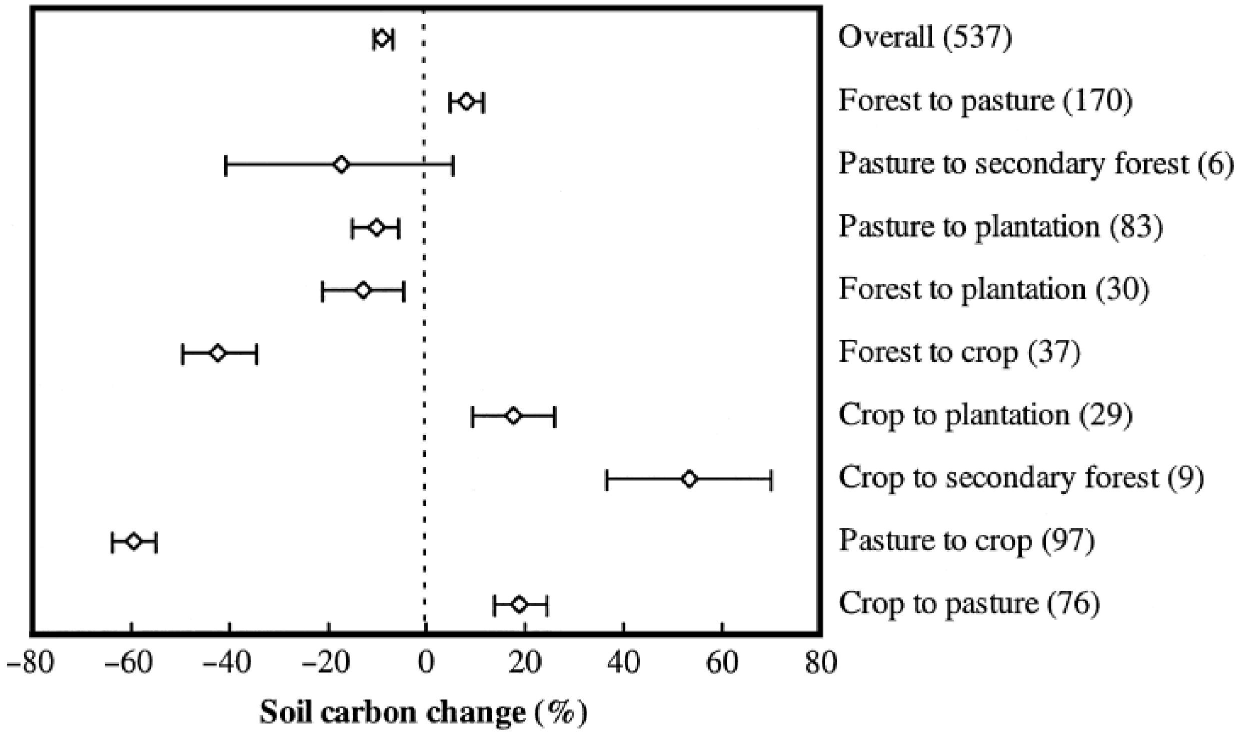

Figure 2. Soil carbon response to various land use changes (95% confidence intervals are shown and numbers of observations are in parentheses). Source: Guo & Gifford, 2002.

The effects of LUC on SOC stocks and dynamics have been studied widely in different ecosystems globally (e.g. Guo & Gifford, 2002), regionally (e.g. Schulp et al., 2008, Poeplau et al., 2011; Poeplau & Don, 2013) and locally (e.g. Guo et al., 2008; Hiltbrunner et al., 2013). Some examples of the results are shown in Table 1. Still, there are hardly any studies investigating the effects of LUC on SOC covering all major European LUC types allowing direct comparisons (Poeplau & Don, 2013). So far, the majority of the LUC studies were only comprised of analysis of topsoils (Hiltbrunner et al., 2013), whereas there are very few studies of deep soil C dynamics. Changes in SOC storage have usually been reported based on stand chronosequences, paired plots or repeated sampling (Jandl et al., 2007). The effects of LUC on SOC turnover rates and mean residence time can be studied by using both stable and radioactive isotope techniques (Kögel-Knabner & Amelung, 2014). Moreover, the C fractionation method can be used to analyze how different physicochemical properties, the degree of stabilization, and the turnover time of SOC changes due to LUC (Poeplau & Don, 2013). As there are various methods used and many different conceptual viewpoints, the studies on the effects of LUC on C dynamics show a wide spectrum of results.

Table 1. Studies investigating the effects of LUC on SOC stocks and dynamics on different spatial and temporal scales.

| Reference | Type of research | Spatial and temporal scales | Key findings |
|---|---|---|---|
| **Haygarth & Ritz, 2009** | Review | All spatial and temporal scales | Pressures from changes in climate and ecosystems will bring about complex and systematic change to soils and their abilities to provide essential functions. |
| **Foley et al., 2005** | Review | All spatial and temporal scales | Challenge: Managing trade-offs between immediate human needs and maintaining the capacity of the biosphere to provide goods and services in the long term. |
| **Guo & Gifford 2002** | Meta-analysis of 74 publications | Global,<br>studies of all temporal scales | Significant changes in soil C stocks after LUC. Wherever one of the LUCs decreased soil C, the reverse process usually increased soil C and vice versa. |
| **Poeplau et al., 2011** | Using carbon response functions to model the results of 95 studies | Temperate zone, 200 years | Grassland establishment and afforestation on former cropland caused a long lasting C sink.<br>C was lost after deforestation and grassland conversion to cropland. There was no soil C sink following afforestation of grasslands |
| **Schulp et al., 2008** | A high-resolution LUC model and four IPCC scenarios | European Union, 30 years | Clear differences in the spatial distribution of sinks and sources between the four scenarios. Land use is an important factor in future changes of C sequestration |
| **Poeplau & Don, 2013** | Experiment of 24 paired sites. Soil carbon fractionation. | Europe,<br>at least 20 years after LUC | Afforestation shifts soil organic C from stable to labile pools |
| **Guo et al., 2008** | Paired site experiment | Australia,<br>16 years | LUC from pasture to pine plantation sequestrated a significant amount of C from the atmosphere |
| **Hiltbrunner et al. 2013** | Space for time experiment | A single mountain hill, 25-120 years after LUC | LUC from subalpine pasture to forest only moderately affected SOC storage |

The effects of LUC from grassland to forest on the soil and vegetation C dynamics are especially interesting. At present, most temperate grasslands are believed to be C sinks with estimates ranging between 0.03 – 1.1 x $10^3$ kg C $ha^{-1}$ $year^{-1}$ (Dawson & Smith, 2007). Forests are also generally thought to be C sinks due to the large amounts of C stored in the biomass (Schulp et al., 2008). Forest soils in general contain similar magnitudes of SOC than grassland soils  (Poeplau & Don, 2013). However, the vertical distribution of the SOC is different in a grassland soil than in a forest soil. Jobbágy & Jackson (2000) found that the relative distribution of SOC in the top meter of soil was deeper in grasslands (42% in the uppermost 20cm) than in forests (50% in the uppermost 20cm). However, the accumulation of SOC in forest ecosystems also depends on tree species. For example, shallow rooting coniferous species tend to accumulate SOC on the forest floor, but less in the mineral soil, compared with deciduous trees (Jandl et al., 2007).

In general, forest soils receive a smaller proportion of the total C input as root litter than grassland soils under similar conditions (Kögel-Knabner & Amelung, 2014) because of the long lifecycle and therefore, a smaller annual turnover of the tree root system (Guo & Gifford, 2002). The mainly root-derived SOC in grasslands leads to a higher proportion of stabilized C compared with forests (Poeplau & Don, 2013), since the root material has a high potential to be stabilized in the soils (Rasse et al., 2005). As a result, almost 90% of total SOC stocks are stabilized in intermediate and passive SOC pools in grassland soils (Wiesmeier et al., 2014). Even though forest soils accumulate C quickly, most of C is in a labile form and only for a limited time (Jandl et al., 2007). This poses the risk of considerable SOC losses caused by any disturbances (Poeplau et al., 2011; Wiesmeier et al., 2014; Jandl et al., 2007), such as LUC or change of management practices.

Soils may gain or lose C, or experience no change in C levels following afforestation (Guo & Gifford, 2002). Usually the changes in aboveground vegetation C are fast, whereas it can take decades until net gains occur in the SOC (Jandl et al., 2007). Due to the generally large C stocks and high root densities in the upper part of the mineral soil in pastures, afforestation only has a small effect on SOC (Guo & Gifford, 2002), even though afforestation of former agricultural land generally increases the C pool in the aboveground biomass and replenishes the SOC pool (Jandl et al., 2007). On the other hand, several studies have shown that the afforestation of grassland can also lead to depletion of the SOC stock (e.g. Alfredsson et al., 1998; Thuille & Schulze, 2006; Poeplau & Don, 2013). Some reasons for this could be the lower input of below-ground biomass (Poeplau & Don, 2013), the stimulated decomposition of SOM due to site preparation and tree planting (Jandl et al., 2007), or decreased bioturbation, after which a part of soil can lose its physical protection (Wiesmeier et al., 2014).

In a meta-analysis of Guo & Gifford (2002), trees planted onto pasture land reduced SOC stocks by 10% rather than increasing them (Figure 2). However, they also found differences between tree types. When established pastures switch to forest, SOC stocks declined under pine plantations but were unaffected by either broadleaf tree plantations or naturally regenerated secondary forests (Guo & Gifford, 2002). In another metadata analysis that compiled LUC effects in the temperate zone, no clear trend after an initial decrease in SOC stock changes in the mineral soils was revealed, partly due to the high variability among the studies (Poeplau et al., 2011; Figure 3). Generally, after the initial loss of SOC after plantation, the C stocks are expected to increase slowly until C input and mineralization equilibrates (Thuille & Schulze, 2006; Hiltbrunner et al., 2013). However, it can take more than 150 years for the mineral soil to reach a new equilibrium, and even more than 200 years if the forest floor is included (Poeplau et al., 2011; Figure 3) since afforestation generally affects the C pool of the forest floor more strongly than that of the mineral soil (Jandl et al., 2007).

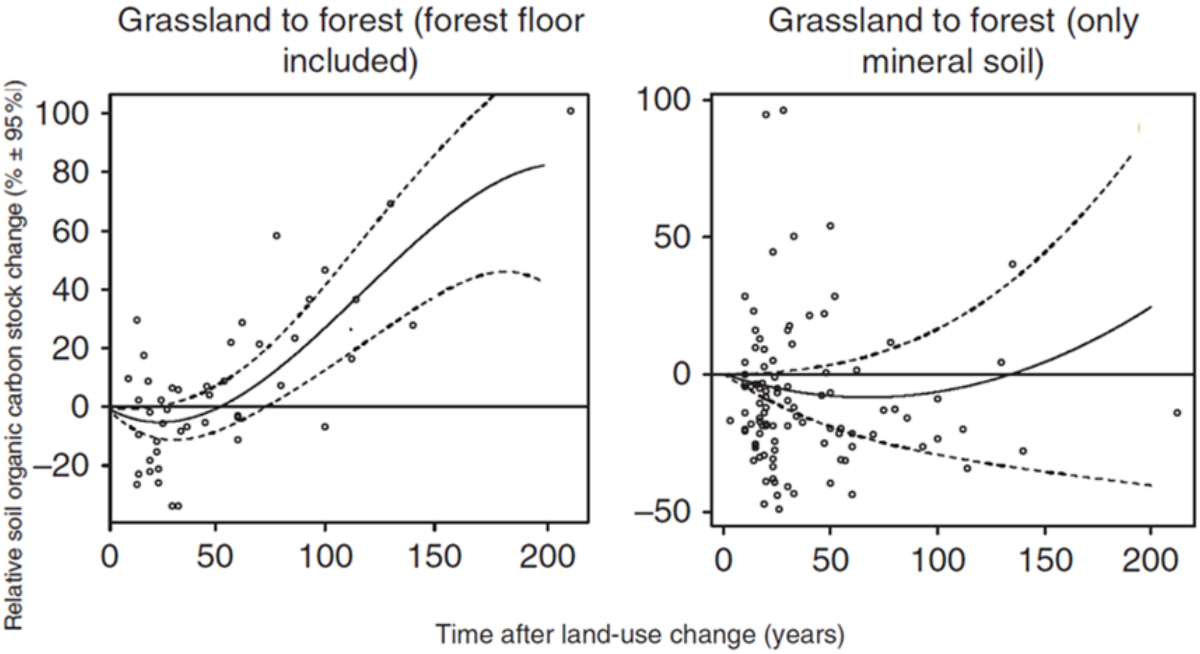

Figure 3. Temporal dynamic of relative SOC change (%) and forest floor carbon accumulation (Mg ha$^{-1}$ year$^{-1}$) after land-use change with fitted carbon response functions (95% confidence interval). Left: grassland to forest (mineral soil and forest floor). Right: grassland to forest (only mineral soil). Adjusted from Poeplau et al., 2011.

The effects of afforestation on SOC in alpine regions have not been thoroughly studied despite the strong increase in forest cover due to land abandonment (Hiltbrunner et al., 2013). The impacts of LUC on SOC at high altitudes in alpine soils might be lower due to smaller plant productivity and SOC cycling rates. On the other hand the responses might be large due to the high amount of labile SOM stored under unfavorable climatic conditions (Hagedorn et al., 2010a; Hiltbrunner et al., 2013). In the study area in Jaunpass, afforestation was shown to have only a moderate impact on total C stocks (Figure 4), whereas it clearly decreased soil respiration rates, which were found to be 30% lower in the old forest than prior to the LUC. Afforestation in Jaunpass was also shown to have altered the SOM quality, with lower fractions of labile SOM and higher C/N ratios in the forest stands, and induced less favorable microclimatic conditions with about 5°C cooler surface soils under forest than under pasture (Hiltbrunner et al., 2013). SOC stocks in the mineral soil transiently decreased after afforestation, reaching a minimum 40 to 45 years after afforestation and increased afterwards (Hiltbrunner et al., 2013). The pasture was turned into a C sink by afforestation mainly due to the accumulation of forest biomass, which resulted in three times more C being stored in the trees than in the soil. Furthermore, soils in the mature spruce forest (120 years) stored more C than pasture soils, due to the accumulation of C in the organic layer (Hiltbrunner et al., 2013). Therefore, afforestation had a positive effect on SOC storage in this subalpine ecosystem in the long term (Hiltbrunner et al., 2013).

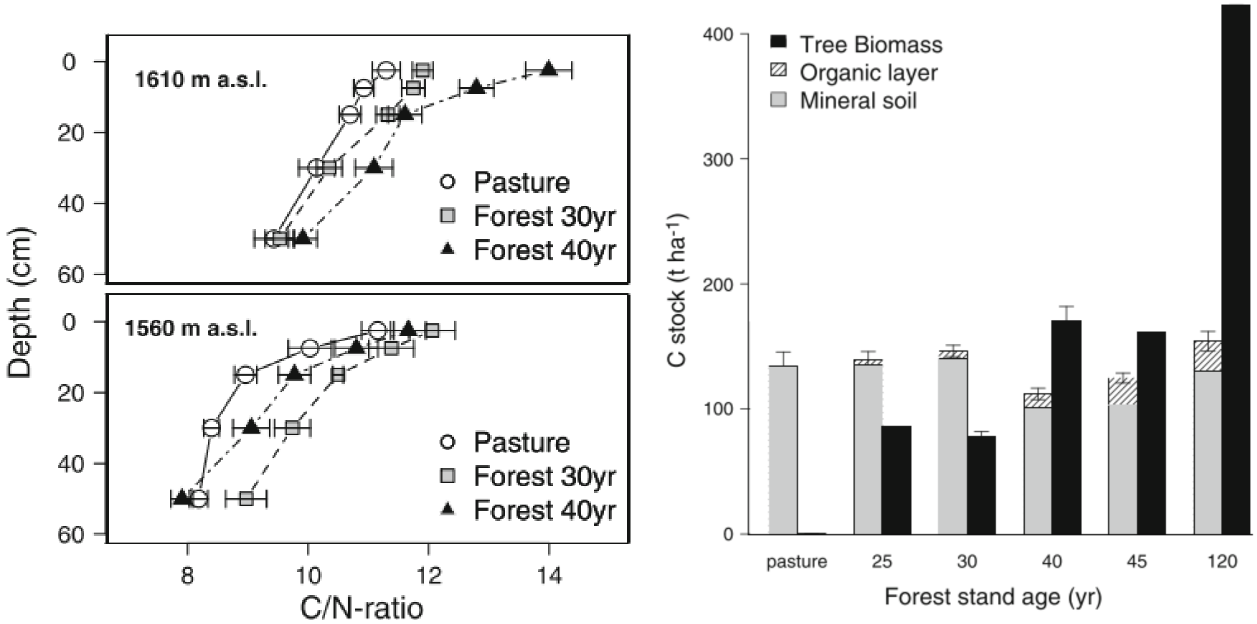

Figure 4. Left: Depth profiles of C/N-ratios (±SE) at different altitudes under pasture and different aged spruce stands. Right: C stocks (±SE) in tree biomass, organic layer, and mineral soil in pasture and different aged spruce stands, with mineral soils being 80 cm thick. Adjusted from Hiltbrunner et al. (2013).

## 2.3 Effects of Climate Change on Soil and Vegetation Carbon Dynamics

Major changes in the global hydrological and energy cycles are likely to occur in this century (Beniston et al., 2007). Extreme precipitation events will very likely become more frequent and intense due to the increase in global mean surface temperature (IPCC, 2013). In the 20th century, the temperature increase in Switzerland was higher than the global average of 1.6°C in western Switzerland, 1.3 °C in the German-speaking part of Switzerland, and 1.0 °C south of the Alps (OcCC & ProClim-, 2007). By 2050, it is expected that mean winter temperatures in Switzerland will increase by about 1.8 °C and mean summer temperatures by about 2.7 °C compared with 1990 (OcCC & ProClim-, 2007). The precipitation regime has also changed in Switzerland during the 20th century. Annual rainfall has increased by 120mm (8%), whereas mean winter precipitation has increased by 20-30% in the northern and western parts of the alpine area (Schmidli et al., 2001). It is also foreseeable that in the future there will be more precipitation in winter and less in summer, with an expected higher variability and an increase in precipitation intensity (OcCC & ProClim-, 2007). Some of the seasonal changes in temperature and precipitation can be seen in Figure 5, and shows the simulated changes for 2070–2099 relative to 1980–2009 for an intermediate greenhouse gas emission scenario in the CH2011 Initiative (Swiss Climate Change Scenarios, CH2011). Local and regional extreme weather and climate events are unfortunately extremely more difficult to estimate because the respective surroundings (relief, distance from the sea, local wind patterns and their oscillations, etc.) have a significant impact (OcCC & ProClim-, 2007).

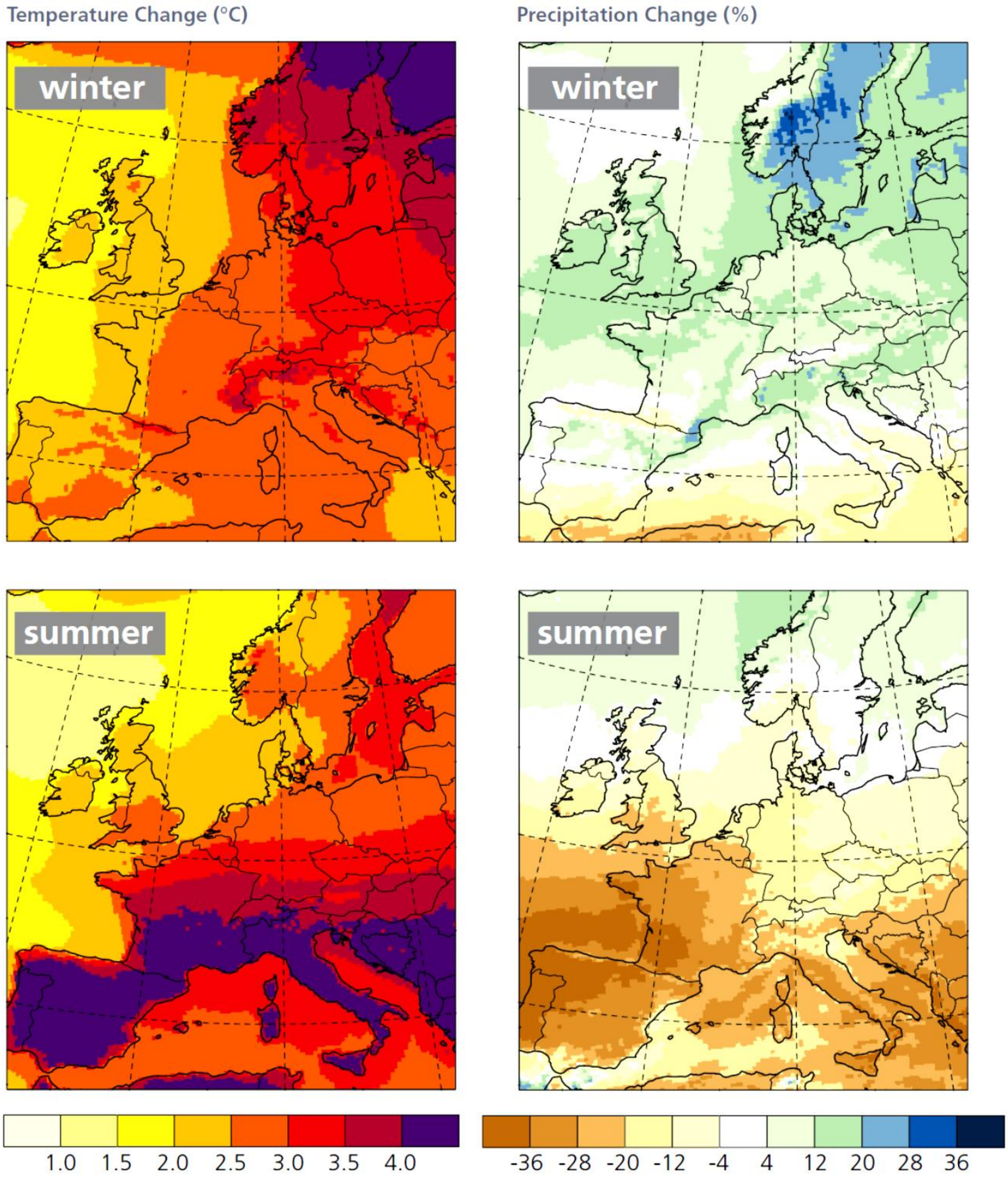

Figure 5. Change of temperature and precipitation for winter and summer as simulated by climate models. The figure shows the multimodel mean change for 2070–2099 relative to 1980–2009, for an intermediate (A1B) greenhouse gas emission scenario. Source: CH2011, 2011.

The changes in precipitation affect the C cycle of terrestrial ecosystems in many ways. Since the ability of soils to store C is thought to be mainly governed by the mean annual precipitation, higher rainfall is thought to be associated with a larger SOC pool (Jenny, 1980). However, C sequestration can either be increased in drier conditions by the suppression of respiration, or decreased through the decreased plant productivity and input of C to the soil (Heimann & Reichstein, 2008). Changes in the frequency or timing of rainfall without changes in the annual total may also have profound effects on ecosystem productivity (Knapp et al., 2002), as these factors determine whether the water will be used by plants and transpired or will just run off and evaporate (Heimann & Reichstein, 2008). The effects of drought on the plant growth and SOC dynamics depend on many factors such as the water-holding capacity of the soil, the vertical distribution of C and roots in the soil, and the general drought sensitivity of the vegetation (Heimann & Reichstein, 2008). Under the impact of drying and rewetting, soils undergo complex changes of soil structure, SOM and microflora compositions (Schmitt & Glaser, 2011). These kind of changes may then have dramatic implications for soil biogeochemical processes during extended summer droughts and periods of intense precipitation (Hentschel et al., 2007). This effect can be seen in the exceptional heat wave and rain deficit in the summer of 2003, as it had a strong impact on plant productivity in many European regions (Hentschel et al., 2007) and it was claimed to have undone the cumulative European C sequestration of five years within a few months (Ciais et al., 2005). However, the effects of precipitation changes on the processes that sequester C are various and generally depend on the ecosystem properties, the time, and the duration of the changes.

Similar to the effects of changes in precipitation amounts and patterns, the changes in temperature can also have various effects on ecosystem C dynamics. In general, increased temperature leads to longer growing seasons, increased vegetation growth and therefore increased C storage (Schaphoff et al., 2006), as long as the photosynthesis is not limited by other factors such as light, $CO_2$ concentration, and water and nutrient availability (Farquhar et al., 1980). On the other hand, increased temperature can also lead to increased rates of decomposition if substrate availability and enzyme activity do not constrain reaction rates (Conant et al., 2011; Davidson & Janssens, 2006). Therefore, soil decomposition rates could exceed the productivity of the plants in a warmer climate, meaning that more C could be lost from the soil, even though the input of new C was higher. However, the effects of rising temperatures on SOM are a subject of controversy despite the large number of studies on this topic (Jandl et al., 2007). For example, predictions from different types of carbon-climate models have indicated that global warming may accelerate due to increased SOM decomposition in a warmer climate (Beier et al., 2008; Allison et al., 2010; Frey et al., 2013). However, several field studies have shown that after the initial stimulating effect of warming, the soil respiration levels in chronically warmed soils returns to ambient levels within a few years (Frey et al., 2013; Allison et al., 2010). This might result from the depletion of the SOC pools at higher temperatures, which could in turn bring about a decline of specific microbial activity or community biomass (Craine et al., 2012). Since even half of the $CO_2$ lost from the soils stems from microbial decomposition, a thorough understanding of how soil microorganisms respond to temperature changes is needed for accurately predicting how climate warming may alter soil $CO_2$ fluxes (Conant et al., 2011; Rousk et al., 2012; Frey et al., 2013).

SOM response to temperature may also differ depending on the temperature sensitivity of the decomposition of different SOM pools and fractions (Savage et al., 2013). This topic is currently debated in the scientific community (Davidson & Janssens, 2006; Smith et al., 2008; Stockmann et al., 2013). According to the chemical theory of single chemical reactions (Arrhenius, 1889), the recalcitrant forms of SOM should be more sensitive to temperature than labile forms (Davidson & Janssens, 2006; Stockmann et al., 2013; Schütt et al., 2014). Craine et al. (2012) concludes that with the decomposition of most biochemically recalcitrant organic matter shows the greatest relative sensitivity to temperature, future increases in temperature could generate a positive feedback to global warming. However, Conant et al. (2011) points out that the decomposition rate of the least decomposable SOC may be kinetically very sensitive to temperature, but the decomposition rate might be so slow that little C would decompose no matter what the temperature. There are also other contradictions. According to the chemical theory, the temperature sensitivity of SOM mineralization should differ among soil horizons and litter types, but there are studies on C mineralization both supporting and questioning this theory (Schütt et al., 2014). The reason for this could be that the theoretical relationship is not valid in the context of describing the sum total of thousands of chemical, physical and biological processes that together make up the observed temperature dependence of SOM decomposition (Kirschbaum, 2006). It seems that the response of the decomposition rate to temperature and the fate of SOC in a warmer world remains unresolved and thus, understanding the processes underlying the inputs and losses in the C cycle in a warmer world is a great challenge (Conant et al., 2011).

The effects of climate change have been widely studied in temperate forest and grassland ecosystems. The effects of more frequent drought concern the permanent grasslands that cover 75% of the agricultural land in Switzerland, sustaining domestic meat and dairy production (Fuhrer et al., 2006). It has been suggested that the productivity of grasslands could benefit from moderately increased temperatures and elevated $CO_2$, but would become more water-limited if the changes in thermal and hydrological conditions were more pronounced (Calanca & Fuhrer, 2005). In turn, the detrimental effects of more frequent periods of droughts on forest health and succession can already be observed in the dry Valais region (Fuhrer et al., 2006). A study conducted in a temperate Norway spruce forest suggests that prolonged summer droughts are likely to lead to a significant reduction of annual $CO_2$ losses, not only during the drought period but also several weeks afterwards (Muhr & Borken, 2009). When it comes to climate warming, forest soils are found to respond more strongly than soils under other land use (Jandl et al., 2007). In addition, forest floors are expected to be more susceptible to climate warming than the mineral soils because of the greatest turnover rate and large amount of C stored in this layer (Smith et al., 2008). Climate change may also influence the timing of soil warming (Mellander et al., 2005). In high altitude forest ecosystems, cold-season processes substantially contribute to annual soil C and N mineralization, with soil microbial activity throughout the winter accounting for 21-50% of the annual C mineralization (Schütt et al., 2014). Since soil frost generally varies inversely with snow depth, less snowfall or a shorter duration of snow on the ground can lead to a deeper and more persistent freezing than when the snowpack is established in early winter (Mellander et al., 2006). These changes can also influence root mortality, SOM quality and C and N concentrations in the soil solutions during winter (Mellander et al., 2007). Overall, the projected changes in the temperature and water cycle can affect the processes within the C cycle in temperate forests and grasslands and lead to remarkable changes in the ecosystem C balance.

## 2.4 Modeling the Plant-Soil-Atmosphere System

Models are tools that can be used to simulate the combined impact of many different factors on the target output (Smith et al., 2008) and therefore effective in tasks such as quantifying the complex interactions and feedback taking place in soils due to global change (Schmidt et al., 2011). Models can be used whenever data is not available, long-term impacts are difficult to calculate, or the system behavior is very complex (Lenhart et al., 2002). Since the 1930s, several models at different levels of complexity have been developed to quantitatively describe the biogeochemical processes in soils spanning various spatial and temporal scales (Manzoni & Porporato, 2009). Today there are models that simulate whole ecosystems (e.g. CENTURY, EPIC, DNDC) or only SOC transformation (RothC and ICBM, Smith et al., 2008). Within process-oriented models, CENTURY and RothC are the most frequently used to simulate SOM dynamics at a local scale (Viaud et al., 2010; Stockmann et al., 2013). In order to analyze the impact of different land uses on water and land recourses, soil-vegetation-atmosphere transfer (SVAT) models such as CoupModel are very effective. Today many models consider soil moisture and temperature as dynamic components, often coupling soil water and heat balance equations to the biogeochemical model (Manzoni & Porporato, 2009). Some models directly describe the coupling between soil C and N, such as CoupModel (Jansson and Karlberg, 2004), DNDC (Li et al., 2000), CENTURY (Parton et al., 1987) and Daisy (Bruun et al., 2003) (Gärdenäs et al., 2011). This is important, since there is an increasing awareness that the interactions between soil C and N need to be taken into account for modeling the impact of climate changes on N-limited ecosystems (Thornton et al., 2007).

Modeling any changes in the terrestrial C cycle is complicated for several reasons. Firstly, the interrelated factors can be biological, physical, or both, and occur over various spatial and temporal scales (Cole, 2013). Secondly, incorporating the complexity of the spatially heterogeneous soil system where solid, liquid, gas and biology all interact and the spatial heterogeneity of biota, environmental conditions and organic matter may have a dominant influence on C turnover into one conceptual model is challenging (Schmidt et al., 2011). Indeed, SOM can rarely be satisfactorily represented in models as a single uniform entity due to the heterogeneity of SOM with respect to its stability (Gärdenäs et al., 2011). Early soil models simulated SOC as one homogeneous compartment (Jenny 1941), then two-compartment models were proposed (Jenkinson, 1966), and as computers became more accessible, multi-compartment models were developed (McGill, 1996; Ostle et al., 2009; Smith et al., 2008). Nowadays virtually all current models represent SOM heterogeneity as either two or more fractions of SOM differing in their specific decay rates or as a continuous quality spectrum, where the specific decay rate is a continuous function of the quality (Gärdenäs et al., 2011). In most existing models, the response of SOC to warming is based on the first-order decay of SOC with the role of microbes as decomposers implicit in the decay constants (Allison et al., 2010). Conventional models of this kind without direct coupling between microbes and SOC turnover cannot simulate negative feedbacks on decomposition caused by reductions in microbial biomass and enzyme production (Allison et al., 2010). Thus, new models are emerging that couple SOC turnover directly to microbial biomass and physiology (Allison et al., 2010).

# 3 Materials and Methods

## 3.1 Study Site

The climatic conditions of Switzerland vary regionally due to the mountainous influence (Bolliger et al., 2007). The climate conditions range from intra-alpine dry and continental climate regime (Central Alps) to oceanic high elevation (Nothern Alps and Jura Mountains), insubrian climate (Southern Alps) and low-elevation climate (Plateau) (Bolliger et al., 2007). This study was conducted in a sub-alpine region in the Canton of Fribourg (7°15'54E; 46°37'17N) on a south-facing slope reaching from 1 450 to 1 800 m above sea level, with mean summer and winter air temperatures of 11.4 and 0.6 °C respectively and mean annual precipitation of 1 250 mm with a maximum in the summer. The entire slope has been under pasture for at least 150 years (Hiltbrunner et al., 2013). However, the eastern part of the slope was gradually afforested with Norway spruce (Picea abies L.) after several avalanches in 1956, while the western part remained as a pasture (Figure 6; Hiltbrunner et al., 2013). A space-for-time study was conducted by Hiltbrunner et al. (2013) between the years 2010 and 2011 in order to quantify the SOC stocks and SOM quality in relation to land use and stand age. Furthermore, they investigated how SOC-cycling and storage in relation to tree biomass changes and which mechanisms drive these changes after LUC. This slope provided a good set-up for a space-for-time study, since the afforestation differs in age (25, 30, 40, and 45 years old), the slope provided homogeneous soil conditions within the whole site and a mature spruce forest (older than 120 years) could be used as a control (Hiltbrunner et al., 2013). Soils across the whole slope were Eutric Cambisols on calcareous bedrock with a mean thickness of 80 cm and carbonate-free to an average depth of 60 cm (Hiltbrunner et al., 2013). The soil texture was spatially highly variable, as seen in Table 2. The details of how the soil sampling and vegetation measurements were made can be found in the paper of Hiltbrunner et al. (2013).

Table 2. Soil bulk density (BD) and texture in the simulated plots (P3, P5, P6, and P8).

| | | | **Soil 0-10cm** | | | | **Soil 20-30 cm** | | | | **Soil 40-60 cm** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Land use** | **Plot** | **Altitude (m)** | **BD (kg dm$^{-3}$)** | **Clay (%)** | **Sand (%)** | **SOC (%)** | **BD (kg dm$^{-3}$)** | **Clay (%)** | **Sand (%)** | **SOC (%)** | **BD (kg dm$^{-3}$)** | **Clay (%)** | **Sand (%)** | **SOC (%)** |
| Pasture | P3 | 1 610 | 0.83 | 50 | 20 | 4.2 | 1.01 | 47 | 21 | 2.1 | 1.1 | 33.7 | 48.35 | 1.44 |
| Pasture | P6 | 1 520 | 0.83 | 54 | 26 | 5.1 | 1.08 | 58 | 27 | 1.6 | 1.1 | 57.9 | 27.4 | 1.53 |
| Forest 40y | P5 | 1 520 | 0.87 | 19 | 71 | 3.6 | 1.17 | 19 | 66 | 1.6 | 1.1 | 19.8 | 64.7 | 1.13 |
| Forest 40y | P8 | 1 510 | 0.83 | 41 | 29 | 4.1 | 1.07 | 39 | 36 | 1.5 | 1.1 | 38.8 | 47.7 | 0.90 |

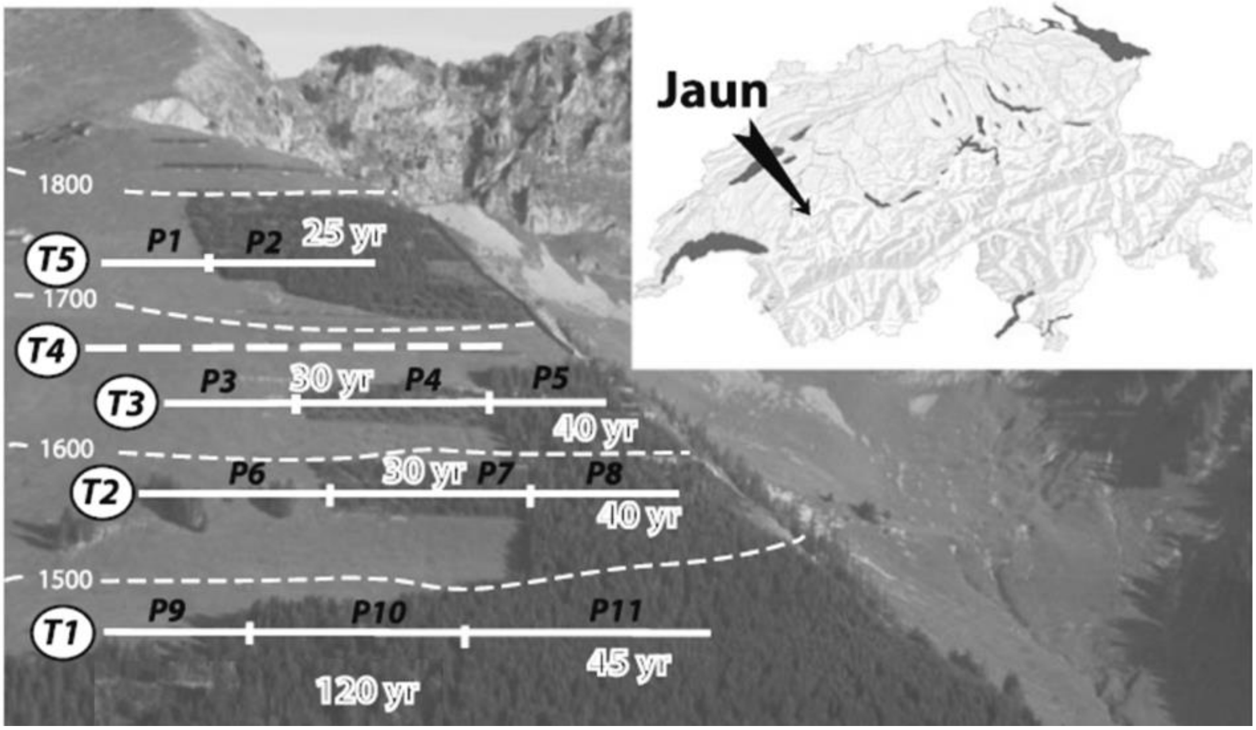

Figure 6. The study site in Jaunpass. T1-T5 refer to altitudinal transects along the slope; P1-P11 to plots with different land uses (grassland or 25, 30, 40, 45, and 120 years old forest).Only the plots P3, P5, P6, and P8 were used in this study. Adjusted from Hiltbrunner et al. (2013).

## 3.2 CoupModel

The ecosystem process model CoupModel (CoupModel 2014; Jansson, 2012) is a numerical, one-dimensional SVAT-model (Soil-vegetation-atmosphere transfer model) that can be used for calculating the vertical heat, water, C and N fluxes in the soil–snow–vegetation– atmosphere system (Mellander et al., 2005; Conrad & Fohrer, 2009). Recently, it has been used for example for simulating the impact of climate change on snow and soil temperature in boreal Scots pine stands (Mellander et al., 2007), investigating the possible changes in the C dynamics of Swedish Norway spruce forest ecosystems (Jansson et al., 2008), and simulating the $CO_2$ fluxes of five different open peatland systems across Europe (Metzger et al., 2014).

The simulations in CoupModel can be made either as single runs in order to represent a unique input or as multiple series of simulations based on random or systematic sampling of parameter values (Jansson, 2012). Driving variables are standard climate parameters such as air temperature, precipitation, relative humidity, global radiation, and wind speed. The model is based on two coupled differential equations for the water and heat flows, which are described by gradients in temperature or water potential. Richards-equation is used for calculating the soil water flow, and Fourier’s law and a surface energy balance equation is used for calculating the heat flow (Mellander et al., 2005). The soil profile is discretized into multiple horizontal layers, each layer having specific physical and thermal properties, whereas the snow is treated as a single, homogenous layer (Mellander et al., 2007). The land surface is represented as a number of different surface compartments such as bare soil, vegetation, and intercepted precipitation, that are also used for estimating water and heat exchange between the soil and the atmosphere (Gustafsson et al., 2004). CoupModel is therefore able to allow for simultaneous water and heat exchange from the vegetation layer and soil/snow surface below (Gustafsson et al., 2004). The most important processes within the mass and heat balances are shown in Figure 7 (CoupModel, 2014). Some of these processes, such as soil evaporation and water uptake by roots, are optional. Detailed descriptions of CoupModel can be found in the literature (Conrad & Fohrer, 2009; Gustafsson et al., 2004; Jansson, 2012; Mellander et al., 2005; Mellander et al., 2006; Stähli & Gustafsson, 2006; Svensson et al., 2008a,b) and online (CoupModel, 2014).

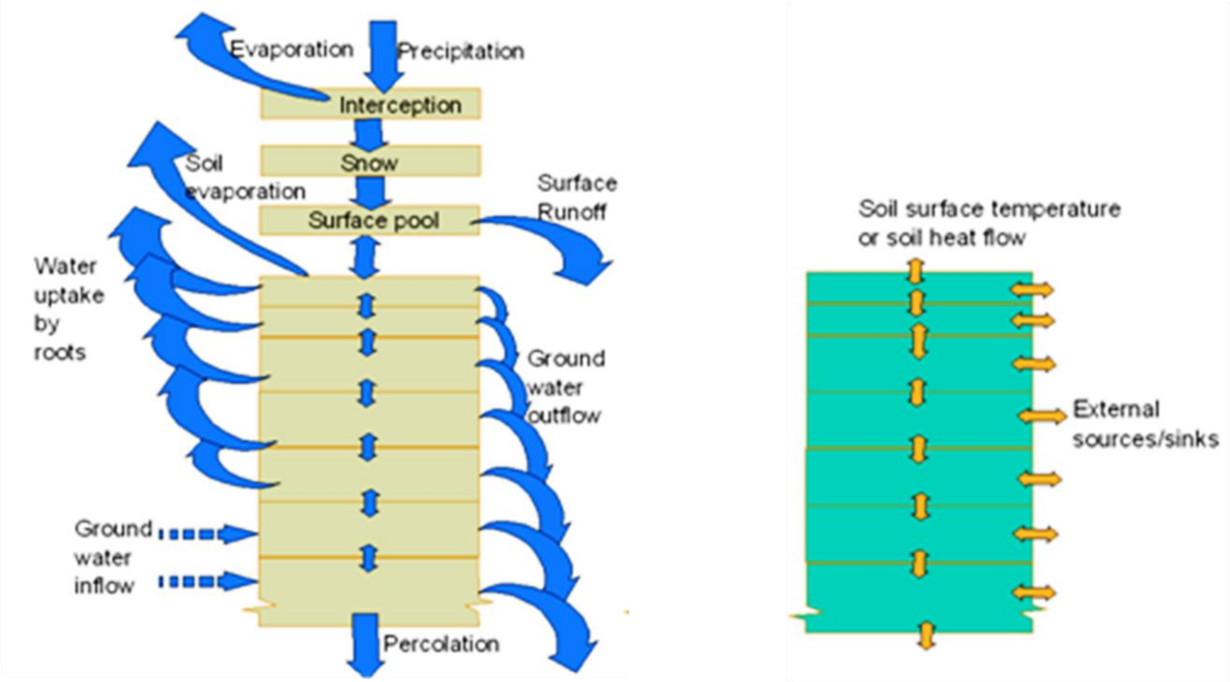

Figure 7. Mass balance (left) and heat balance (right) of CoupModel. Source: CoupModel (2014).

Vegetation related processes such as transpiration, dynamic plant growth, and water uptake may be optionally included in CoupModel. The latest developments in CoupModel have included a wide range of limiting factors for the plant development (Jansson, 2012), which improves the simulations of C sequestration in forest ecosystems (Svensson et al., 2008a), and how it is affected by climate (Jansson, 2012). C and N dynamics can also be simulated with CoupModel. C and N turnover can be calculated in several soil and plant compartments (Figure 8). In CoupModel, the canopy can be treated either as a single big leaf (implicitly or explicitly), or as multiple canopies. Competition is enabled between the different plant layers with respect to the interception of light, and the uptake of water and N (Svensson et al., 2008a). C and N are allocated to leaf, stem, coarse and fine roots, and fruiting body according to predefined allocation factors and C/N ratios (Conrad & Fohrer, 2009). Litter is produced as the fraction of above- and belowground plant residues and entered into the SOC pool (Conrad & Fohrer, 2009). Different turnover rates can be considered for different litter and humus pools. With all these processes describing the C and N dynamics of the soil-plant-atmosphere system, CoupModel makes it possible to calculate the C balance of the system. By definition, the C balance of the ecosystem is the difference between its C gains and losses at any point of time (Heimann & Reichstein, 2008).

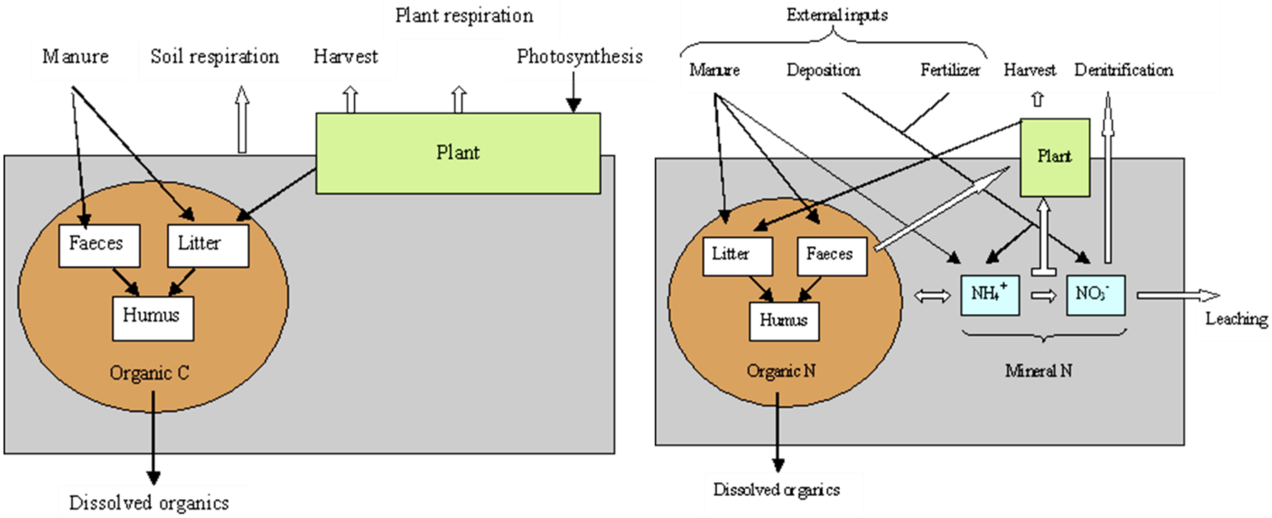

Figure 8. Carbon flows (left) and Nitrogen fluxes (right) in CoupModel. Source: CoupModel (2014).

## 3.3 Model Set-up

Out of eleven plots shown in Figure 6, only four (P3 and P6 (grassland), P5 and P8 (forest 40 years)) were chosen for the simulations due to lack of data on the other plots. The model used a daily time step with 96 iterations per day. The meteorological data of precipitation, air temperature, wind speed, and air humidity were given as a time series on a daily resolution, whereas the solar radiation was estimated by the model due to the lack of long-term data. Measured data was used for the land use change simulations (1960 – 2010) and scenarios for the climate change simulations (2010 – 2100). The meteorological data was divided into two different driving files according to the altitude (1500m and 1650m above the sea level). Mean air temperature and annual precipitation were different between different altitudes, and also between time periods and climate scenarios (Table 3). The validation period (2010-2011) was on average drier and warmer than the years before (1960-2011). The vegetation data was given as table parameters in the model. The parameter values for grassland were based on a study in intensively managed grassland in Eifel Mountains, Germany (Mischurow, 2014; Table 4). The corresponding parameter values for the forest were taken from CoupModel tutorial “Forest C system”, which represents 40-year-old forest in central Sweden. Vegetation in both land uses was simulated in two layers: the canopy and the undergrowth. Soil properties, such as texture and SOC, were inserted into CoupModel soil database separately for every simulated site. The measured soil profiles were divided for the simulations into 16 layers, with the thinner layers at the upper soil (5 layers of 2cm each and 3 layers of 10cm each) and thicker layers in the deeper soil (8 layers of 20cm each), with a boundary level of 2m. An overview of the data used for the simulations can be found in Table 4.

Table 3. Differences in the mean values of annual air temperature and annual precipitation within the different simulation periods.

| **Variable** | **Mean 1500m** | **Mean 1650m** |
|---|---|---|
| **Air temperature (°C)** | | |
| Land use change simulations 1960 - 2012 | 5.12 | 4.36 |
| Validation period 2010 – 2011 | 6.99 | 6.19 |
| CLM 2012 – 2100 | 8.47 | 7.41 |
| RCA 2012 – 2100 | 8.45 | 7.35 |
| REGCM3 2012 – 2100 | 7.88 | 6.79 |
| **Precipitation (mm)** | | |
| Land use change simulations 1960 - 2012 | 1512 | 1394 |
| Validation period 2010 – 2011 | 1365 | 1169 |
| CLM 2012 – 2100 | 1513 | 1359 |
| RCA 2012 – 2100 | 1448 | 1297 |
| REGCM3 2012 – 2100 | 1512 | 1341 |

Table 4. Data used for input and validation for the simulations.

| Data | Parameters | Description | Resolution | Type | Source |
|---|---|---|---|---|---|
| Meteorological | Precipitation,<br>Air temperature,<br>Wind speed,<br>Air humidity | 1960 – 2012:<br>Extrapolated climate data<br>2010 – 2100:<br>Climate scenarios CLM, RCA, REGCM3.<br>Data sets for two altitudes: 1500m and 1650m | Daily | Input | Meteotest, 2013 |
| Vegetation / grassland | Table parameters for grassland | Vegetation parameters from a study site in Rollesbroich, recently-established highly-instrumented research site in an intensively managed grassland in Eifel mountains, Germany. | Static | Input | Mischurow, 2014 |
| Vegetation / forest | Table parameters for 40-year-old forest | 40 year old trees in central Sweden | Static | Input | CoupModel tutorial "Forest C system", downloaded from CoupModel (2014) |
| Vegetation | C and N stocks | Measurements conducted 2010 – 2011 | One point in time | Comparison with simulations | Hiltbrunner et al. 2012 and 2013 |
| Soil | Texture<br>Porosity<br>C content | Measurements conducted 2010 – 2011 | One point in time | Input | Hiltbrunner et al. 2012 and 2013 |
| Soil | Soil temperature and volumetric water content in 5cm, 25cm and 50cm depth | Measurements conducted 2010 – 2011 | Daily averages of 4 plots | Validation | Hiltbrunner et al. 2012 and 2013 |
| Soil | C stocks | Measurements conducted 2010 – 2011 | One point in time | Input, comparison with simulations | Hiltbrunner et al. 2012 and 2013 |
| Soil | Soil $CO_2$ efflux | Measurements conducted during the year 2006 | Four measurement days for every plot | Comparison with simulations | Hiltbrunner et al. 2012 and 2013 |

In this section, all the model settings that were set to something other than the default settings are described. For the time period of 1960 – 2011, the radiation input style was estimated due to the lack of long term data. Annual air temperature cycle was assumed, with amplitude of 20 °C and a mean of 5.7°C (1500m above sea level) or 5°C (1650m above sea level). The heat flux unit of the model was set to Watt. For calculating the evaporation, radiation input style was used, which means that a physical based equation is used that accounts for both the net radiation and the transport of vapor in the atmosphere boundary layer. The hydraulic function of Brooks and Corey was used and the unsaturated conductivity in the soil matric domain was given by the equation of Mualem. The soil hydraulic conductivity properties were generated from the soil texture using pedotransfer functions. The saturation and wilting point of the soil was determined using the Soil Triangle Hydraulic Properties Calculator (Pedosphere.com, 2015). Bypass flow was included in the simulations, meaning that bypass water flow is calculated if the incoming flow rate to one soil layer exceeds a sorption capacity rate as calculated from a simple empirical equation. The lower boundary for water equation was calculated from the assumption of a constant pressure head of the bottom layer, which was given as a parameter value. The heat capacity of solid soil was assumed to be a constant. Iterative energy balance was used as the soil evaporation method, which is derived from an iterative solution of the soil surface energy balance using an empirical parameter for estimating the vapor pressure and temperature on the soil surface. The soil surface temperature was also calculated as an iterative numerical solution.

The canopy was represented as “explicit big leaves”, meaning that soil evaporation and transpiration from the canopy are treated as separate flows and several plant layers can be considered by the model. The albedo, canopy height, LAI, and root depth and length were simulated based on vegetation parameters. Plant development was chosen to start on the day when the accumulated sum of air temperatures above a critical value reached the predefined value.  The accumulation of temperatures started when the day length exceeds 10 hours and ended when five consecutive days in the autumn had day lengths shorter than 10 hours and temperatures were below a critical value. During winter, plants were set to go into dormancy. The plant growth was determined by radiation use efficiency and reduced by limiting factors such as unfavorable water, nitrogen and temperature conditions.  Precipitation interception and snow interception were both taken into account. The interception rate was calculated by an exponential function. The stability correction of the aerodynamic resistance was calculated as a function of the Monin-Obukhov length. Litter fall was calculated as a function of the accumulated difference between +5 °C and the air temperature when the temperature is below +5 °C. Carbon and nitrogen were simulated to have dynamic interaction with the water and heat equations of the model.  For more details on the equations used, see Official Documentation of CoupModel (2014).

## 3.4 Model Validation and Calibration

The model is acceptable for its intended use if it meets specified performance requirements (Rykiel, 1996). The purpose of validation is to study the model performance without changing any of the parameters (Jansson, 2012). Calibration, in turn, is used for improving the agreement between model output and a data set by adjusting model parameters and constants that are otherwise unknown (Rykiel, 1996). In CoupModel, validation can be done by combining validation variables with the corresponding output variables and by further evaluating the performance of the model by graphs and statistics. Calibration can be obtained by two different approaches: Bayesian or generalized likelihood uncertainty estimation (GLUE). In general, when the modeled system is simple, the errors in model structure are small, and the measurement errors are easy to estimate, the more formal Bayesian calibration approach is recommended (Jansson, 2012). In contrast, when the model structural uncertainty and the measurement error uncertainty are difficult to evaluate, the GLUE approach may be preferred (Jansson, 2012). Many recent users of CoupModel have used the GLUE method instead of Bayesian calibration because of the flexibility of the GLUE approach (Jansson, 2012). The GLUE method was proposed by Beven & Binley (1992) and it applies high numbers of Monte Carlo simulations to find the parameter sets of equally good modeling performance (Conrad & Fohrer, 2009). If random parameter sampling is performed, the GLUE approach usually requires a large number of multiple simulations. For example, Uhlenbrook & Sieber (2005) recommended upwards of 10,000 runs. Some limitations of the GLUE approach are the subjective nature of the likelihood, chosen threshold values, and the data quantity (Conrad & Fohrer, 2009).

In this study, the simulated soil temperatures and volumetric water contents in 5cm, 25cm and 50cm depth were used as validation variables and compared with the measured data from four different plots (P3, P6, P5, and P8) within the years 2010 – 2011. All parameter values that were not measured, derived from other studies, or generated from the soil texture using pedotransfer functions were calibrated within a certain range by using the model setting “Set (parameter) for multirun simulations”. Calibrations were conducted by stochastic linear method for meteorological and soil parameters. Uniform probabilities were assumed for all selected input variables in the GLUE calibration. Altogether, at least 10,000 multirun simulations were performed for each plot (P3, P5, P6 and P8). After the calibrations, the multirun simulations were divided into acceptable and unacceptable ones based on the root mean square error (RMSE) between the simulated and measured values. The best sets of parameters were then selected based on the lowest RMSE values within the acceptable simulations. The importance of the parameters in the model was further evaluated by a sensitivity analysis (see Section 3.5). Parameters that were judged to be of major significance to the performance of the model and the C budget of the site were used in the calibration process with additional 10 000 model runs, whereas the insensitive parameters were set back to their default values. The parameters that were calibrated after the sensitivity analysis can be found in Table 5. The proper calibration range of the parameters was determined by single model runs before the calibration.

Table 5. Parameters that were calibrated after the sensitivity analysis (GLUE, n=10 000) with a value range indicated below. These were selected because they were unknown and according to the sensitivity analysis, important for the model output.

| Parameter | Unit | Value range | Description (if available) |
|---|---|---|---|
| Meteorological parameters | | | |
| ZeroTemp_WaterLimit | kg $m^{-2}$ | 0.01 – 1000 | Liquid snow water threshold to put soil surface temperature to 0 ºC. |
| RoughLBareSoilMom | m | $1e^{-5}$ – 0.05 | Surface roughness length for momentum above bare soil. |
| WindLessExchangeSoil | - | 0 – 1 | Minimum turbulent exchange coefficient (inverse of maximum allowed aerodynamic resistance) over bare soil. Avoids exaggerated surface cooling in windless conditions or extreme stable stratification. |
| AlbLeafSnowCoef | - | 0 – 1 | Fraction of snow albedo in the albedo of a snow-covered canopy. |
| DensityCoefWater | kg $m^{-3}$ | 50 – 200 | Liquid water coefficient in the calculation of snow density as a function of liquid and ice content. The snow density increase with this value when the liquid water content in the snow pack becomes equal to the total retention capacity. |
| Equil Adjust PSI | - | 0 – 2.5 | Factor to account for differences between water tension in the middle of top layer and actual vapor pressure at soil surface. Normal values ranges from 0 to 2. A value of 0 implies that there is no difference in soil moisture between the soil surface and the uppermost soil layer. 1 implies that the surface can be two orders of magnitudes drier and one order of magnitude wetter than the uppermost soil layer, if the “MaxSurf” parameters are set to their default values. |
| Soil parameters | | | |
| FreezepointF0 | - | 9 – 11 | Empirical freezing-point coefficient parameter used to estimate the liquid water content as a function of change of energy storage when freezing takes place in the soil. |
| FreezepointFWi | - | 0.1 – 1 | Fraction of wilting point remaining as unfrozen water at -5 °C. Normal values will be in the range between 0.3 and 1.0. |
| AScaleSorption | - | 0.001 – 1000 | Sorption scaling coefficient for flow in the matric pore domain. A low value (<0.001) will result in a poor capacity of the aggregate to adsorb water during infiltration and a high degree will be bypassed in the macropores. High values give the opposite effect. Appropriate values can be found in a wide range depending on the corresponding values assigned to the saturated conductivity for the matric pore domain. |
| AlphaHeatCoef | W $m^{-1}$ °C | 0.1 – 20 000 | Heat transfer coefficient regulating refreezing of water in the high-flow domain. This parameter depends on the shape and the geometry of the pore structure and the interface between the ice and the liquid water in the soil in combination with the thermal properties of ice and liquid water. It has to be determined by calibration and no experience exists concerning appropriate values for different soil types. |
| ClayFrozenC3 | - | 0.001 – 0.004 | - |
| ClayUnfrozenC1 | - | 0.01 – 0.133 | - |
| ClayUnfrozenC3 | - | 0.01 – 0.7 | - |
| OrganicC2 | - | 0.001 – 100 | - |
| OrganicFrozenC | - | 1.3 – 3 | - |
| SandFrozenC2 | - | 0.01 – 100 | - |
| SandFrozenC4 | - | 0.01 - 100 | - |
| SandUnfrozenC2 | - | 0.01 - 100 | - |

## 3.5 Sensitivity Analysis

The calibration procedure implies a clear understanding about all the parameters used as input to the model and of the processes represented in the model (Lenhart et al., 2002). Since soil-vegetation-atmosphere-transfer models are often overparameterized relative to their calibration data (Conrad & Fohrer, 2009), it is important to determine which parameters are the most important in terms of the model output, so that time is not uselessly spent on the non-sensitive ones. In this way, sensitivity analysis may help to simplify the model, since the parameters that have no effect on the model output can be set back to their default values. Furthermore, understanding how much the model parameters affect the model output can lead to a better understanding about the model structure, better estimated values, and thus reduced uncertainty (Lenhart et al., 2002).

The first approach (variant A) of the sensitivity analysis method of Lenhart et al. (2002) was chosen for the sensitivity analysis, since it is probably the simplest way of conducting a sensitivity analysis and is frequently found in literature (Lenhart et al., 2002). In this approach, parameters are changed ± 10% of their initial values, one at a time, regardless of the potential range of the parameter. In the second approach, not chosen here, the different relative width of the parameter ranges is taken into account by varying the parameters by 25% of the entire predefined parameter range. In both approaches, the sensitivity is expressed by a dimensionless index, which is calculated as the ratio between the relative change of the model output and the relative change of the input parameter. The sign of the index shows whether an increase in the parameter leads to an increase in the output variable and a decrease of the parameter leads to a decrease of the variable, or whether the inverse is true (Lenhart et al., 2002). The sensitivity is then classified as very high (sensitivity index $|I| \geq 1$), high ($0.2 \leq |I| \leq 1$), medium ($0.05 \leq |I| \leq 0.2$) or small to negligible ($0 \leq |I| \leq 0.05$). The details of how to calculate the sensitivity index can be found in Lenhart et al. (2002).

In this study, 85 input parameters were selected for the sensitivity analysis. The effects of a change of ±10% in the initial parameter value on the output data of soil temperature, volumetric water content, evapotranspiration, water and C balance, plant C, SOC and soil total respiration were investigated by running the simulations separately for each parameter of plot P3 (grassland) from the year 2010 to 2011. The insensitive parameters were set back to their default values due to their minor effect on the investigated output data.

## 3.6 Land Use Change Simulations (1960-2012)

The simulation of land use change was conducted by running the model with measured meteorological data from 01.01.1960 to 31.12.2012. The parameter representing the mean annual air temperature was changed according to Table 3 to represent the average air temperature of the whole simulation period. The 92 parameters shown in Appendix 1 were changed stepwise during the simulation period. These parameters represent soil thermal properties, snow layer, vegetation characteristics and soil organic processes, which are all likely to change after a LUC. These parameters were changed linearly with a 5 year time step within 1970 and 2010 (1st July in 1970, 1975, 1980, 1985, 1990, 1995, 2000, 2005, and 2010). For this purpose, the model setting "Change (parameter) value during simulation" was used. In this way, sites P3 and P6 remained as grassland during the whole simulation period, whereas sites P5 and P8 were subjected to gradual afforestation. The output variables are listed in Table 6. In addition to the LUC simulations, also simulations without LUC were run for the same time period in order to allow the comparison of the results with the LUC simulations.

The effects of LUC on the SOC stocks were analyzed using a simplified version of the carbon response function (CRF) developed by (Poeplau et al., 2011). CRF is a simple statistical modeling approach to describe the relative SOC change rate after LUC as a function of time:

$$\Delta \mathrm{SOC} = \frac{\mathrm{SOC(LU2)} - \mathrm{SOC(LU1)}}{\mathrm{SOC(LU1)}} \times 100,$$

where ΔSOC is the relative SOC stock change (%), SOC(LU1) is the soil C stock before the land use change, and SOC(LU2) the soil C stock after the land use change. The modeling approach used six different regression models and was developed for analyzing the results of multiple studies in the temperate zone. In this modeling study, only the equation mentioned here was used to analyze the data. A similar approach was used to analyze the effects of land use and climate change on the total system (soil and vegetation) stock change. In this approach, the total stocks (soil and vegetation) 40 years after the simulation start were compared with the stocks at the beginning of the simulation.

Table 6. Output variables determined for all simulations. The numbers in parentheses indicate either plant layers (1 and 2) or soil layers (1-16).

| Type | Group | Output variable | Unit | Description (if available) |
|---|---|---|---|---|
| Auxiliary variables | Plant | Canopy height (1), (2) | m | Height from the soil surface to the top of the canopy. |
| | | Root depth (1), (2) | m | Depth of roots. |
| | Soil heat flows | Temperature (1) – (16) | °C | Temperature of a soil layer |
| | Soil water flows | WaterContent (1) – (16) | vol % | Volumetric water content (liquid non-frozen) of soil layers |
| | Plant Growth | C Plant (1), (2) | g m$^{-2}$ | C content in the new and old plant biomass pools. |
| | | C Plant AboveG (1), (2) | g m$^{-2}$ | C content in the new and old plant above ground biomass pools. |
| | | C Plant Resp (1), (2) | g m$^{-2}$ day$^{-1}$ | Plant respiration. |
| | | Croots (1), (2) | g m$^{-2}$ | C content in roots. |
| | | C total plant | g m$^{-2}$ | The total C content in the new and old plant biomass pools for all plants |
| | | C Total Plant AboveG | g m$^{-2}$ | The total C content in the new and old plant above ground biomass pools for all plants |
| | | C Total Plant Litter | g m$^{-2}$ day$^{-1}$ | The total transfer of C from the plant(s) to litter. |
| | | C Total Roots | g m$^{-2}$ | The total C content in the new and old root pools for all plants |
| | Soil organic processes | CTotSoil Faeces | g m$^{-2}$ | C content in the faeces pool in the whole soil profile. |
| | | CTotSoilHumus | g m$^{-2}$ | C content in the humus pool in the whole soil profile. |
| | | CTotSoil Litter1 | g m$^{-2}$ | C content in the litter pool 1 in the whole soil profile. |
| | | CTotSoil Litter2 | g m$^{-2}$ | C content in the litter pool 2 in the whole soil profile. |
| | | CTotSoilMicrobes | g m$^{-2}$ | C content in the microbial pool in the whole soil profile if microbes are treated explicitly. |
| | | CTotSoilOrg | g m$^{-2}$ | C content in all soil organic pools in the whole soil profile. |
| | | CTotSoil RespRate | g m$^{-2}$ day$^{-1}$ | Respiration from all organic pools in the whole soil profile. |
| | | CN Ratio Humus (1), (5), (7), (9), (10) | - | C nitrogen ratio in the humus pool. |
| | Additional variables | Evapotranspiration | mm day$^{-1}$ | Total evaporation and transpiration (including evaporation from snow). |
| Flow variables | Additional biotic variables | Carbon Flux | g m$^{-2}$ day$^{-1}$ | |
| | | Carbon Balance Rate | g m$^{-2}$ day$^{-1}$ | Photosynthesis subtracted by total respiration from the soil and the plant. |
| | | Nitrogen Balance Rate | g m$^{-2}$ day$^{-1}$ | |
| | | Soil resp no roots | g m$^{-2}$ day$^{-1}$ | |
| | | Soil respiration | g m$^{-2}$ day$^{-1}$ | |
| | | Total PhotoSynt | g m$^{-2}$ day$^{-1}$ | |
| | | Total respiration | g m$^{-2}$ day$^{-1}$ | |
| State variables | Snow Pack | Snow Depth | m | |
| | Additional variables | Water balance check | mm | |
| | Additional biotic variables | Carbon balance check | gC | Sum of the inputs subtracted by the outputs of C to the profile, compared with the difference in C storage in the system. |
| | | Nitrogen balance check | gN | Sum of the inputs subtracted by the outputs of nitrogen to the profile, compared with the difference in nitrogen storage in the system. |

## 3.7 Climate Change Simulations (2010 - 2100)

The effects of climate change on the C balance of the system were simulated using three climate scenarios from three different regional climate models (CLM, RCA and REGCM3), which differ mainly in the intensity of temperature increase and rainfall variation. CLM has a temperature increase of 4.2 °C in the period 2070 – 2100 in comparison with the period 1981 – 2000. RCA has an increase of 3.2 °C and REGCM3 an increase of 2.9 °C for the same period (METEOTEST, 2013). CLM shows a 13.7% decrease of rainfall in the period 2070 – 2100 in comparison with the period of 1981 – 2000. In RCA the decrease is 7.8%, whereas in REGCM3, the rainfall increases by 4.6%. CLM is the "driest" of the models, whereas REGCM3 has the highest amount of rainfall.

The model was run with these three different input data sets for the period 2010 – 2100. The year 2010 was selected as a starting point for the simulation because of the availability of measured data for the initial values. The mean annual air temperature of every simulation file was changed according to Table 3.

## 3.8 Statistical Analyses

The software STATISTICA was used for producing the correlation matrices and regression analysis of 22 selected model output variables. For the land use change files, the correlation matrices were calculated for every plot separately (grassland plots P3 and P6, forest plots P5 and P8), whereas the linear regression was calculated using average values of the land use (grassland or afforestation). For the climate scenario files, the correlation matrices were calculated using average values of the land use.

# 4 Results

## 4.1 Sensitivity Analysis

The sensitivity analysis revealed the input parameters that have a significant impact on the model output variables. On the other hand, it also showed which parameters do not have a large impact and can thus be set back to their default values. Table 7 shows all 85 parameters that were analyzed with the simulation period 2010 – 2011, including their sensitivities expressed as a sensitivity index according to Lenhart et al. (2002). Out of 20 meteorological parameters, 10 were shown to have an impact on the selected output data of the model (soil temperature, soil volumetric water content, evapotranspiration, the C stocks of the plants and soil, and the total respiration of plants and soil). The soil-related parameters were not much more sensitive: out of 42 parameters, 20 were shown to be sensitive. The vegetation related parameters were the most sensitive: almost all selected parameters were shown to have a large impact on the water balance of the model. The change in only 5 and 6 parameters was found to affect the simulated soil temperature and volumetric water content, respectively. The most important parameters for the soil temperature were found to be ClayUnfrozenC1 and ClayUnfrozenC3, which both showed medium to very high sensitivity in all validation depths (5cm, 25cm and 50cm). For soil volumetric water content (liquid non-frozen), the most important parameters were saturation (high – very high sensitivity in all depths), air entry (medium – high sensitivity in all depths), and pressure head bottom (medium sensitivity in all depths). For evapotranspiration (total evaporation and transpiration, including evaporation from snow) and water balance check, there were 7 and 25 sensitive parameters, respectively.

The C balance check (the sum of the inputs subtracted by the outputs of C to the profile, compared with the difference in C storage in the system) was found to be sensitive to the change of ten parameters. The most important parameters for the C balance were found to be Saturation (very high sensitivity), Air Entry, MeltCoefGlobRad, and TempCoefA (all high sensitivity). The C total plant (the total C content in the new and old plant biomass pools for all plants) was found to be sensitive to 8 parameters, of which saturation and TempCoefA had the highest impact. C tot soil org (C content in all soil organic pools in the whole soil profile) was not sensitive to any of the selected parameters. This might result from the fact that the simulation period was so short (2010 – 2011; two years) in relation to the rate at which the changes take place in the vast pool of SOC. Total respiration was found to not only be mostly sensitive to the parameters of soil organic processes and two plant parameters, but also to soil saturation. Due to the short simulation period (2010 – 2011), the model output variables might seem insensitive to some of the input parameters. This includes especially any parameters that could in the long term affect the total SOC stocks, which is likely to vary on a longer time scale than this simulation period.

Table 7. Results of the sensitivity analysis on P3 (grassland). Sensitivity of the parameters was calculated according to Lenhart et al. (2002) and was classified as very high (sensitivity index |I| ≥1), high (0.2 ≤ |I| ≤ 1), medium (0.05 ≤ |I| ≤ 0.2), or small to negligible (0 ≤ |I| ≤0.05). The sign of the index shows if the model reacts codirectionally to the input parameter change, i.e., if an increase of the parameter leads to an increase of the output variable and a decrease of the parameter to a decrease of the variable, or if the inverse is the case. The parameters that were codirectionally sensitive are indicated in orange; the inverse ones in blue. Small or negligible sensitivity is shown as blank cells.

| **Parameter** | **Soil temp. 5cm** | **Soil temp. 25cm** | **Soil temp. 50cm** | **Vol.w. cont. 5cm** | **Vol.w. cont. 25cm** | **Vol.w. cont. 50cm** | **Evapo-transpiration** | **Water balance check** | **C balance check** | **C total plant** | **C tot soil org** | **Total respiration** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Meteorological parameters** | | | | | | | | | | | | |
| CritDepthSnowCover | | | | | | | | | medium | | | |
| SnowReduceLAI Threshold | | | | | | | | | | | | |
| WaterRetention | | | | | | | | | | | | |
| ZeroTemp_ WaterLimit | | | | | | | | very high | | | | |
| MaxSoilCondens | | | | | | | | | | | | |
| MaxSurfDeficit | | | | | | | | | | | | |
| MaxSurfExcess | | | | | | | | | | | | |
| RaIncreaseWithLAI | | | | | | | | | | medium | | |
| RoughLBareSoilMom | | | | | | | medium | | | | | |
| WindLess ExchangeSoil | | | | | | | | very high | | | | |
| AlbLeafSnowCoef | | | | | | | | very high | | | | |
| AlbSnowMin | | | | | | | | | | | | |
| AlbedoDry | | | | | | | | | | | | |
| AlbedoWet | | | | | | | | | | | | |
| DensityCoefMass | | | | | | | | | | | | |
| DensityCoefWater | | | | | | | | very high | | | | |
| MeltCoefAirTemp | | | | | | | | very high | | | | |
| MeltCoefGlobRad | | | | | | | | | high | | | |
| MeltCoefSoilHeatF | | | | | | | | | | | | |
| Equil Adjust PSI | medium | | | | | | | very high | | | | |
| **Soil parameters** | | | | | | | | | | | | |
| MinimumCondValue | | | | | | | | | | | | |
| TempFacAtZero | | | | | | | | | | | | |
| TempFacLinIncrease | | | | | | | | | | | | |
| FreezepointF0 | | | | | | | | very high | | | | |
| FreezepointFWi | | | | | | | | | medium | | | |
| AScaleSorption | | | | | | | | very high | | medium | | |
| DVapTortuosity | | | | | | | | | | | | |
| SurfCoef | | | | | | | | | | | | |
| PressureHeadBottom | | high | | medium | medium | medium | medium | | | | | |
| AlphaHeatCoef | | | | | | | | very high | | | | |
| HighFlowDampC | | | | | | | | | | | | |
| LowFlowCondImped | | | | | | | | | | | | |
| MaxSwell | | | | | | | | very high | | | | |
| ShrinkRateFraction | | | | | | | | very high | | | | |
| InitialPressureHead | | | | | | | | | | | | |
| Saturation | | medium | medium | very high | very high | high | high | very high | very high | high | | high |
| Macro Pore | | | | | | | | | | | | |
| n Tortuosity | | | | | | | | very high | | | | |
| Air Entry | | | | high | high | medium | medium | very high | high | | | |
| Wilting Point | | | | | | | | | | | | |
| Residual Water | | | | | | | | | | | | |
| Matrix Conductivity | | | | medium | medium | | | | | | | |
| Total conductivity | | | | | | | | | | | | |
| CfrozenMaxDamp | | | | | | | | | | | | |
| CfrozenSurfCorr | | | | | | | | | | | | |
| ClayFrozenC1 | | | | | | | | | | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ClayFrozenC2 | | | | | | | | | | | | |
| ClayFrozenC3 | | | | | | | | | medium | | | |
| ClayFrozenC4 | | | | | | | | | | | | |
| ClayUnfrozenC1 | medium | very high | high | medium | | | medium | very high | | | | |
| ClayUnfrozenC2 | | | | | | | | | | | | |
| ClayUnfrozenC3 | medium | very high | medium | medium | | | medium | | | medium | | |
| OrganicC1 | | | | | | | | | | | | |
| OrganicC2 | | | | | | | | very high | | | | |
| OrganicFrozenC | | | | | | | | very high | | | | |
| SandFrozenC1 | | | | | | | | | | | | |
| SandFrozenC2 | | | | | | | | very high | | | | |
| SandFrozenC3 | | | | | | | | | | | | |
| SandFrozenC4 | | | | | | | | very high | | | | |
| SandUnfrozenC1 | | | | | | | | | | | | |
| SandUnfrozenC2 | | | | | | | | very high | | | | |
| SandUnfrozenC3 | | | | | | | | | | medium | | |
| **Vegetation parameters** | | | | | | | | | | | | |
| RootFracExpTail | | | | | | | | very high | medium | | | |
| SnowCapasityPerLAI | | | | | | | | high | | | | |
| WaterCapasityPerLAI | | | | | | | | high | | | | |
| AirMinContent | | | | | | | | very high | | | | |
| AirRedCoef | | | | | | | | very high | | | | |
| CritThresholdDry | | | | | | | medium | | medium | medium | | medium |
| DemandRelCoef | | | | | | | | | | | | |
| TempCoefA | | | | | | | medium | | high | high | | medium |
| **Soil organic processes** | | | | | | | | | | | | |
| CN ratio microbe | | | | | | | | | | | | medium |
| Eff Litter1 | | | | | | | | | medium | medium | | medium |
| Eff Humus | | | | | | | | | | | | medium |
| HumFracLitter1 | | | | | | | | | | | | |
| RateCoefHumus | | | | | | | | | | | | medium |
| RateCoefLitter 1 | | | | | | | | | | | | medium |
| Init H Frac Exp tail | | | | | | | | | | | | |
| Init L1 FracExpTail | | | | | | | | | | | | |
| **Soil Mineral N processes** | | | | | | | | | | | | |
| DenitPotentialRate | | | | | | | | | | | | |
| InitAmmoniumConc | | | | | | | | | | | | medium |
| InitNitrateConc | | | | | | | | | | | | |
| NitrateAmmRatio | | | | | | | | | | | | |
| DenitThetaPowerC2 | | | | | | | | | | | | |
| DenitThetaRange | | | | | | | | | | | | |
| NUptMaxAvailFrac | | | | | | | | | | | | |

## 4.2 Validation

In general, CoupModel could simulate the soil volumetric water contents in the years 2010 and 2011 better than the soil temperatures (Figure 9, Figure 10, Figure 11, and Figure 12, and Table 8). The simulations could not reproduce the temperature differences between grassland and forest. In the grassland sites, the simulated soil temperatures remained up to 5 degrees colder than the measured values in all depths. However, this difference decreased to almost negligible during the winter months (November – February 2010) in the topsoil layers. High soil temperatures were generally underestimated in grassland sites, especially in the deeper soil Figure 10 (upper row). Contrary to the grassland sites, simulated soil temperature values exceeded the measured values by several degrees in the forest sites. Figure 10 (lower row) shows how the lower temperatures were generally simulated well, whereas higher temperatures were rather overestimated.

The temporal fluctuations in the soil volumetric water content were in general better represented in the topsoil layers than deep soil in both land uses, but not all large fluctuations in the volumetric water content could be reproduced by the simulations (Figure 11 and Figure 12). The simulated forest sites were generally drier than the grassland sites, which is in line with the measured data. As seen in Table 8, the RMSE of soil volumetric water content was relatively high in both land uses and all depths. In grassland, the low soil volumetric water contents in the upper soil were generally overestimated by the model (Figure 12, upper row), but this trend faded in the deeper soil. In forest sites, no clear trend of over- or underestimation was found between the simulated and measured values because the data was so scattered.

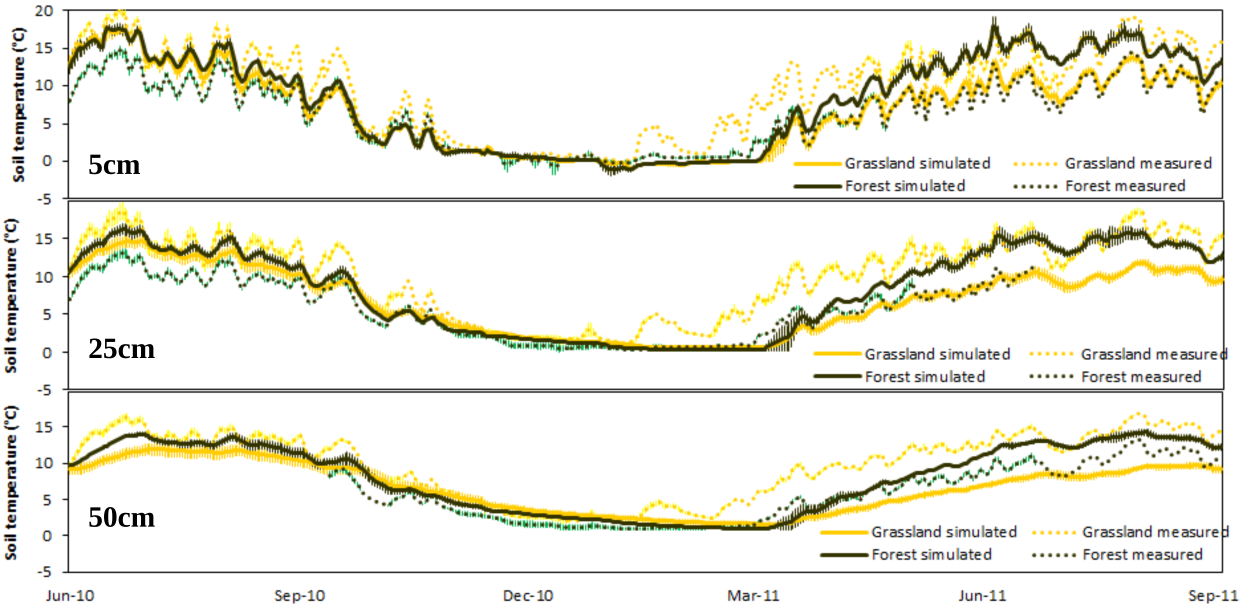

Figure 9. Average measured and simulated soil temperatures (±SE) during the validation period (July 2010 – September 2011) in grassland and 40-year-old forest sites in 5cm, 25cm, and 50cm depth.

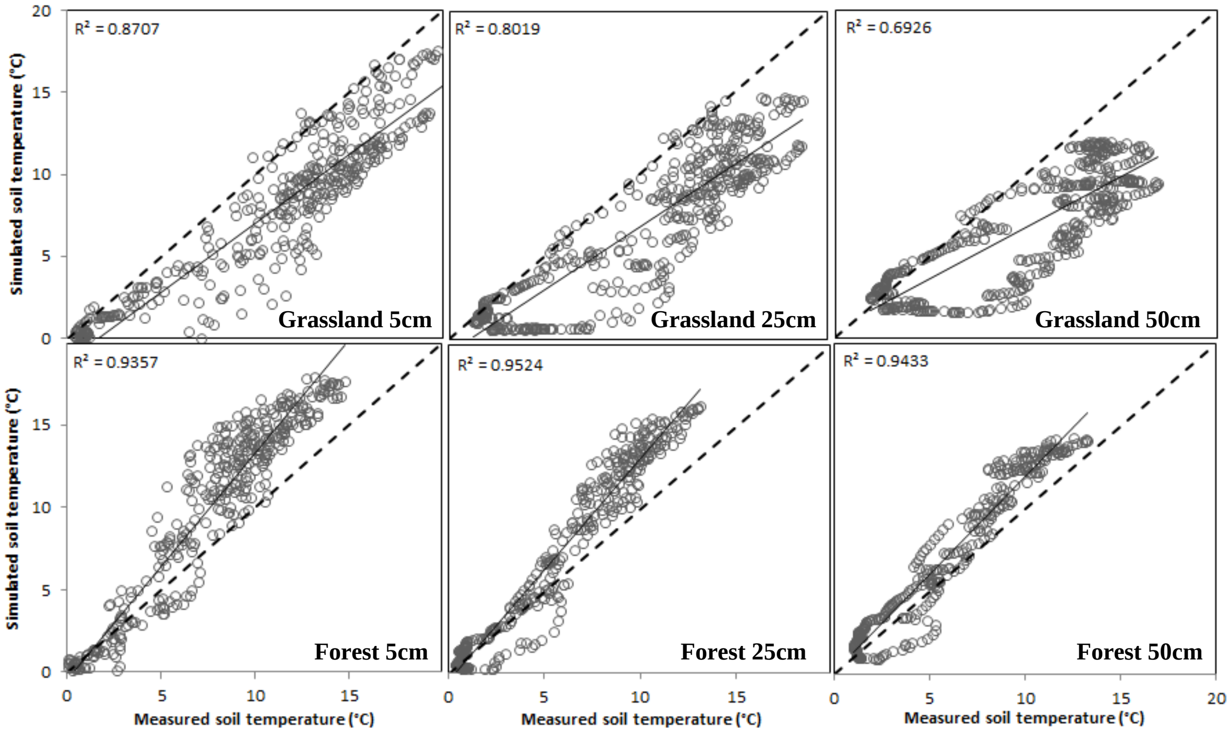

Figure 10. Linear regression between the average measured and simulated soil temperature during the validation period (July 2010 – September 2011) in grassland sites and 40-year-old forest sites at 5cm, 25cm, and 50cm depth. The dotted line shows the 1:1 line.

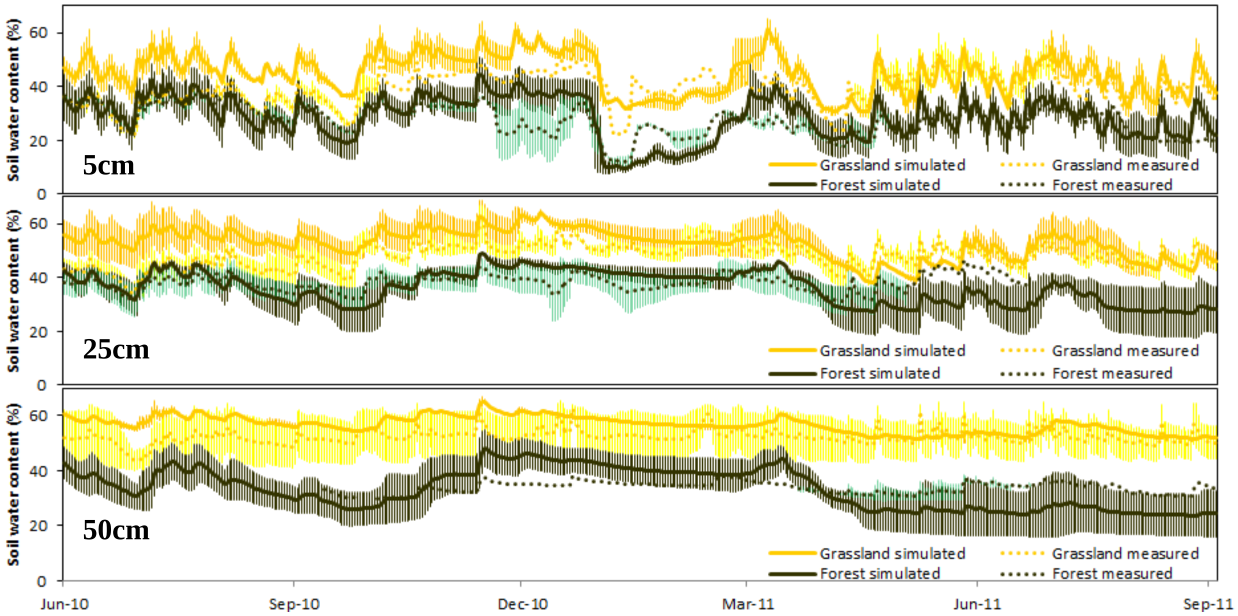

Figure 11. Average measured and simulated soil volumetric water contents (±SE) during the validation period (July 2010 – September 2011) in grassland and 40-year-old forest sites at 5cm, 25cm, and 50cm depth.

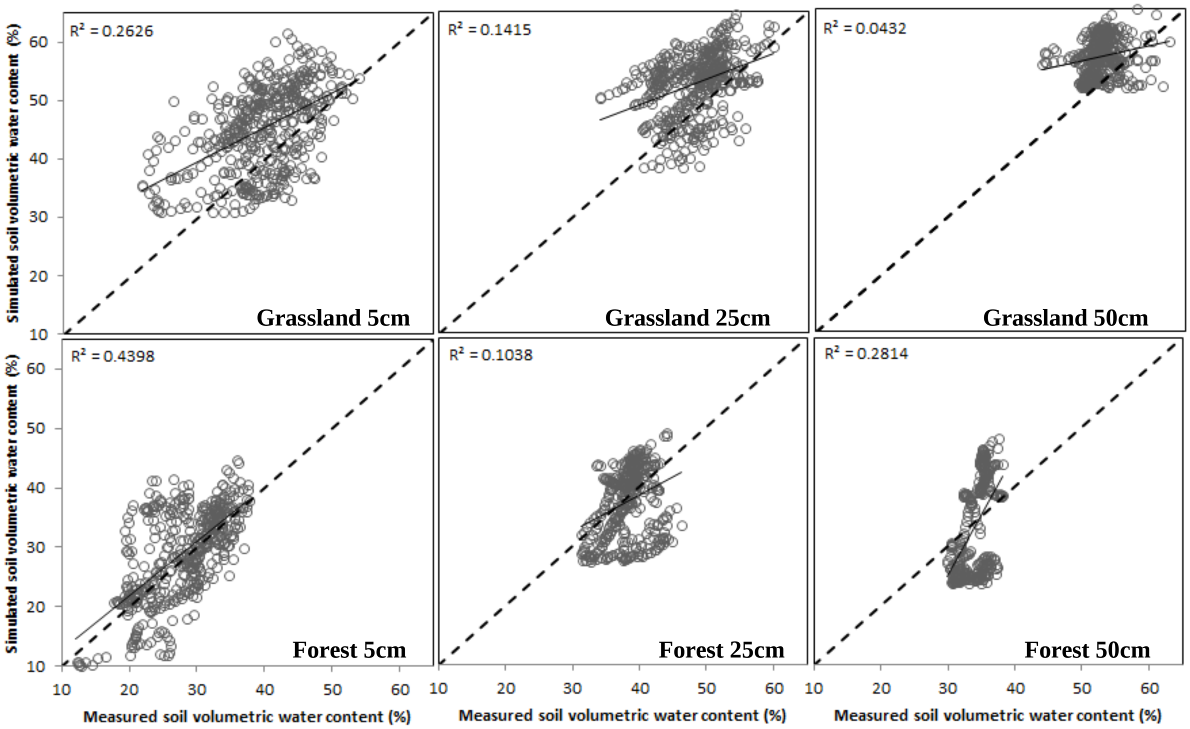

Figure 12. Linear regression between the average measured and simulated soil volumetric water contents during the validation period (July 2010 – September 2011) in grassland sites and 40-year-old forest sites at 5cm, 25cm, and 50cm depth. The dotted line shows the 1:1 line.

Table 8. Statistical measures showing the differences between simulated and measured soil temperatures and soil volumetric water contents at 5cm, 25cm, and 50cm depth in grassland (P3 and P6) and forest sites (P5 and P8). The tables show the coefficient of determination ($r^2$), intercept and slope for linear regression equation, root mean square error (RMSE), normalized root mean square error (NRMSE; RMSE normalized to the mean of the observed data), mean of simulated (Mean Sim.) and mean of measured (Mean Meas.) data.

| Depth | Soil temperature | | | | | | | | Soil volumetric water content | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **n** | **r2** | **Intercept** | **Slope** | **RMSE, °C** | **NRMSE** | **Mean Sim.°C** | **Mean Meas. °C** | **n** | **r2** | **Intercept** | **Slope** | **RMSE, %** | **NRMSE** | **Mean Sim. %** | **Mean Meas. %** |
| Grassland (P3) | | | | | | | | | | | | | | | | |
| 5cm | 462 | 0.85 | 3.10 | 1.08 | 4.31 | 0.43 | 6.38 | 9.98 | 462 | 0.32 | 18.80 | 0.49 | 6.50 | 0.17 | 41.84 | 39.16 |
| 25cm | 462 | 0.80 | 3.20 | 1.16 | 4.90 | 0.47 | 6.35 | 10.53 | 462 | 0.18 | 21.12 | 0.50 | 6.07 | 0.13 | 48.37 | 45.30 |
| 50cm | 462 | 0.71 | 2.51 | 1.23 | 4.68 | 0.47 | 6.09 | 9.97 | 462 | 0.26 | 29.48 | 0.53 | 3.65 | 0.06 | 57.37 | 59.82 |
| Grassland (P6) | | | | | | | | | | | | | | | | |
| 5cm | 206 | 0.69 | 4.36 | 0.76 | 2.64 | 0.20 | 11.20 | 12.93 | 206 | 0.01 | 32.09 | 0.15 | 13.87 | 0.35 | 47.98 | 39.25 |
| 25cm | 462 | 0.79 | 2.62 | 0.96 | 3.28 | 0.34 | 7.44 | 9.76 | 462 | 0.07 | 41.27 | 0.17 | 9.31 | 0.18 | 57.05 | 50.88 |
| 50cm | 462 | 0.66 | 2.31 | 1.02 | 3.62 | 0.37 | 7.22 | 9.70 | 462 | 0.01 | 49.64 | -0.08 | 12.40 | 0.28 | 56.25 | 44.89 |
| Forest (P5) | | | | | | | | | | | | | | | | |
| 5cm | 462 | 0.93 | 0.95 | 0.62 | 3.57 | 0.57 | 8.54 | 6.29 | 462 | 0.57 | 14.69 | 0.58 | 6.89 | 0.24 | 23.42 | 28.21 |
| 25cm | 386 | 0.94 | 1.07 | 0.62 | 2.97 | 0.53 | 7.39 | 5.64 | 386 | 0.43 | 34.70 | 0.22 | 11.25 | 0.27 | 32.91 | 41.93 |
| 50cm | 283 | 0.86 | 0.80 | 0.68 | 1.80 | 0.41 | 5.24 | 4.35 | 94 | 0.38 | 38.13 | -0.19 | 15.46 | 0.45 | 20.24 | 34.19 |
| Forest (P8) | | | | | | | | | | | | | | | | |
| 5cm | 327 | 0.94 | 0.39 | 0.81 | 1.73 | 0.33 | 6.02 | 5.25 | 327 | 0.17 | 17.07 | 0.30 | 11.94 | 0.44 | 34.47 | 27.26 |
| 25cm | 334 | 0.96 | 0.06 | 0.83 | 1.56 | 0.30 | 6.26 | 5.26 | 334 | 0.23 | 12.56 | 0.49 | 9.70 | 0.29 | 42.40 | 33.29 |
| 50cm | 359 | 0.95 | -0.10 | 0.86 | 1.46 | 0.25 | 6.81 | 5.79 | 359 | 0.40 | 24.87 | 0.22 | 8.24 | 0.25 | 39.66 | 33.61 |

## 4.3 Carbon Dynamics after Land Use Change: Simulations 1960 – 2010

### 4.3.1 Soil Organic Carbon Stocks

SOC stocks increased in both grasslands and afforestation within 40 years after LUC (1970 – 2010), but the accumulation of the organic layer resulted in a remarkable increase in the total simulated SOC stocks in afforestation (Figure 13). Even though the SOC stocks were of similar magnitude in the grassland and the forest at the start of the LUC (134.9 ± 0.1 tC ha$^{-1}$), the grassland and forest total SOC stocks increased by 3.3% and 26%, respectively, within the whole simulation period (Figure 14). Whereas the grassland SOC was steadily increasing at the rate of 0.2 tC ha $^{-1}$ year $^{-1}$ within the first 5 – 20 years, the forest mineral SOC slightly declined at the same time, with the strongest decline after 13 years being -1.5% (Figure 14). 23 years after the LUC, the forest mineral SOC stocks again reached the same level as the grassland SOC stocks.

After 40 years, the difference between the measured and simulated total SOC stocks of the 40-year-old forest was remarkable: the simulated total SOC stocks were 165.9 ± 2.3 tC ha$^{-1}$, whereas the measured stocks were only 101.5 ± 4.6 tC ha$^{-1}$ (Figure 13). This resulted from the strong decline in the measured mineral SOC stocks, which was not reproduced by the simulations. Within 40 years, the simulated total SOC stocks increased 29.5 ± 0.8 tC ha$^{-1}$, of which 18.4 ± 0.9 tC ha$^{-1}$ was stored in the organic layer. After 40 years, the simulated accumulation rate of forest floor was 0.46 tC ha$^{-1}$ year $^{-1}$, which is too high when compared with the rate of 0.19 tC ha$^{-1}$ year $^{-1}$ found by Hiltbrunner et al. (2013). As a conclusion, the model overestimated the SOC stocks in the forest within the simulation period (Figure 13).

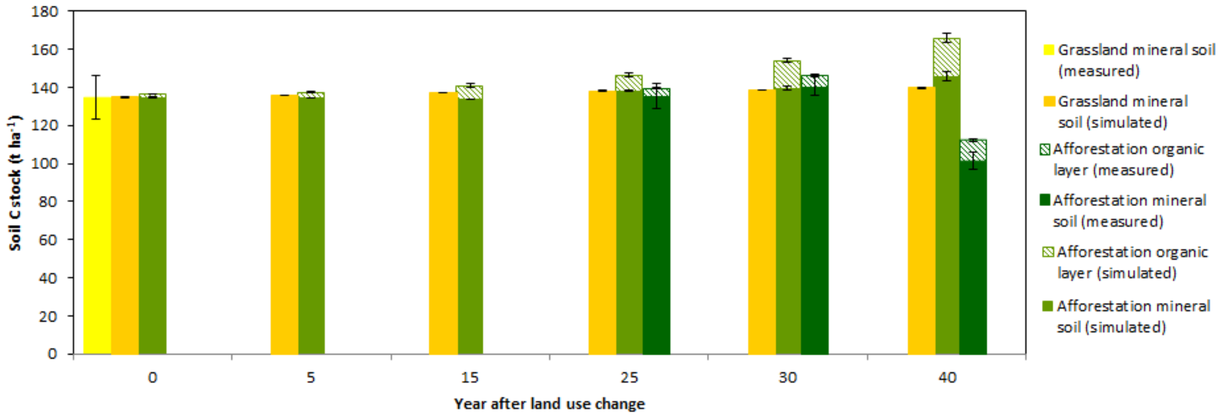

Figure 13. The simulated annual mean (±SE) soil organic C stocks after 0, 5, 15, 25, 30 and 40 years after LUC from grassland to forest, compared with the measured values from 25, 30, and 40-year-old forest sites. Grassland refers to a site where land use was grassland for the whole simulation period. Notice that the x-axis is not linear but refers to the age of the forest site in the space-for-time study of Hiltbrunner et al. (2013).

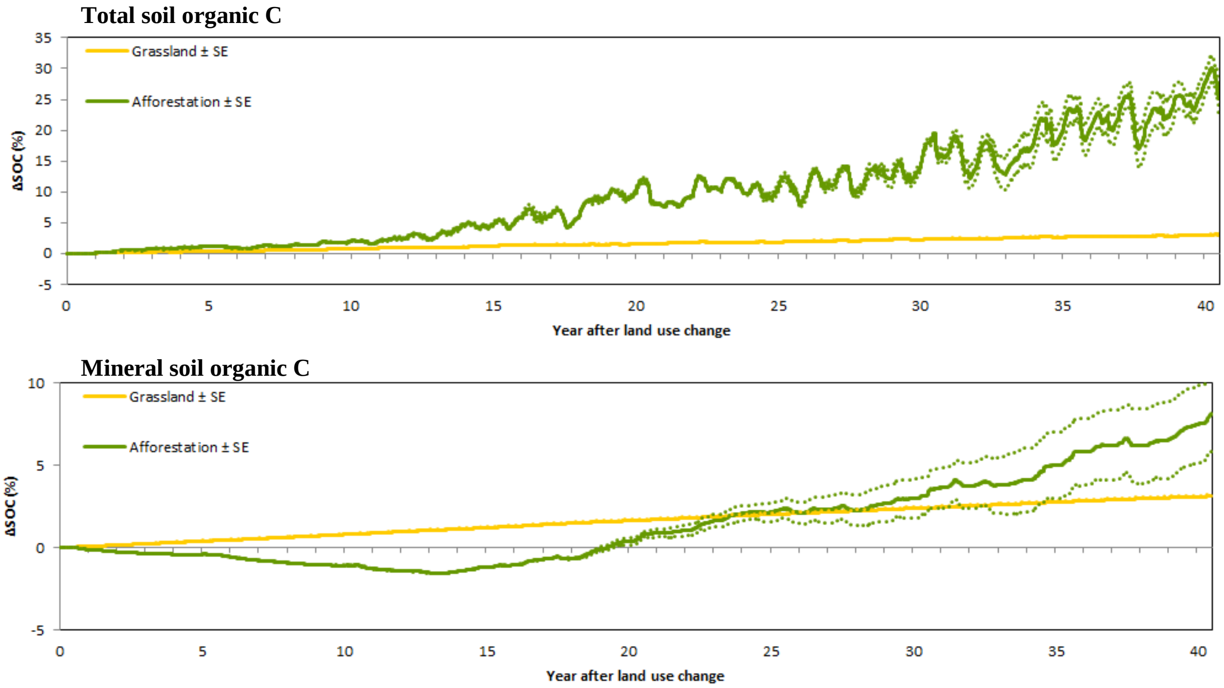

Figure 14. Relative changes in the total (upper figure) and mineral (lower figure) soil organic C stocks as calculated by a simplified version of the carbon response function developed by Poeplau et al. (2011).

### 4.3.2 Soil Respiration and Litter Quality

Soil respiration considerably increased due to afforestation (Table 9). Within 40 years, the annual soil respiration of grassland ranged from 119.1 ± 8.1 gC $m^{-2}$ $year^{-1}$ (min, year 2000) to 219.6 ± 7.1 gC $m^{-2}year^{-1}$ (max, year 1961), whereas it increased from 167.6 ± 2.7 gC $m^{-2}$ $year^{-1}$ (min, year 1971, one year after LUC) to 2324.0 ± 279.6 gC $m^{-2}$ $year^{-1}$ (max, year 2007). Thus, the 30% lower soil respiration in the old forest sites found by Hiltbrunner et al. (2013) was not reproduced by the simulations. Soil respiration (with roots) was found to correlate with heterotrophic respiration in the forest ($r^2 = 0.82$, Table 10 and Appendix 2), but not in grassland. Unexpectedly, the SOM quality decreased, even though the soil respiration considerably increased due to afforestation. The simulated C/N ratio of the soil increased with forest age and decreased with soil depth (Figure 15). In grasslands, no change in simulated C/N ratios was found with soil depth, even though measured C/N ratios strongly decreased with soil depth. On the contrary, the trend of decreasing C/N ratio with soil depth was noticeable in forest soils, yet much stronger in simulated than measured data. The measured C/N ratios ranged from approximately 9.5 to 14, whereas the simulated range was larger: 9.5 – 16.9. Consequently, the simulated forest soils had an even lower SOM quality than the measured data would suggest.

Table 9. Annual sum (±SE) of soil respiration without roots in grassland and afforestation at the start of LUC and 10, 20, 30, and 40 years thereafter.

|  | **Grassland** | **Afforestation** |
|---|---|---|
| **Year after LUC** | **gC m$^{-2}$ year$^{-1}$** | **gC m$^{-2}$ year$^{-1}$** |
| 0 | 129 ± 4 | 154 ± 8 |
| 10 | 132 ± 2 | 724 ± 43 |
| 20 | 131 ± 0 | 1 238 ± 88 |
| 30 | 119 ± 8 | 1 334 ± 112 |
| 40 | 127 ± 2 | 2 206 ± 221 |

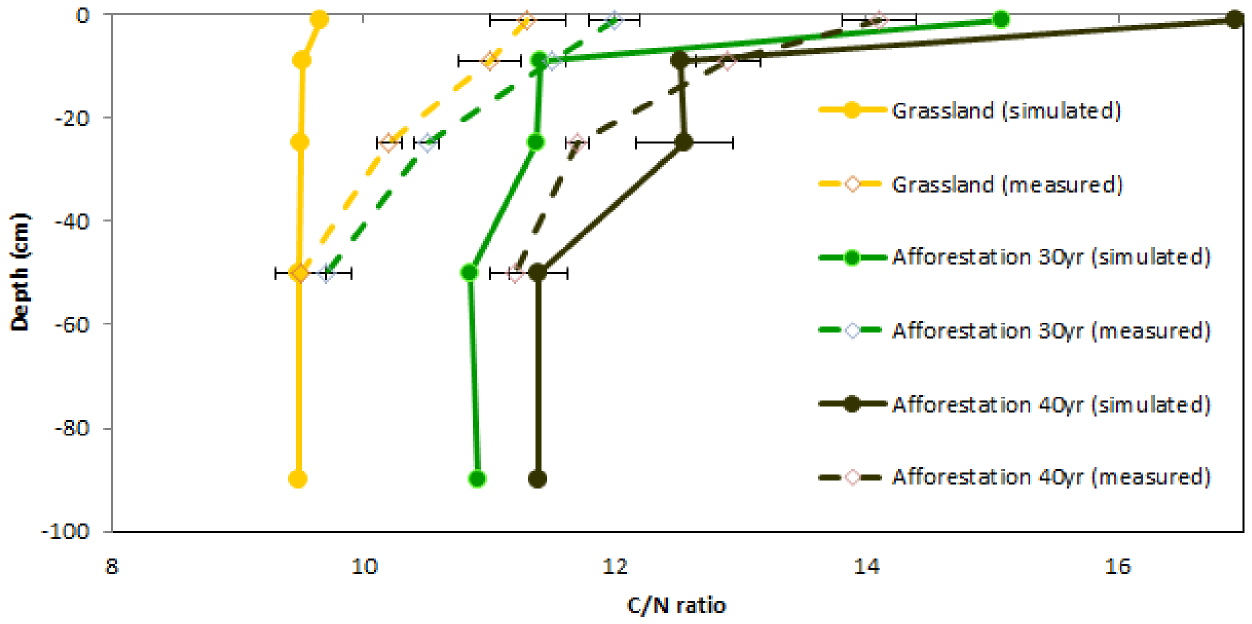

Figure 15. Depth profile of measured (±SE) and simulated mean (±SE) soil C/N ratios in grasslands and different aged forest stands.

### 4.3.3 Vegetation Carbon Stocks

The grassland vegetation C stocks stayed approximately the same within 40 years after LUC (1970 – 2010), whereas gradual afforestation resulted in a considerable increase in The C stocks (Figure 16). The measurements in Jaunpass (Hiltbrunner et al., 2013) suggested that between 30 and 40 years after LUC, the forest aboveground biomass almost doubled. The simulations could not reproduce this growth. Instead, trees started to allocate more C to the roots 25 years after LUC. In the 30 and 40 year old forest sites, the simulated root C stocks were almost twice as high as the measured. The simulated aboveground C stocks were similar to measured stocks after 30 years, but remained 43% lower than the measured values in the 40-year-old forest. The root C stocks and mineral SOC stocks were found to strongly correlate in the afforested sites ($r^2$ = 0.95, Table 10; Appendix 2), whereas no correlation was found in grasslands. Similarly, the plant aboveground C stocks were correlated with soil litter C stocks in forests ($r^2$ = 0.74), but not in grasslands.

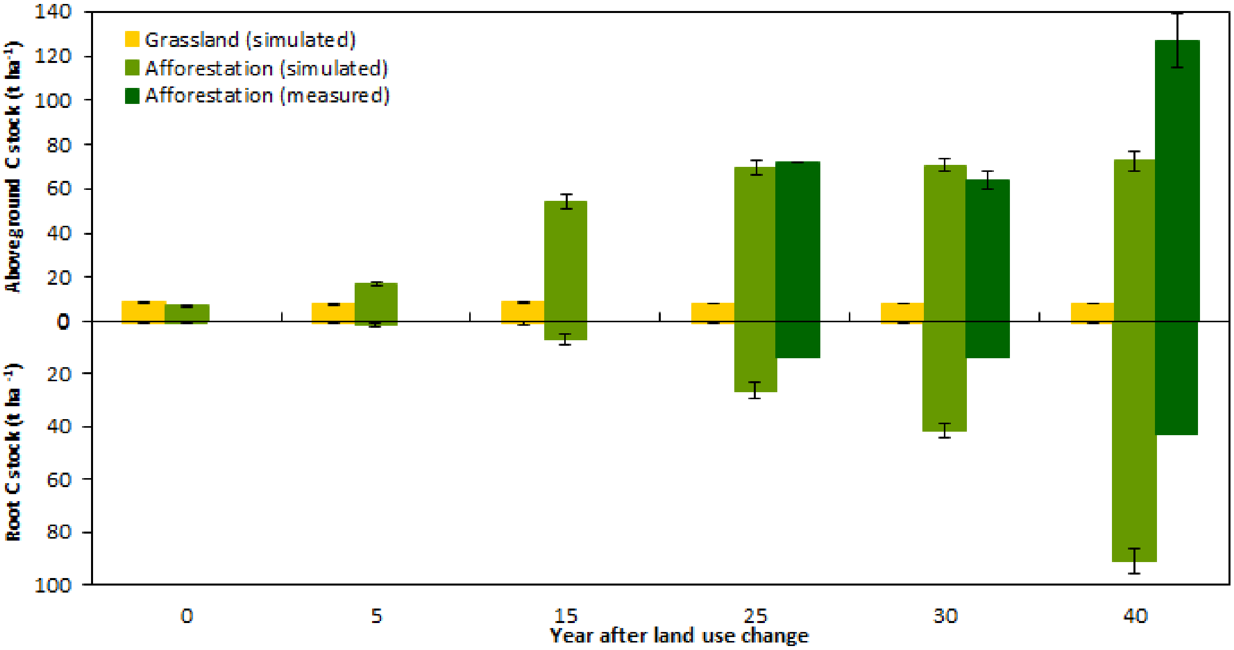

Figure 16. The simulated annual mean (±SE) aboveground and root C stocks after 5, 15, 25, 30 and 40 years after land use change from grassland to forest, compared with the measured values from 25, 30, and 40-year-old forest sites. Grassland refers to a site where land use was grassland for the whole simulation period. Notice that the x-axis is not linear but refers to the age of the forest site in the space-for-time study of Hiltbrunner et al. (2013). Simulated aboveground values show the total aboveground C stocks (grasslands) and the tree C stocks (afforestation), whereas the simulated root C stocks refer to the total root C stocks (grassland) and the tree root C stocks (afforestation). The measured C stocks were calculated using allometric functions depending on tree height and stem diameter at breast height (Hiltbrunner et al. 2013). No measurements of the grassland vegetation C stocks were available.

Table 10. Simplification of the correlation matrix of 22 simulated variables. Grassland is indicated in orange, afforestation in dark green. Cells with two * indicate that these two variables were correlated in both land uses. The original correlation matrices for all plots (P3, P5, P6, and P8) can be found in the Appendix 2.

**Summary of correlation matrices for grassland and afforestation**

| | Variable | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | C total plant | | | | | | | | | | | | | | | | | | | | | |
| 2 | C Total Plant AboveG | * * | | | | | | | | | | | | | | | | | | | | |
| 3 | C Total Roots | * | | | | | | | | | | | | | | | | | | | | |
| 4 | CTotSoil Humus | * | | * | | | | | | | | | | | | | | | | | | |
| 5 | CTotSoil Litter1 | * | * | * | * | | | | | | | | | | | | | | | | | |
| 6 | CTotSoilOrg | * | * | * | * * | * | | | | | | | | | | | | | | | | |
| 7 | Evapo-transpiration | | | | | | | | | | | | | | | | | | | | | |
| 8 | Carbon Balance Rate | | | | | | | | | | | | | | | | | | | | | |
| 9 | NitrogenBalance Rate | | | | | | | | | | | | | | | | | | | | | |
| 10 | Soil resp no roots | | | | | | | | | | | | | | | | | | | | | |
| 11 | Soil respiration | | | | | | | | | | * | | | | | | | | | | | |
| 12 | Total respiration | | | | | | | | | | * | * * | | | | | | | | | | |
| 13 | Total Photosynt | | | | | | | | * * | | | * * | * | | | | | | | | | |
| 14 | Snow depth | | | | | | | | | | | | | | | | | | | | | |
| 15 | Precipitation | | | | | | | | | | | | | | | | | | | | | |
| 16 | Air temp | | | | | | | * | | | | | | | | | | | | | | |
| 17 | Soil temp 5cm | | | | | | | * | | | | | * | * | | | * | | | | | |
| 18 | Soil temp 25cm | | | | | | | | | | | | | | | | | * * | | | | |
| 19 | Soil temp 50cm | | | | | | | | | | | | | | | | | | * * | | | |
| 20 | Soil vol.wat cont 5cm | | | | | | | | | | | | | | | | | | | | | |
| 21 | Soil vol.wat cont 25cm | | | | | | | | | | | | | | | | | | | | | |
| 22 | Soil vol.wat cont 50cm | | | | | | | | | | | | | | | | | | | | | * * |

N=18992. * = statistically significant (p<0.05) correlation and a strong relationship between the variables (correlation coefficient >0.8). All statistically significant and strong correlations were positive.

### 4.3.4 Carbon Balance of the System

LUC had a positive effect on the C stocks of the vegetation and soil (Table 11). At the start of the LUC, there were no remarkable differences between the grassland and afforestation C. Ten years after LUC from grassland to forest, the C stocks of the afforestation had increased by 26%, whereas the grassland C stocks increased only 3% within the same time period. Thus, the afforestation resulted in a net increase of 23% if the simultaneous change in the grassland C stocks was taken into account as a reference. Within 10 years of simulation without LUC (1960 – 1970), the C stocks of the 40-year-old forest (no LUC) had increased by 118%. After 40 years of simulation, the grassland C stocks had changed 4% compared with the initial stocks, whereas afforestation resulted in an increase of 133%. The C stocks of the mature forest increased by 342% in 50 years (from 40-year-old forest to 90-year-old forest). This not only indicates that clearly more C was sequestered in the simulated soil-vegetation system due to LUC from grassland to forest, but also that mature forests could sequester remarkably more C within the same time period than young forest stands (see Figure 19).

Table 11. Absolute and relative changes in the C stocks of the simulated system (soil and vegetation) at the start of LUC and 10, 20, 30, and 40 years thereafter. Grassland (no LUC) and forest (no LUC) were used as a reference without LUC. For the simulation of the reference forest, initial parameter values of a 40-year-old forest were used. ΔC % refers to mean percentage change when compared with the stocks of the year 2010. The forest sites (no LUC) were 40-years-old at the start of the simulations.

| | | **Grassland (no LUC)** | | **Afforestation (LUC)** | | **Forest (no LUC)** | |
|---|---|---|---|---|---|---|---|
| **Year of simulation** | **Years after LUC** | **tC ha$^{-1}$** | **ΔC %** | **tC ha$^{-1}$** | **ΔC %** | **tC ha$^{-1}$** | **ΔC %** |
| 1960 | 0 | 144.0 ± 0.3 | 0 | 143.8 ± 0.3 | 0 | 168.4 ± 0.7 | 0 |
| 1970 | 0 | 146.5 ± 0.0 | 1 | 145.8 ± 0.1 | 1 | 366.4 ± 0.8 | 118 |
| 1980 | 10 | 147.6 ± 0.0 | 3 | 181.8 ± 0.3 | 26 | 522.4 ± 0.7 | 210 |
| 1990 | 20 | 148.9 ± 0.1 | 3 | 218.3 ± 0.2 | 52 | 621.7 ± 0.4 | 269 |
| 2000 | 30 | 149.5 ± 0.0 | 4 | 272.0 ± 0.2 | 89 | 711.9 ± 0.5 | 323 |
| 2010 | 40 | 150.2 ± 0.0 | 4 | 335.4 ± 0.1 | 133 | 744.1 ± 0.4 | 342 |

## 4.4 Carbon Dynamics in Climate Change Scenarios: Simulations 2010 – 2100

### 4.4.1 Soil Organic Carbon Stocks

In this section, the results of all scenarios are reported only until the year 2090 or 2095, because the input data for REGCM3 scenario ended earlier than in other scenarios. Changes in air temperature and precipitation resulted in an increase of 6 – 7% in SOC in grasslands and a reduction of 35 – 47% in forests within the simulation period 2010 – 2090 (Figure 17). The simulated grassland SOC stocks corresponded to the measured values quite well within the first year of the simulations (year 2010), whereas the simulated forest C stocks were somewhat larger than the measured stocks. In the first year, no clear differences were found between simulations under the current climate and the three scenarios in either land uses.

After 80 years of simulation (in the year 2090), most C in grassland was stored in CLM ("hot and dry") and RCA ("middle") scenarios (145.1 ± 0.0 tC ha$^{-1}$ and 145.7 ± 0.0 tC ha$^{-1}$, respectively) and least in REGCM3 ("wet and cold", 143.6 ± 0.0 tC ha$^{-1}$). Thus, the differences between the scenarios were not very large. In the forest, the decrease in the mineral SOC stocks was the largest in CLM scenario (-53.4 ± 0.3 tC ha$^{-1}$ from 40-year-old to 120-year-old forest) and lowest in RCA (-41.2 ± 0.3 tC ha$^{-1}$). Within the same time period, the strongest decrease in the organic layer was found in the REGCM3 scenario (-4.1 ± 0.6 tC ha$^{-1}$; a reduction of 75%), whereas considerably less organic material was lost in other scenarios (CLM: 33%, RCA: 17%). These decreases resulted in large differences between the simulated and measured C stocks by the year 2090: The simulated total C stocks were approximately 40% (CLM), 49% (RCA), and 43% (REGCM3) of the measured C stocks of the measured C stocks in the 120-year-old forest. As a conclusion, the simulated SOC stocks in the 120-year-old forest in all scenarios were considerably lower than the measured stocks.

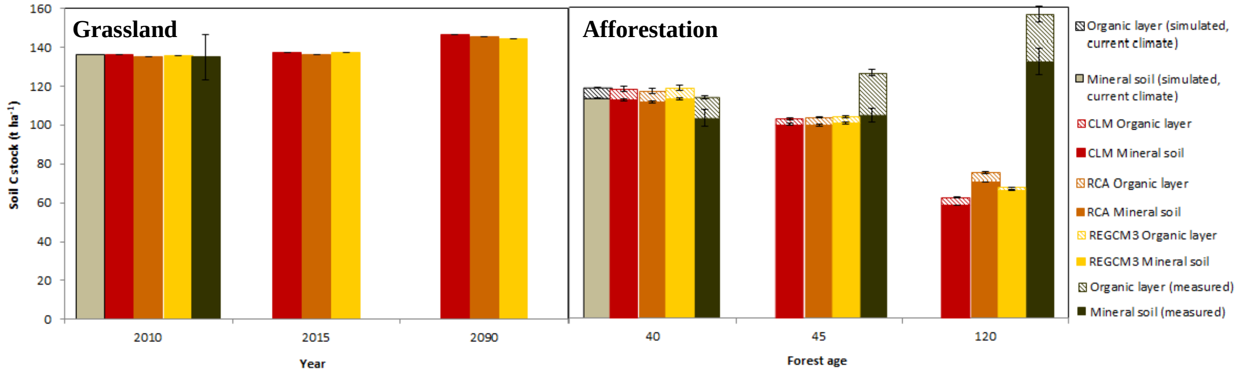

Figure 17. The simulated annual mean (±SE) soil organic C stocks 40, 45, and 120 years after LUC (=simulation years 2010, 2015 and 2090), compared with the measured values from the forest sites. Grassland refers to a site where land use was grassland for the whole simulation period. Notice that the x-axis is not linear but refers to the simulation year (left figure) or age of the forest site in the space-for-time study of Hiltbrunner et al. (2013) (right figure).

### 4.4.2 Soil Respiration

In grasslands, the mean annual heterotrophic respiration rate slightly increased from 2010 to 2090 in CLM and RCA scenarios and decreased in REGCM3 (Table 12). In the first year of the simulation (2010), the highest heterotrophic respiration rate was found in REGCM3 scenario (140 ± 2 gC m$^{-2}$ year$^{-1}$) and lowest in CLM and RCA (128 ± 2 gC m$^{-2}$ year$^{-1}$and 127 ± 2 gC m$^{-2}$ year$^{-1}$). By the year 2095, soil respiration rate increased to 161 ± 10 gC m$^{-2}$ year$^{-1}$ and 174 ± 1 gC m$^{-2}$ year$^{-1}$ in CLM and RCA scenarios, respectively, whereas it decreased to 137 ± 1 gC m$^{-2}$ year$^{-1}$ in REGCM3 scenario. In grassland, no high correlations (correlation coefficient >0.8) were found between variables representing air temperature, precipitation, soil temperature, soil volumetric water content and the output variables representing The C stocks or fluxes within the plant-soil system (see correlation matrices in Appendix 3).

In the forest, the mean annual heterotrophic respiration rate decreased within the same time period. Just as in grassland, the highest rate within the first year of simulation was found in REGCM3 scenario (1817 ± 2 gC m$^{-2}$ year$^{-1}$), and lowest in CLM and RCA (1747 ± 22 gC m$^{-2}$ year$^{-1}$ and 1721 ± 32 gC m$^{-2}$ year$^{-1}$, respectively). By the year 2095, the highest rate was found in RCA scenario (1218 ± 35 gC m$^{-2}$ year$^{-1}$), whereas rates in CLM and REGCM3 scenarios were somewhat smaller (960 ± 64 gC m$^{-2}$ year$^{-1}$and 981 ± 57 gC m$^{-2}$ year$^{-1}$, respectively). In the forest, a high positive correlation ($r^2$ >0.8, Appendix 3) was found between soil temperature and soil respiration (with roots) in all scenarios (see correlation matrices in Appendix 3), especially in the upper soil. Thus, as the soil temperatures increased, in general soil respiration rates also increased. The highest increase in the mean annual soil temperatures at 5cm depth was found in the RCA scenario, which also had the highest heterotrophic respiration rate by the year 2095. No other correlations between variables representing air temperature, precipitation, soil volumetric water content and the output variables of the C stocks or fluxes within the plant-soil system were found.

Table 12. Annual sum (±SE) of soil respiration without roots in grassland and forest in three different climate change scenarios (CLM, RCA, REGCM3) in the years 2010, 2030, 2050, and 2095.

| | **Grassland** | | | **Forest** | | |
|---|---|---|---|---|---|---|
| | **CLM** | **RCA** | **REGCM3** | **CLM** | **RCA** | **REGCM3** |
| **Year** | **gC $m^{-2}$ $year^{-1}$** | **gC $m^{-2}$ $year^{-1}$** | **gC $m^{-2}$ $year^{-1}$** | **gC $m^{-2}$ $year^{-1}$** | **gC $m^{-2}$ $year^{-1}$** | **gC $m^{-2}$ $year^{-1}$** |
| 2010 | 128 ± 2 | 127 ± 2 | 140 ± 2 | 1747 ± 22 | 1721 ± 32 | 1817 ± 2 |
| 2030 | 127 ±0 | 122 ± 6 | 115 ± 1 | 1111 ± 79 | 1349 ± 84 | 975 ± 58 |
| 2050 | 139 ± 4 | 146 ± 0 | 121 ± 2 | 1178 ± 82 | 1235 ± 41 | 1199 ± 0 |
| 2095 | 161 ± 10 | 174 ± 1 | 137 ± 1 | 960 ± 64 | 1218 ± 35 | 981 ± 57 |

### 4.4.3 Vegetation Carbon Stocks

In grassland, no clear differences in the vegetation C stocks were found between the three climate scenarios (Figure 18). However, there was considerably less aboveground C and more root C in all scenarios than in simulations with current climate (simulations of grasslands 1960 – 2010). In the long term, the simulated plants tended to allocate more C in the aboveground biomass than roots. In the afforested sites, the vegetation C stocks varied considerably between the three different climate scenarios (CLM, RCA, REGCM3) in the long term. According to the “dry and hot” CLM scenario, the aboveground vegetation C stocks were considerably smaller (-15%) than measured in the 120-year-old forest, but this was offset by an increase of the same magnitude in the root C stocks. In RCA which is the “middle” scenario, the aboveground vegetation C stocks were only 5% lower than measured, whereas the root C stocks were larger than in any other scenario: 26% more than measured. The “wet and cold” REGCM3 scenario showed 12% less aboveground C stocks and 21% more root C stocks than measured. Thus, the effect of climate change on the vegetation C stocks was the strongest in the RCA scenario. Compared with the measured forest data, the plants had more root C and less aboveground C in all scenarios by the year 2090.

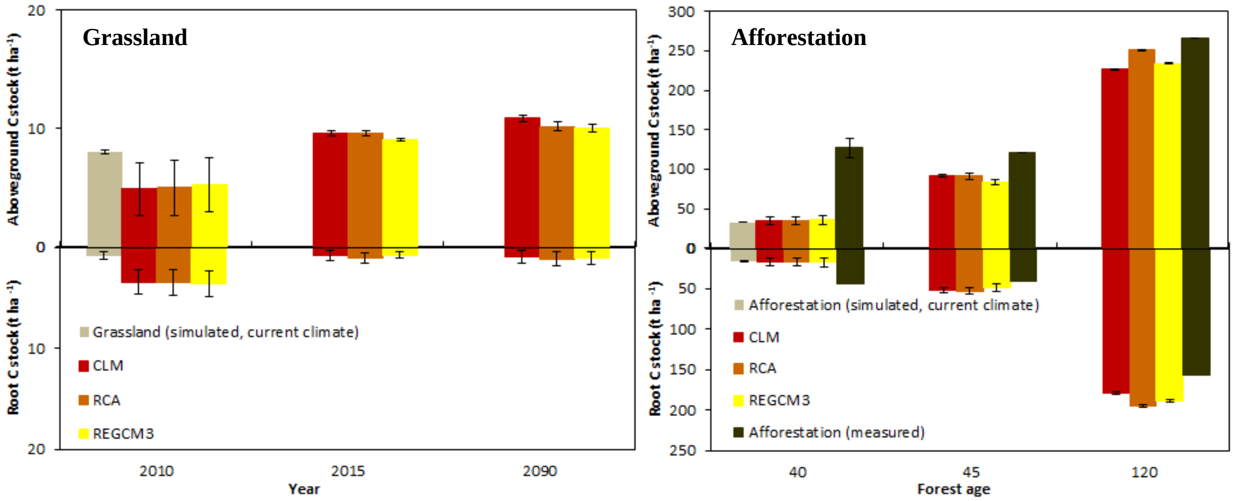

Figure 18. Simulated annual mean (±SE) aboveground and root C stocks after 40, 45, and 120 years after LUC (=simulation years 2010, 2015 and 2090), compared with the measured values from the forest sites. Grassland refers to a site where land use was grassland for the whole simulation period. Notice that the x-axis is not linear but refers to the simulation year (left figure) or age of the forest site in the space-for-time study of Hiltbrunner et al. (2013) (right figure). The simulated aboveground values show the total aboveground C stocks (grasslands) and the tree C stocks (afforestation), whereas the simulated root C stocks refer to the total root C stocks (grassland) and the tree root C stocks (afforestation). The measured C stocks were calculated using allometric functions depending on tree height and stem diameter at breast height (Hiltbrunner et al., 2013). No measurements of the grassland vegetation C stocks were available.

### 4.4.4 Carbon Balance of the System

In grassland, the C stocks (soil and vegetation) increased by 3% in CLM and RCA scenarios within the first 20 years of simulation (Table 13). The increase in C stocks was similar under the current climate and slightly smaller in REGCM3 scenario (2%). After 40 years of simulation (in the year 2050), the C stocks in grassland were still only slightly affected by climate change: there was an increase of 5%, 5%, and 3% in CLM, RCA, and REGCM3 scenarios, respectively, compared with an increase of 4% without climate change (Table 13). Thus, more C was accumulated in CLM and RCA scenarios than in the current climate and less in REGCM3 within 40 years of simulation, but the effect was very small. After 80 years of simulation, the largest change (+10%) in the C stocks was found in the CLM scenario; the smallest change (+8%) in REGCM3.

In the forest, the C stocks (soil and vegetation) increased 131%, 156%, and 129% in CLM, RCA, and REGCM3 scenarios, respectively, compared with a much larger increase of 210% in 20 years under the current climate (Table 14). After 40 years, the differences between the simulations with and without climate change were even larger: the C stocks were increased only by 185%, 218%, and 193% in CLM, RCA, and REGCM3 scenarios, respectively, compared with a larger increase of 323% without climate change. This indicates that within 40 years of simulation, the C stocks of the forest were considerably decreased by climate change (Figure 19). Therefore, the negative effects of climate change on the C stocks might even offset the positive effects of afforestation in the long term, especially in the CLM scenario, where the forest C stocks increased only 177% after 80 years of simulation. The losses in SOC exceeded the simulated increases in root C stocks in all scenarios.

Table 13. Absolute and relative changes in the C stocks of the simulated system (soil and vegetation) in grassland in three different climate change scenarios (CLM, RCA, REGCM3, simulations 2010 – 2100) and without climate change (simulations 1960 – 2010). ΔC % refers to the mean percentage change when compared with the stocks of the year 2010.

| **Year** | **CLM** | | **RCA** | | **REGCM3** | | **Year** | **Grassland, no climate change** | |
|---|---|---|---|---|---|---|---|---|---|
| | **tC ha$^{-1}$** | **ΔC %** | **tC ha$^{-1}$** | **ΔC %** | **tC ha$^{-1}$** | **ΔC %** | | **tC ha$^{-1}$** | **ΔC %** |
| 2010 | 143.6 ± 0.3 | 0 | 143.8 ± 0.3 | 0 | 144.2 ± 0.3 | 0 | 1960 | 144.0 ± 0.3 | 0 |
| 2030 | 147.3 ± 0.0 | 3 | 148.4 ± 0.0 | 3 | 146.9 ± 0.0 | 2 | 1980 | 147.6 ± 0.0 | 3 |
| 2050 | 150.7 ± 0.0 | 5 | 151.2 ± 0.1 | 5 | 148.4 ± 0.0 | 3 | 2000 | 149.5 ± 0.0 | 4 |
| 2090 | 157.3 ± 0.1 | 10 | 157.3 ± 0.1 | 9 | 155.0 ± 0.1 | 8 | - | - | - |

Table 14. Absolute and relative changes in the C stocks of the simulated system (soil and vegetation) in forest in three different climate change scenarios (CLM, RCA, REGCM3, simulations 2010 – 2100) and without climate change (simulations 1960 – 2010). For the simulation of the reference forest, initial parameter values of a 40-year-old forest were used. ΔC % refers to the mean percentage change when compared with the stocks of the year 2010. All forest sites were 40-year-old at the start of the simulations.

| **Year** | **CLM** | | **RCA** | | **REGCM3** | | **Year** | **Forest, no climate change** | |
|---|---|---|---|---|---|---|---|---|---|
| | **tC ha$^{-1}$** | **ΔC %** | **tC ha$^{-1}$** | **ΔC %** | **tC ha$^{-1}$** | **ΔC %** | | **tC ha$^{-1}$** | **ΔC %** |
| 2010 | 168.8 ± 0.7 | 0 | 168.6 ± 0.6 | 0 | 170.1 ± 0.7 | 0 | 1960 | 168.4 ± 0.7 | 0 |
| 2030 | 390.0 ± 0.5 | 131 | 431.2 ± 0.6 | 156 | 389.9 ± 0.4 | 129 | 1980 | 522.4 ± 0.7 | 210 |
| 2050 | 481.2 ± 0.3 | 185 | 535.9 ± 0.3 | 218 | 498.6 ± 0.2 | 193 | 2000 | 711.9 ± 0.5 | 323 |
| 2090 | 468.3 ± 0.2 | 177 | 523.0 ± 0.2 | 210 | 493.1 ± 0.2 | 190 | - | - | - |

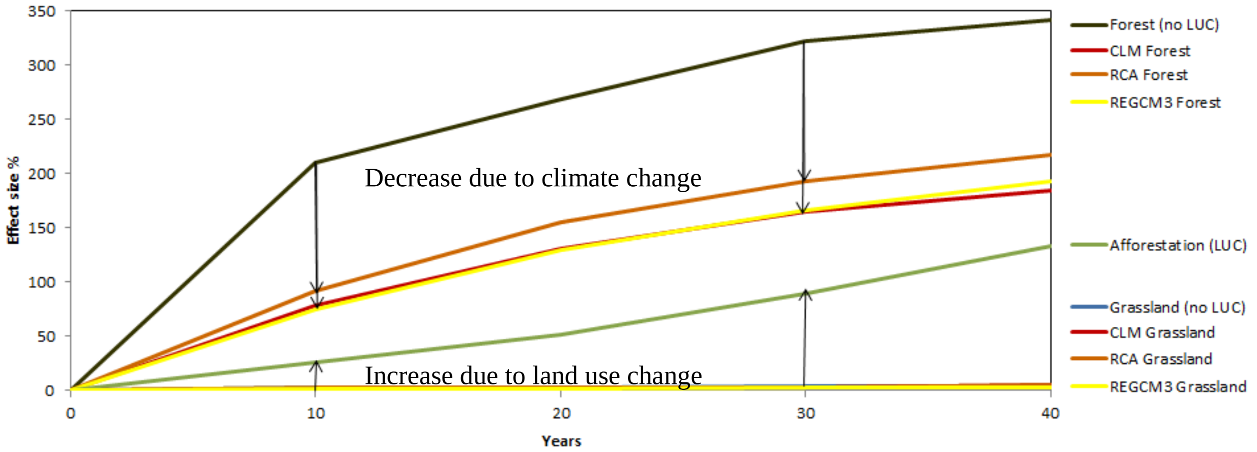

Figure 19. The relative changes (%) in the C stocks of the soil and vegetation in different land uses (grassland (no LUC) and forest (no LUC)), after LUC (afforestation (LUC)) and in three different climate change scenarios (CLM, RCA, REGCM3). Effect size (%) refers to the values represented in Tables 12, 14, and 15 (ΔC %; refers to the mean percentage change when compared with the stocks of the year 2010). Forest (no LUC) refers to a 40-year-old forest at the start of the simulation. Afforestation refers to a gradual, stepwise LUC from grassland to forest, as described earlier.

# 5 Discussion

## 5.1 Using CoupModel for Simulating Land Use Change

The changes in the vegetation and SOC stocks after LUC could be only partly reproduced by soil-plant-atmosphere system modeling in this study. The effects of afforestation on the root dynamics, SOM quality, soil temperature and water content could only partly reproduce the results of the studies of Hiltbrunner et al. (2012; 2013) (see results in Sections 4.2 and 4.3). The overestimation of root growth and SOM quality and the underestimation of the aboveground C stocks in the long term might result from the way in which the vegetation was parameterized in the model. First of all, the LUC was not implemented as a smooth gradual function, but stepwise with the parameter values changing every five years. Needless to say, this purely theoretical approach is far from ideal in representing the changes in vegetation realistically. Secondly, even though measured data was available, it was difficult to convert them into parameter values that can be used in the model. A good example of this is the use of data on the vegetation C stocks in this study, since measured data was provided but most of the parameter values describing the plant growth and C allocation had to be taken from other studies. The parameterization differs widely between species and site quality. Therefore, differences, for example, in the parameters describing the rate, quality and quantity of organic C input to the soil might also affect the simulation of the SOC stocks. Thus, the differences in the simulated and measured aboveground C stocks in forests could be caused, for example, by a higher planting density in Jaunpass than in the naturally growing forest which was used as a reference.

SOC stocks were overestimated by the simulations compared with the measured data (see Section 4.4.1). Even though afforestation generally affects the C pool of the forest floor more strongly than that of the mineral soil (Jandl et al., 2007), here the response of the organic layer was too high. 40 years after LUC, the SOC stocks were 165.9 ± 2.3 tC ha $^{-1}$, which is approximately 36 tC ha$^{-1}$ too high compared to the mean value for Swiss alpine forest soils, ~130 tC ha$^{-1}$ (Hagedorn et al., 2010b; Hiltbrunner et al., 2013). Also the difference between the SOC stocks of grassland and forest sites was too high if compared to the average difference of 22 tC ha$^{-1}$ between the two land use types in Switzerland (Bolliger et al., 2008). There can be two reasons for these differences. Firstly, the aboveground inputs, the low decomposability, and long lifetime of the tree roots could increase SOM in the surface soils of forests compared to grasslands (Guo & Gifford, 2002). Thus, the parameterization of the vegetation could affect the rates at which C is accumulated on the forest organic layer. Secondly, the differences could result from the parameter values for soil organic processes, since they were taken from other studies that might have different circumstances for humus and litter decay (for example, in terms of N availability).

In contrast to the hypothesis, the temporal scale of the changes in the soil and vegetation C stocks after LUC differed from the results gained from a space-for-time study by Hiltbrunner et al. (2013). The measured decline (-25%) in the mineral SOC stocks 40-45 years after land use change could not be reproduced by the simulations. On the contrary, the strongest simulated decline of -1.5% took place much earlier: after 13 years (see Section 4.3.1). This is in line with the results of Poeplau et al. (2011), who found a decrease of -4 ±4% in the mineral SOC stocks after 20 years of LUC from grassland to forest. In this study, the initial C loss was offset by the accumulation of forest floor C already after 20 years. However, as modelled by carbon response functions covering 16 grassland afforestation sites in the temperate zone, it has been suggested to take up to 48 years for this to happen (Poeplau et al., 2011). Guo & Gifford (2002) showed in their meta-analysis that the final result might be negative: trees planted onto pasture land reduced SOC stocks by 10% rather than increasing it. Also Berthrong et al. (2009) reported a decline: in their global meta-analysis, total SOC content was decreased by 15% in Pinus plantations. It has been suggested that these declines result from site preparation (Jandl et al., 2007), decreased bioturbation due to decreasing soil biota activity, or cessation of the dense grass cover in young stands (Poeplau et al., 2011). Neither the disturbance by site preparation nor the decreased bioturbation could be taken into account in the model. The effect of disturbance by site preparation was anyway minimal in this site, since the spruce saplings were planted manually on the relatively steep subalpine slope (Hiltbrunner et al., 2013). Another possible reason for the mismatch of measured and simulated C losses might be that the simulated soil temperatures were too high in the forest sites (see Section 4.2).

The simulated soil respiration in the 40-year-old forest (2 206 ± 221 gC $m^{-2}$ $year^{-1}$) was almost three times higher than reported literature values for temperate ecosystems (745 ± 421 gC $m^{-2}$ $year^{-1}$, Bond-Lamberty & Thomson, 2010) or temperate coniferous forests (681 ± 95 gC $m^{-2}$ $year^{-1}$, Raich & Schlesinger, 1992). Therefore, the 30% decrease in soil respiration in the old forest compared to the grasslands found by Hiltbrunner et al. (2013) could not be reproduced in this study. One reason for this could be that the model could not reproduce the measured soil temperatures in grassland or forest (see Section 4.2). Another reason for the high respiration rates could be the model parameterization. The input parameters of the parameter group of “soil organic processes” were found to greatly affect total respiration ranges (see Section 4.1), which might explain why the simulated soil respiration in the afforestation was too high in this study. This is supported by the fact that in forests, there was a strong correlation between the heterotrophic respiration and soil respiration (with roots). This indicates that the part of the heterotrophic respiration governs the whole respiration dynamics and therefore, the reason for the high respiration rates lies in the parameters that define the soil organic processes. Even though SOC stock (“C tot soil org”) was insensitive to any of the input (see Section 4.1), later testing with longer simulation periods (1960 – 2012 instead of 2010 – 2011) and with larger parameter ranges (more than ±10% as suggested by Lenhart et al., 2002) showed that this output variable was actually very sensitive to the input parameters of soil organic processes. Thus, using values from other studies to define the soil organic processes might have accounted for the observed discrepancy between measured and simulated data.

There are some challenges in using data from a space-for-time study for simulating LUC. Firstly, the space-for-time method relies on homogeneous soil conditions (Hiltbrunner et al., 2013) and landscape. In this study, the simulated sites spanned an altitudinal gradient of 100m (1510m – 1610m above sea level), whereas the two afforested plots differed only 10m in altitude. Even though the rate of organic matter cycling might be affected by the slightly different temperature and length of the vegetation period along the altitudinal gradient, Hiltbrunner et al. (2013) did not find any statistical differences in SOC concentrations within pasture soils either along the altitudinal gradient or along an East–West transect. There are, however, other factors (for example, soil texture) that were not very similar in all the simulated plots. According to the sensitivity analysis, for example, parameters describing soil hydraulic properties – which were derived from soil texture using pedofunction – had a great effect on the model outcome. This might influence the output data in a way that the differences between plots are not due to LUC, but due to the differences between the simulated plots. Ideally, the soil parameters for all simulated plots would be similar so that the effects of only LUC could be observed. This could have been done in this study, for example, by only choosing one plot for the simulations and changing the land use of that single plot. However, by taking into account several plots, there is more validation data available and the representation of the simulated site is more realistic. Secondly, the model output might be affected by the soil thickness which was unintentionally overestimated in the simulations. However, since the SOC stocks were given as a parameter value, the changes in SOC stocks during the simulation period were calculated in relation to the starting value (in g m$^{-2}$). Finally, LUC is often inherently coupled with an alteration in soil bulk density (Poeplau et al., 2011), but this could not be changed during the simulation in CoupModel.

## 5.2 Using CoupModel for Simulating the Effects of Climate Change

In principle, this kind of a modeling approach can be used for assessing the future changes in the soil and vegetation C stocks by using climate scenarios. Since there was no climate scenario with current air temperature and precipitation available for the same simulation period (2010 – 2100), the effects of climate change on vegetation and SOC are hard to distinguish from the effects of model structure and parameterization. The differences during the first 50 years can be compared with the simulations of 1960 – 2010, but the long term changes can only be analyzed between the scenarios and not against a reference.

According to the simulations, the changes in air temperature and amount of precipitation will result in an increase in the SOC stocks in grasslands and a reduction in forests in all scenarios (see Section 4.4.1). There were no clear differences between the scenarios in grasslands, unlike in forests. In theory, the SOC stocks should react differently in the different climate scenarios. Generally, the SOC stocks increase with increasing precipitation and constant temperature, and decrease with increasing temperature and constant precipitation (Jenny 1980; Post et al., 1982). Therefore, the SOC stocks should increase (or not change) in REGCM3 and decrease in CLM and RCA. The decrease in the mineral SOC stocks in CLM scenario in the forest goes well with this theory. Generally, forest floors are expected to be more susceptible to climate warming than mineral soils because of their greater turnover rate and large amount of labile C stored in this layer (Smith et al. 2008). This might explain why a great amount of C is lost from the simulated forest organic layer in all of the scenarios. Another reason for this could be that the aboveground C stocks seem to be underestimated by the model for decades after the start of the simulation (see Section 4.3.3). However, the reason why the largest amount of C is lost in REGCM3 scenario is unclear. As noted before, the model parameterization might be slightly false for this study site and purpose. Therefore, the strong declines in the organic layer might stem from the parameterization of the aboveground litter fall or the litter decay rate. Moreover, simulated soil temperature was found to be too high in forest and too low in grassland in the validation of the model (see Section 4.2). Due to this, the results of the long term simulations with climate change scenarios could be different if the model validation with the measured data was better.

In grassland, there was generally less aboveground C and more root C in all scenarios than in simulations under current climate conditions. However, no differences between scenarios were found (see Section 4.4.3). Even though more differences between the three scenarios were found in the forest, the same allocation pattern (less aboveground C and more root C than under current climate conditions) was visible in all scenarios. One theoretical explanation for this could be drought stress which is generally thought to be a frequent cause for tree defoliation (Fuhrer et al., 2006). This could also explain why the vegetation needs to allocate more C to the roots in order to ensure the water availability. For example, in a study conducted close to the study area in Valais, defoliation and mortality in Scots pine was found to be related to the precipitation deficit and hot conditions of the previous year (Rebetez & Dobbertin, 2004). However, with the high precipitation in Jaunpass, drought seems unlikely even though the precipitation rates decreased considerably. Moreover, the same allocation pattern was already found in the LUC simulations under current climate conditions (see Section 4.3.3), which means that the model generally simulates less aboveground C and more root C than measurements suggest. Since transfer of C through roots of plants to the soil has been claimed to play a primary role in regulating ecosystem responses to climate change (Bardgett, 2011), it would be essential to further investigate why the model overestimates the root C and how this could be changed in order to increase the quality of the results.

In grasslands, the annual heterotrophic respiration increased with time, with the highest values in the RCA scenario and lowest in REGCM3 by the year 2095. This means that the decomposition rate of SOM was getting higher as affected by climate change. In the forest, the trend was the opposite; the annual heterotrophic respiration decreased with time. However, the highest values were in RCA scenario by the year 2095, just like in grasslands. At the same time, the highest increase in the soil temperatures at 5cm depth were in the RCA scenario and lowest in REGCM3 (data not shown). A clear correlation between soil respiration (with roots) and soil temperature at 5cm depth was found in forests in every scenario (daily resolution) but not in grasslands on a daily or annual resolution (see Appendix 3). The general decreases in soil respiration rates under elevated air temperature and decreased rainfall is theoretically in line with the results of Muhr & Borken (2009) who expect a negative feedback between the increased frequency and magnitude of summer droughts and soil respiration in Norway spruce stands. However, as shown in the model validation, the model tends to overestimate soil temperatures in the forest sites and underestimate them in grasslands, which means that the trend of increasing soil respiration with higher soil temperatures might also be overestimated in the simulations. Moreover, the decline in soil respiration could also be linked to the declining litter quality in the older forests, shown in the LUC simulations (see Section 4.3.2). According to the sensitivity analysis, the simulated total respiration is greatly affected by C/N ratio, efficiency of the litter and humus decay, and the rate coefficients for the decay of litter and humus. This could mean that these parameters should be better adjusted for this site in order to fit the measured values.

## 5.3 Importance of Land Use and Climate Change for Carbon Dynamics in the Simulated System

Afforestation increased the C stocks (soil and vegetation) by 133% within the years 1960–2010 (40 years of simulation with current climate). Thus, the hypothesis that afforestation increases the C stocks of soil and vegetation was supported. In the climate change simulations, the grassland C stocks (soil and vegetation) increased by 3% – 5% in 40 years (2010 – 2050), which is in the same range as the increase of 4% within the years 1960 – 2010 (40 years of simulation, no LUC). Therefore, the hypothesis that LUC has a larger impact than climate change on the C stocks of the soil-plant system was supported by the simulations (see Sections 4.3.4 and 4.4.4).

The forest C stocks (soil and vegetation) were negatively affected by the climate change already within 40 years of simulation (2010 – 2050) when compared to the simulations with the current climate (simulations 1960 – 2010, no LUC; see Section 4.4.4.). Thus, the hypothesis that the changes in temperature and precipitation have a negative effect on soil and vegetation C stocks in the future only applied to forest sites in this study. The reason for this was the substantial decrease in SOC in all climate scenarios, even though the vegetation C stocks were relatively high compared to the forest simulations of 1960 – 2010. In line with this, forest soils are found to respond more strongly to climate warming than soils under other land use (Jandl et al., 2007) and simulating the effects of climate change on the C dynamics has been shown to turn for example large areas of the boreal forests to a future $CO_2$ source (Schaphoff et al., 2006). This suggests that the C stocks gained by afforestation could be offset by the increased C losses from the forests due to climate change in the long run.

## 5.4 Limitations of this Study

Ecosystems respond to climate change in more complicated ways than represented in this simulation study. Here the effects of shifts in vegetation type, the adaptation of soil microbial community, and changes in soil properties or properties on SOC could not be taken into account, yet they can cause important changes in SOC dynamics and occur over much longer time periods than changes in SOC decomposition and net primary productivity in response to climate change (Smith et al., 2008). Moreover, measured values used for the simulations might differ considerably due to the inherent uncertainty of ecosystem studies and due to differences in sampling methodology. For example, it has been suggested that depending on the sampling and analytical protocols used to estimate the C stocks at the same single site, the results might differ by 10 – 20% due to the high variability in SOC pool at all spatial scales (Bird et al., 2001).

The more complex the model, the more data and information are required (Ostle et al., 2009) and the harder it becomes to understand all the different relationships and interactions between parameters. In order to better understand the relationships between model input and output, a sensitivity analysis was conducted in this study. However, it was only performed for one grassland plot and not for the forest. Therefore, some parameters may have been of importance in the forest but still ignored by this sensitivity analysis. The chosen method of sensitivity analysis does not allow considering the interactions, relationships and nonlinearity of parameters (Lenhart et al., 2002), which might also affect the results. Moreover, model calibration plays a major role in influencing their predictive ability. Therefore, calibration with long-term data sets is critical (Stockmann et al., 2013). Here, some of the parameters associated with the C dynamics could not be calibrated due to the model structure. Instead, they were taken from other studies and slightly adjusted manually in order to find the parameter set that best fits the measured data on the soil and plant C stocks and fluxes. The challenge of finding the right set of model parameters is more generally linked to the whole modeling approach, since simulating the gradual change from one land use to another is very complex. In this approach, it is not enough to find one correct set of parameters over a certain validation period, but instead the parameters need to change as the land use change proceeds. As discussed earlier, the model tends to overestimate soil temperatures in the forest sites and underestimate them in grasslands, which also might contribute to the results of the long term simulations. After all, it is good to keep in mind that the model's ability to simulate measurable variables does not necessarily relate to its ability to simulate non-measurable variables (Jansson, 2012). Thus, models developed using historical data might not be able to correctly simulate the future phenomena.

# 6 Conclusions

This study was conducted in a sub-alpine region on a south facing slope with fertile limestone soil. Due to the high altitude, fertile soil and other environmental conditions of the site, the results might not apply to another site with different properties. Here, afforestation clearly increased the C stocks of soil and vegetation, whereas climate change considerably decreased the C stocks of the simulated forest but did not affect the grassland C stocks. As discussed in the literature review (Section 2.2), these responses could be site specific and depend, for example, on the land use history, tree and plant species, soil properties, and site productivity. Moreover, the model parameterization with values from other studies resulted in the overestimation of root growth and soil respiration in forest sites, whereas aboveground tree biomass grew, in general, too slowly. Therefore, these results should not be directly compared with experimental values but rather used as a starting point for more specific modeling studies in other study sites around Switzerland.

Since translating the whole complexity of natural systems into a mathematical representation is an impossible task, models are by definition simplifications. In this case, the properties of the simulated system were changing over time due to land use change, which makes finding a good set of parameters very challenging without the possibility of a proper calibration with long term data. Therefore, further research would be needed in order to improve the parameter set so that: i) the land use change would be more gradual than the stepwise representation shown here, ii) the model output variables of the soil and vegetation C stocks and fluxes would better fit the measured data of this study site, and iii) this modeling approach could be used in other study sites in Switzerland. As shown here, this kind of a modeling approach could be used for increasing our understanding about the time scale of the changes taking place in the soil-plant-atmosphere system due to climate change and afforestation, if the parameter set is well defined for the study site. Since land use and climate change affect the whole ecosystem, a clear asset of using a soil-plant-atmosphere system model for this purpose is that various physical and biological processes can be simulated at the same time. On the other hand, the more complex the model, the more data is needed for validation and the more uncertainties are associated with the parameter values. Thus, future studies should collect long term experimental data of specific species and soils so that these could be further used for modeling purposes.

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# Appendices

Appendix 1. 92 Parameters that were changed linearly from 01.07.1970 to 01.07.2010 within time steps of 5 years when simulating the land use change from grassland to forest.

| **Parameter** | **Unit** | **Description (if available)** | **Grassland** | **Forest** |
|---|---|---|---|---|
| Soil thermal parameters | | | | |
| Organic Layer Thick | m | Thickness of the humus layer. This parameter is only used as a thermal property. | 0 | 0.06 |
| Snow pack | | | | |
| CritDepth SnowCover | m | | 0.01 | 0.06 |
| MeltCoefAirTemp | kg °C$^{-1}$ m$^{-2}$ day$^{-1}$ | Temperature coefficient in the empirical snow melt function. A value of 2 is normal for forests. Similar as for MeltCoefGlobRad a two or three fold increase is expected if adaptation to an open field is to be done. | 4 | 2 |
| MeltCoefGlobRad | kg J$^{-1}$ | Global radiation coefficient in the empirical snow melt function. A normal value for forests 1.5e-7 implies that a global radiation of 15 MJ m$^{-2}$ during a sunny day in the spring will melt 2.2 mm of new snow or 6.6 mm of old snow with the value MeltCoefGlobRadAge1 put to 2. Values of open fields may be 2-3 times larger. | 4.49e-7 | 1.5e-7 |
| Meteorological data | | | | |
| ReferenceHeight | m | Height above ground which represent the level for air temperature, air humidity and wind speed. | 2 | 30 |
| Plant, interception, potential transpiration, and water uptake | | | | |
| InitEvapFracMin | - | Scaling parameter for the leaf coverage of intercepted water used in the calculation of potential interception evaporation. | 0.1 | 0.01 |
| WaterCapacity PerLAI | mm m$^{-2}$ | Interception water storage capacity per LAI unit. | 0.3021 | 0.3 |
| CritThresholdDry | cm water | Critical pressure head for reduction of potential water uptake. | 7817.8657 | 1409.7871 |
| TempCoefA | - | Temperature coefficient in the temperature response function. | 19.8447 | 0.8 |

| | | | | |
|---|---|---|---|---|
| DemandRelCoef | 1 day$^{-1}$ | Coefficient for the dependence of potential water uptake in the reduction function. The dependence of the potential uptake rate has frequently been reported as an important phenomenon for reduction of water uptake. | 0.3 | 0.3799 |
| Soil organic processes and mineral N processes | | | | |
| CN Ratio Microbe | - | | 13.9514 | 20 |
| Init H Ctot | g m$^{-2}$ | Initial total amount of C contained in humus in the whole soil profile | 13398.86 | 11203.49 |
| Init H Depth | m | The initial depth to where the humus is distributed. | -1 | -2 |
| Init H Frac Exp tail | - | Fraction of C in the humus pool remaining when the rest has been distributed to the layers above a specified depth by an exponential function. This remaining fraction is evenly distributed among the same layers as the rest of the C in the faeces pool. | 0.03 | 0.1 |
| Init H N tot | g m$^{-2}$ | Initial total amount of nitrogen contained in humus in the whole soil profile | 1415 | 973 |
| Init L1 Ctot | g m$^{-2}$ | Initial total amount of C contained in litter 1 | 0 | 1056 |
| Init L1 Depth | m | The initial depth to where the litter 1 is distributed. | 0 | -0.5 |
| Init L1 FracExpTail | - | Fraction of C in the litter pool 1 remaining when the rest has been distributed to the layers above a specified depth by an exponential function. This remaining fraction is evenly distributed among the same layers as the rest of the C in the faeces pool. | 0.005 | 0.1 |
| Init L1 Ntot | g m$^{-2}$ | Initial amount of nitrogen contained in litter 1 in the whole soil profile. | 0 | 32 |
| RateCoefHumus | day$^{-1}$ | Rate coefficient for the decay of humus. | 1.48E-05 | 5.00E-04 |
| RateCoefLitter1 | day$^{-1}$ | Rate coefficient for the decay of litter 1. | 0.016 | 0.0352 |
| DenitThetaPower C2 | - | Coefficient in the function for soil moisture effect on denitrification. A value of 1 corresponds to a linear response whereas a higher value results in a concave response. | 10 | 2 |

| | | | | | | |
|---|---|---|---|---|---|---|
| DenitThetaRange | vol % | Water content range from saturation in the function for soil moisture on denitrification. | 10 | | 17 | |
| NUptMaxAvailFrac | day$^{-1}$ | Fraction of mineral N available for plant uptake. A value of 0.1 is means that 10% of the total mineral-N pool is available at one time-step. Normal range 0.05-0.12. | 0.08 | | 0.2 | |
| NitrateAmmRatio | - | Nitrate-ammonium ratio in the nitrification function. Normal range for agricultural soils 1-15. | 8 | | 0.25 | |
| **Parameter** | **Unit** | **Description (if available)** | **Grassland upper layer** | **Grassland lower layer** | **Forest tree layer** | **Forest under-growth layer** |
| Size and shape of growing plant | | | | | | |
| Specific Leaf area | gC m$^{-2}$ | The inverse of specific leaf area, i.e. leaf mass per unit leaf area. | 86 | 98.5836 | 98.7 | 97 |
| Max height | m | | 0.5 | 0.5 | 30 | 0.2 |
| Height massCoef | m$^2$g$^{-1}$ | | 0.05 | 0.05 | 0.05 | 0.05 |
| Height AgeCoef | 1 days$^{-1}$ | | 7.E-05 | 1 | 7e-5 | 7e-5 |
| Root Lowest depth | m | | -0.7 | -0.7 | -2 | -0.2 |
| Root IncDepth | m | | -2 | -2 | -2 | -2 |
| Albedo VegStage | % | | 10 | 10 | 10 | 20 |
| AlbedoGrainStage | % | | 40 | 40 | 10 | 40 |
| Surface canopy cover – multiple canopies | | | | | | |
| Max Cover | m$^2$m$^{-2}$ | | 1 | 1 | 0.85 | 1 |
| Area kExp | - | | 0.4406 | 0.4406 | 0.5 | 2 |
| Evapotranspiration – multiple canopies | | | | | | |
| Canopy Dens Max | - | The density maximum of canopy in relation to the canopy height | 0.3 | 0.3 | 0.7 | 0.3 |
| Roughness Min | m | The minimum roughness length used when estimating roughness length of different canopies | 1.00E-05 | 1.00E-05 | 1.75 | 1.75 |
| Air Resist LAI Effect | s m$^{-1}$ | The increase of air resistance inside a canopy as a factor of LAI. | 20 | 20 | 20 | 0 |
| Conduct Ris | J m$^{-2}$ day$^{-1}$ | The global radiation intensity that represents half-light saturation in the light response | 5.00E+06 | 5.00E+06 | 1.123e+7 | 1.123e+7 |
| Conduct VPD | Pa | The vapor pressure deficit that corresponds to a 50% reduction of stomata conductance | 100 | 100 | 359 | 359 |
| Conduct Max | m s$^{-1}$ | The maximal conductance of a fully open stomata | 0.02 | 0.02 | 0.0172 | 0.0172 |
| Roughness Max | m | The maximum roughness length used when estimating roughness length of different canopies | 3 | 3 | 3 | 3 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Allocation parameters | | | | | | |
| Leaf c1 | - | Fraction of the mobile C assimilates allocated to the new shoots | 0.6198 | 0.6198 | 0.1814 | 0.28 |
| Root CN c1 | - | Fraction of the mobile C assimilates allocated to the roots in the response function for nitrogen concentration in leaves | 0.5 | 0.5 | 0.3918 | 0.2523 |
| AlloRateCoef | - | | 1 | 1 | 0.5 | 0.5 |
| Coarse Root versus remaining C | | | | | | |
| Fraction R | - | | 0.2 | 0.2 | 0.5 | 0.1495 |
| Initial C conditions of plants | | | | | | |
| I C leaf | g m$^{-2}$ | | 7.3148 | 7.3148 | 72 | 7 |
| I C stem | g m$^{-2}$ | | 2.8 | 2.8 | 116 | 2.8 |
| I C roots | g m$^{-2}$ | | 50 | 50 | 98 | 50 |
| I C OldLeaf | g m$^{-2}$ | | 42 | 42 | 195 | 42 |
| I C OldStem | g m$^{-2}$ | | 24 | 24 | 2126 | 24 |
| I C Oldroots | g m$^{-2}$ | | 15 | 15 | 24 | 15 |
| I C CRoots | g m$^{-2}$ | | 0.7 | 0.7 | 98 | 0.7 |
| I C OldCRoots | g m$^{-2}$ | | 6 | 6 | 536 | 6 |
| Initial conditions of plants | | | | | | |
| I plant age | days | Initial plant age | 1000 | 1000 | 13500 | 13500 |
| I N Leaf | g m$^{-2}$ | Initial nitrogen mass in leaves | 2 | 2 | 0.76 | 0.0852 |
| I N Stem | g m$^{-2}$ | Initial nitrogen mass in stem. | 0.2 | 0.2 | 1.36 | 0.0521 |
| I N Roots | g m$^{-2}$ | Initial nitrogen mass in roots | 0.2 | 0.2 | 2.31 | 1.3 |
| I N OldLeaf | g m$^{-2}$ | Initial nitrogen mass in old leaves | 0.8 | 0.8 | 3.56 | 0.85 |
| I N OldStem | g m$^{-2}$ | Initial nitrogen mass in old stem | 0.5 | 0.5 | 2.91 | 0.36 |
| I N OldRoots | g m$^{-2}$ | Initial nitrogen mass in old roots | 0.8 | 0.8 | 0.6 | 0.375 |
| I N CRoots | g m$^{-2}$ | | 0.1 | 0.1 | 0.038 | 0.0134 |
| I N OldCRoots | g m$^{-2}$ | | 0.1 | 0.1 | 0.77 | 0.0996 |
| Litter fall Above Ground | | | | | | |
| LeafRate1 | day$^{-1}$ | | 0.00191 | 0.00191 | 0.000181 | 0.00023 |
| LeafRate2 | day$^{-1}$ | | 0.009117 | 0.009117 | 0.000181 | 0.000181 |
| LeafTSum1 | day°C | | 776.2444 | 776.2444 | 1 | 1 |
| LeafTSum2 | day°C | | 1479.7717 | 1479.7717 | 1 | 1 |
| StemRate1 | day$^{-1}$ | | 0.0364 | 0.0364 | 3.62e-5 | 0.0001824 |
| StemRate2 | day$^{-1}$ | | 0.6223 | 0.6223 | 3.62e-5 | 0.0001824 |
| StemTSum1 | day°C | | 776.2444 | 776.2444 | 1 | 1 |
| StemTSum2 | day°C | | 1479.7717 | 1479.7717 | 1 | 1 |
| GrainRate1 | day$^{-1}$ | | 0.001 | 0.001 | 0.001 | 0.001 |
| Litter fall Below Ground | | | | | | |
| RootRate1 | day$^{-1}$ | | 0.002738 | 0.002738 | 0.004919 | 0.005226 |
| RootRate2 | day$^{-1}$ | | 0.002738 | 0.002738 | 0.004919 | 0.005226 |
| RootTsum1 | day°C | | 776.2444 | 776.2444 | 1 | 1 |
| RootTsum2 | day°C | | 1479.7717 | 1479.7717 | 1 | 1 |
| CoarseRootRate1 | day$^{-1}$ | | 2.74E-05 | 2.74E-05 | 3.62e-5 | 0.0001824 |
| CoarseRootRate2 | day$^{-1}$ | | 2.74E-05 | 2.74E-05 | 3.62e-5 | 0.000182 |
| CoarseRootTsum1 | day°C | | 1 | 1 | 1 | 1 |
| CoarseRootTsum2 | day°C | | 1 | 1 | 1 | 1 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Maximum CN Ratios of Leaf Litter | | | | | | |
| CN Ratio Max Litter | - | | 30 | 30 | 50 | 30 |
| Minimum CN Ratios of plants | | | | | | |
| CN Ratio Min Stem | - | | 40 | 40 | 100 | 20 |
| CN Ratio Min Leaf | - | | 20 | 20 | 22 | 22 |
| CN Ratio Min CRoots | - | | 40 | 40 | 100 | 20 |
| Photosynthesis Response | | | | | | |
| CN LTh | - | | 347.0794 | 347.0794 | 75 | 100 |
| Plant Behaviour | | | | | | |
| Max Leaf Lifetime | year | Maximum leaf lifetime. | 5 | 1 | 1 | 1 |
| Radiation use efficiency | | | | | | |
| RadEfficiency | gDw $MJ^{-1}$ | | 2.1356 | 2.1356 | 8 | 8 |
| FixN supply | - | | 0.4416 | 0.4416 | 0.1511 | 0.4416 |
| Respiration of plants | | | | | | |
| MCoefLeaf | $day^{-1}$ | | 0.0015 | 0.0015 | 0.001171 | 0.001171 |
| MCoefStem | $day^{-1}$ | | 0.0015 | 0.0015 | 0.000120 | 0.000120 |
| MCoefRoot | $day^{-1}$ | | 0.005 | 0.005 | 0.005145 | 0.005145 |
| MCoefCoarseRoot | $day^{-1}$ | | 0.00015 | 0.00015 | 0.000120 | 0.000120 |

Appendix 2. Correlation matrixes of the land use change simulations. In all tables, red values were statistically significant ($p<0.05$) and bold values had a strong relationship between the variables ($r^2>0.8$, n=18 992).

## P3 – Grassland

| | Variable | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | C total plant | **1.00** | | | | | | | | | | | | | | | | | | | | |
| 2 | C Total Plant AboveG | **0.82** | **1.00** | | | | | | | | | | | | | | | | | | | |
| 3 | C Total Roots | 0.70 | 0.17 | **1.00** | | | | | | | | | | | | | | | | | | |
| 4 | CTotSoil Humus | -0.34 | -0.30 | -0.21 | **1.00** | | | | | | | | | | | | | | | | | |
| 5 | CTotSoil Litter1 | 0.64 | 0.78 | 0.13 | -0.52 | **1.00** | | | | | | | | | | | | | | | | |
| 6 | CTotSoilOrg | -0.26 | -0.19 | -0.22 | **0.99** | -0.39 | **1.00** | | | | | | | | | | | | | | | |
| 7 | Evapo-transpiration | 0.22 | 0.07 | 0.29 | 0.08 | -0.12 | 0.09 | **1.00** | | | | | | | | | | | | | | |
| 8 | Carbon Balance Rate | -0.20 | -0.22 | -0.06 | 0.03 | -0.16 | 0.02 | 0.34 | **1.00** | | | | | | | | | | | | | |
| 9 | NitrogenBalance Rate | 0.06 | 0.05 | 0.04 | 0.02 | 0.01 | 0.02 | 0.03 | 0.00 | **1.00** | | | | | | | | | | | | |
| 10 | Soil resp no roots | 0.61 | 0.42 | 0.53 | -0.21 | 0.27 | -0.17 | 0.59 | 0.09 | 0.06 | **1.00** | | | | | | | | | | | |
| 11 | Soil respiration | 0.33 | 0.04 | 0.52 | -0.10 | -0.02 | -0.10 | 0.64 | 0.70 | 0.04 | 0.65 | **1.00** | | | | | | | | | | |
| 12 | Total respiration | 0.25 | 0.04 | 0.39 | -0.04 | -0.06 | -0.04 | 0.70 | 0.75 | 0.03 | 0.59 | **0.97** | **1.00** | | | | | | | | | |
| 13 | Total Photosynt | -0.08 | -0.16 | 0.06 | 0.01 | -0.14 | 0.00 | 0.46 | **0.98** | 0.01 | 0.24 | **0.81** | **0.86** | **1.00** | | | | | | | | |
| 14 | Snowdepth | -0.18 | 0.02 | -0.33 | -0.20 | 0.14 | -0.20 | -0.51 | -0.19 | 0.01 | -0.28 | -0.39 | -0.41 | -0.26 | **1.00** | | | | | | | |
| 15 | Precipitation | 0.02 | 0.01 | 0.03 | -0.01 | -0.01 | -0.02 | 0.06 | 0.02 | 0.00 | 0.08 | 0.06 | 0.06 | 0.04 | 0.07 | **1.00** | | | | | | |
| 16 | Air temp | 0.24 | 0.07 | 0.34 | 0.08 | -0.15 | 0.09 | **0.82** | 0.29 | 0.01 | 0.57 | 0.59 | 0.67 | 0.42 | -0.52 | -0.01 | **1.00** | | | | | |
| 17 | Soil temp 5cm | 0.33 | 0.08 | 0.47 | 0.06 | -0.18 | 0.05 | **0.86** | 0.23 | 0.04 | 0.72 | 0.69 | 0.72 | 0.39 | -0.45 | 0.06 | **0.84** | **1.00** | | | | |
| 18 | Soil temp 25cm | 0.41 | 0.11 | 0.58 | 0.07 | -0.18 | 0.05 | 0.75 | 0.12 | 0.04 | 0.71 | 0.64 | 0.64 | 0.27 | -0.45 | 0.06 | 0.75 | **0.96** | **1.00** | | | |
| 19 | Soil temp 50cm | 0.47 | 0.13 | 0.66 | 0.07 | -0.16 | 0.05 | 0.56 | -0.02 | 0.04 | 0.63 | 0.53 | 0.49 | 0.12 | -0.41 | 0.04 | 0.61 | **0.83** | **0.95** | **1.00** | | |
| 20 | Soil vol.wat cont 5cm | -0.17 | -0.13 | -0.13 | -0.04 | -0.10 | -0.07 | -0.28 | 0.01 | -0.11 | 0.04 | -0.08 | -0.13 | -0.03 | 0.18 | 0.25 | -0.23 | -0.29 | -0.30 | -0.29 | **1.00** | |
| 21 | Soil vol.wat cont 25cm | -0.31 | -0.20 | -0.28 | -0.02 | -0.12 | -0.05 | -0.44 | -0.02 | -0.07 | -0.21 | -0.25 | -0.28 | -0.10 | 0.24 | 0.08 | -0.38 | -0.50 | -0.52 | -0.50 | **0.81** | **1.00** |
| 22 | Soil vol.wat cont 50cm | -0.28 | -0.22 | -0.21 | -0.02 | -0.17 | -0.05 | -0.38 | 0.01 | -0.04 | -0.20 | -0.20 | -0.24 | -0.06 | 0.17 | 0.03 | -0.34 | -0.44 | -0.47 | -0.46 | 0.68 | **0.89** |

## P6 – Grassland

| | Variable | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | C total plant | **1.00** | | | | | | | | | | | | | | | | | | | | |
| 2 | C Total Plant AboveG | **0.81** | **1.00** | | | | | | | | | | | | | | | | | | | |
| 3 | C Total Roots | 0.71 | 0.15 | **1.00** | | | | | | | | | | | | | | | | | | |
| 4 | CTotSoil Humus | -0.12 | -0.02 | -0.17 | **1.00** | | | | | | | | | | | | | | | | | |
| 5 | CTotSoil Litter1 | 0.55 | 0.69 | 0.08 | -0.47 | **1.00** | | | | | | | | | | | | | | | | |
| 6 | CTotSoilOrg | -0.04 | 0.09 | -0.18 | **0.99** | -0.34 | **1.00** | | | | | | | | | | | | | | | |
| 7 | Evapo-transpiration | 0.22 | 0.08 | 0.27 | 0.08 | -0.13 | 0.09 | **1.00** | | | | | | | | | | | | | | |
| 8 | Carbon Balance Rate | -0.20 | -0.22 | -0.08 | 0.00 | -0.15 | -0.01 | 0.34 | **1.00** | | | | | | | | | | | | | |
| 9 | NitrogenBalance Rate | 0.29 | 0.45 | -0.06 | 0.06 | 0.29 | 0.12 | 0.06 | 0.03 | **1.00** | | | | | | | | | | | | |
| 10 | Soil resp no roots | 0.57 | 0.36 | 0.53 | -0.10 | 0.17 | -0.06 | 0.65 | 0.09 | 0.10 | **1.00** | | | | | | | | | | | |
| 11 | Soil respiration | 0.34 | 0.03 | 0.53 | -0.06 | -0.06 | -0.06 | 0.65 | 0.68 | 0.04 | 0.67 | **1.00** | | | | | | | | | | |
| 12 | Total respiration | 0.26 | 0.04 | 0.39 | -0.01 | -0.09 | -0.01 | 0.71 | 0.73 | 0.07 | 0.62 | **0.97** | **1.00** | | | | | | | | | |
| 13 | Total Photosynt | -0.08 | -0.16 | 0.05 | 0.00 | -0.14 | -0.01 | 0.47 | **0.98** | 0.05 | 0.25 | **0.80** | **0.85** | **1.00** | | | | | | | | |
| 14 | Snowdepth | -0.22 | -0.03 | -0.34 | -0.14 | 0.13 | -0.13 | -0.50 | -0.18 | 0.02 | -0.33 | -0.40 | -0.42 | -0.26 | **1.00** | | | | | | | |
| 15 | Precipitation | 0.01 | 0.01 | 0.01 | 0.03 | -0.03 | 0.03 | 0.07 | 0.02 | -0.01 | 0.06 | 0.05 | 0.06 | 0.03 | 0.06 | **1.00** | | | | | | |
| 16 | Air temp | 0.27 | 0.09 | 0.35 | 0.09 | -0.16 | 0.09 | **0.83** | 0.28 | 0.05 | 0.63 | 0.62 | 0.69 | 0.42 | -0.54 | 0.00 | **1.00** | | | | | |
| 17 | Soil temp 5cm | 0.36 | 0.09 | 0.50 | 0.06 | -0.19 | 0.05 | **0.85** | 0.21 | 0.02 | 0.77 | 0.71 | 0.74 | 0.38 | -0.46 | 0.05 | **0.85** | **1.00** | | | | |
| 18 | Soil temp 25cm | 0.46 | 0.12 | 0.62 | 0.07 | -0.20 | 0.05 | 0.71 | 0.08 | -0.04 | 0.76 | 0.65 | 0.63 | 0.24 | -0.45 | 0.04 | 0.73 | **0.95** | **1.00** | | | |
| 19 | Soil temp 50cm | 0.51 | 0.13 | 0.71 | 0.07 | -0.19 | 0.05 | 0.49 | -0.07 | -0.11 | 0.65 | 0.53 | 0.46 | 0.08 | -0.40 | 0.03 | 0.58 | 0.80 | **0.94** | **1.00** | | |
| 20 | Soil vol.wat cont 5cm | -0.10 | -0.12 | -0.02 | 0.10 | -0.15 | 0.08 | -0.19 | 0.00 | -0.25 | 0.08 | -0.02 | -0.08 | -0.02 | 0.07 | 0.21 | -0.16 | -0.19 | -0.17 | -0.14 | **1.00** | |
| 21 | Soil vol.wat cont 25cm | -0.26 | -0.24 | -0.15 | 0.15 | -0.26 | 0.11 | -0.34 | -0.01 | -0.23 | -0.14 | -0.17 | -0.22 | -0.07 | 0.09 | 0.11 | -0.30 | -0.38 | -0.36 | -0.30 | 0.68 | **1.00** |
| 22 | Soil vol.wat cont 50cm | -0.28 | -0.25 | -0.17 | 0.19 | -0.31 | 0.15 | -0.28 | 0.02 | -0.20 | -0.21 | -0.17 | -0.19 | -0.04 | 0.06 | 0.05 | -0.25 | -0.34 | -0.36 | -0.33 | 0.52 | **0.86** |

## P5 –Forest

| | Variable | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | C total plant | **1.00** | | | | | | | | | | | | | | | | | | | | |
| 2 | C Total Plant AboveG | **0.93** | **1.00** | | | | | | | | | | | | | | | | | | | |
| 3 | C Total Roots | **0.94** | 0.74 | **1.00** | | | | | | | | | | | | | | | | | | |
| 4 | CTotSoil Humus | **0.89** | 0.68 | **0.98** | **1.00** | | | | | | | | | | | | | | | | | |
| 5 | CTotSoil Litter1 | **0.94** | **0.85** | **0.91** | **0.89** | **1.00** | | | | | | | | | | | | | | | | |
| 6 | CTotSoilOrg | **0.96** | **0.83** | **0.95** | **0.95** | **0.98** | **1.00** | | | | | | | | | | | | | | | |
| 7 | Evapo-transpiration | 0.39 | 0.38 | 0.35 | 0.31 | 0.30 | 0.34 | **1.00** | | | | | | | | | | | | | | |
| 8 | Carbon Balance Rate | 0.13 | 0.16 | 0.08 | 0.07 | 0.09 | 0.12 | 0.60 | **1.00** | | | | | | | | | | | | | |
| 9 | NitrogenBalance Rate | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | **1.00** | | | | | | | | | | | | |
| 10 | Soil resp no roots | 0.39 | 0.39 | 0.33 | 0.32 | 0.34 | 0.36 | 0.32 | 0.02 | 0.00 | **1.00** | | | | | | | | | | | |
| 11 | Soil respiration | 0.53 | 0.53 | 0.47 | 0.42 | 0.42 | 0.47 | 0.56 | 0.27 | 0.01 | **0.90** | **1.00** | | | | | | | | | | |
| 12 | Total respiration | 0.58 | 0.61 | 0.49 | 0.43 | 0.46 | 0.50 | 0.66 | 0.41 | 0.01 | **0.80** | **0.97** | **1.00** | | | | | | | | | |
| 13 | Total Photosynt | 0.45 | 0.48 | 0.36 | 0.32 | 0.35 | 0.39 | 0.75 | **0.80** | 0.01 | 0.54 | 0.78 | **0.88** | **1.00** | | | | | | | | |
| 14 | Snowdepth | -0.20 | -0.18 | -0.19 | -0.16 | -0.15 | -0.17 | -0.36 | -0.25 | 0.01 | -0.13 | -0.24 | -0.29 | -0.32 | **1.00** | | | | | | | |
| 15 | Precipitation | 0.03 | 0.04 | 0.01 | 0.00 | 0.02 | 0.02 | 0.08 | 0.03 | -0.01 | 0.05 | 0.07 | 0.08 | 0.06 | 0.05 | **1.00** | | | | | | |
| 16 | Air temp | 0.12 | 0.11 | 0.12 | 0.08 | 0.03 | 0.07 | 0.71 | 0.55 | 0.01 | 0.15 | 0.39 | 0.50 | 0.62 | -0.49 | 0.00 | **1.00** | | | | | |
| 17 | Soil temp 5cm | 0.34 | 0.32 | 0.32 | 0.27 | 0.20 | 0.26 | 0.74 | 0.58 | 0.02 | 0.43 | 0.74 | **0.81** | **0.84** | -0.36 | 0.06 | 0.75 | **1.00** | | | | |
| 18 | Soil temp 25cm | 0.37 | 0.35 | 0.34 | 0.28 | 0.21 | 0.27 | 0.70 | 0.50 | 0.02 | 0.43 | 0.74 | **0.81** | 0.79 | -0.36 | 0.06 | 0.71 | **0.98** | **1.00** | | | |
| 19 | Soil temp 50cm | 0.40 | 0.38 | 0.37 | 0.30 | 0.22 | 0.28 | 0.63 | 0.39 | 0.02 | 0.39 | 0.70 | 0.77 | 0.71 | -0.35 | 0.05 | 0.66 | **0.93** | **0.98** | **1.00** | | |
| 20 | Soil vol.wat cont 5cm | -0.40 | -0.37 | -0.38 | -0.38 | -0.39 | -0.40 | -0.23 | -0.19 | -0.03 | 0.18 | -0.02 | -0.11 | -0.18 | 0.18 | 0.17 | -0.19 | -0.24 | -0.25 | -0.27 | **1.00** | |
| 21 | Soil vol.wat cont 25cm | -0.59 | -0.56 | -0.54 | -0.52 | -0.57 | -0.58 | -0.35 | -0.21 | -0.01 | -0.07 | -0.27 | -0.35 | -0.34 | 0.28 | -0.01 | -0.30 | -0.41 | -0.43 | -0.45 | 0.70 | **1.00** |
| 22 | Soil vol.wat cont 50cm | -0.73 | -0.71 | -0.65 | -0.62 | -0.70 | -0.70 | -0.38 | -0.17 | 0.00 | -0.25 | -0.42 | -0.49 | -0.42 | 0.27 | -0.03 | -0.27 | -0.43 | -0.47 | -0.51 | 0.56 | **0.87** |

## P8 – Forest

| | Variable | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | C total plant | **1.00** | | | | | | | | | | | | | | | | | | | | |
| 2 | C Total Plant AboveG | **0.94** | **1.00** | | | | | | | | | | | | | | | | | | | |
| 3 | C Total Roots | **0.94** | 0.76 | **1.00** | | | | | | | | | | | | | | | | | | |
| 4 | CTotSoil Humus | **0.88** | 0.68 | **0.96** | **1.00** | | | | | | | | | | | | | | | | | |
| 5 | CTotSoil Litter1 | **0.92** | **0.87** | **0.86** | **0.82** | **1.00** | | | | | | | | | | | | | | | | |
| 6 | CTotSoilOrg | **0.95** | **0.87** | **0.91** | **0.89** | **0.98** | **1.00** | | | | | | | | | | | | | | | |
| 7 | Evapo-transpiration | 0.40 | 0.39 | 0.36 | 0.32 | 0.32 | 0.36 | **1.00** | | | | | | | | | | | | | | |
| 8 | Carbon Balance Rate | 0.15 | 0.17 | 0.11 | 0.11 | 0.14 | 0.18 | 0.57 | **1.00** | | | | | | | | | | | | | |
| 9 | NitrogenBalance Rate | -0.07 | -0.06 | -0.06 | -0.07 | -0.05 | -0.06 | -0.02 | 0.09 | **1.00** | | | | | | | | | | | | |
| 10 | Soil resp no roots | 0.40 | 0.40 | 0.36 | 0.34 | 0.35 | 0.38 | 0.36 | 0.09 | -0.23 | **1.00** | | | | | | | | | | | |
| 11 | Soil respiration | 0.56 | 0.54 | 0.51 | 0.46 | 0.43 | 0.49 | 0.57 | 0.29 | -0.18 | **0.91** | **1.00** | | | | | | | | | | |
| 12 | Total respiration | 0.60 | 0.61 | 0.52 | 0.47 | 0.48 | 0.53 | 0.66 | 0.41 | -0.15 | **0.82** | **0.98** | **1.00** | | | | | | | | | |
| 13 | Total Photosynt | 0.48 | 0.50 | 0.41 | 0.37 | 0.40 | 0.45 | 0.74 | 0.79 | -0.05 | 0.60 | **0.81** | **0.89** | **1.00** | | | | | | | | |
| 14 | Snowdepth | -0.19 | -0.18 | -0.18 | -0.17 | -0.15 | -0.17 | -0.37 | -0.24 | 0.02 | -0.14 | -0.24 | -0.29 | -0.32 | **1.00** | | | | | | | |
| 15 | Precipitation | 0.02 | 0.04 | 0.01 | 0.00 | 0.02 | 0.02 | 0.10 | 0.03 | 0.00 | 0.06 | 0.07 | 0.07 | 0.07 | 0.05 | **1.00** | | | | | | |
| 16 | Air temp | 0.12 | 0.10 | 0.12 | 0.09 | 0.04 | 0.07 | 0.71 | 0.52 | 0.01 | 0.17 | 0.39 | 0.49 | 0.60 | -0.48 | 0.00 | **1.00** | | | | | |
| 17 | Soil temp 5cm | 0.39 | 0.38 | 0.36 | 0.31 | 0.26 | 0.32 | 0.73 | 0.56 | -0.01 | 0.48 | 0.76 | **0.83** | **0.85** | -0.36 | 0.06 | 0.73 | **1.00** | | | | |
| 18 | Soil temp 25cm | 0.46 | 0.45 | 0.42 | 0.35 | 0.28 | 0.33 | 0.65 | 0.38 | -0.02 | 0.46 | 0.76 | **0.82** | 0.75 | -0.35 | 0.05 | 0.64 | **0.95** | **1.00** | | | |
| 19 | Soil temp 50cm | 0.57 | 0.56 | 0.52 | 0.43 | 0.36 | 0.41 | 0.51 | 0.18 | -0.03 | 0.40 | 0.68 | 0.73 | 0.58 | -0.32 | 0.04 | 0.49 | 0.79 | **0.93** | **1.00** | | |
| 20 | Soil vol.wat cont 5cm | -0.43 | -0.41 | -0.40 | -0.39 | -0.44 | -0.44 | -0.21 | -0.15 | -0.15 | 0.08 | -0.09 | -0.16 | -0.19 | 0.15 | 0.14 | -0.14 | -0.25 | -0.28 | -0.32 | **1.00** | |
| 21 | Soil vol.wat cont 25cm | -0.64 | -0.62 | -0.57 | -0.55 | -0.67 | -0.66 | -0.33 | -0.21 | -0.10 | -0.10 | -0.28 | -0.37 | -0.36 | 0.26 | -0.01 | -0.26 | -0.40 | -0.42 | -0.47 | 0.69 | **1.00** |
| 22 | Soil vol.wat cont 50cm | -0.68 | -0.67 | -0.61 | -0.57 | -0.68 | -0.68 | -0.39 | -0.21 | -0.06 | -0.23 | -0.40 | -0.48 | -0.43 | 0.27 | -0.02 | -0.30 | -0.48 | -0.52 | -0.58 | 0.67 | **0.91** |

Appendix 3. Correlation matrixes of the climate change simulations. In all tables, red values were statistically significant ($p<0.05$) and bold values had a strong relationship between the variables ($r^2>0.8$, n=33 236).

## CLM – Forest

| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Soil temp 5cm | **1.00** | | | | | | | | | | | | | | | | | | | | |
| 2 | Soil temp 25cm | **0.99** | **1.00** | | | | | | | | | | | | | | | | | | | |
| 3 | Soil temp 50cm | **0.94** | **0.98** | **1.00** | | | | | | | | | | | | | | | | | | |
| 4 | Soil vol.wat cont 5cm | -0.45 | -0.47 | -0.49 | **1.00** | | | | | | | | | | | | | | | | | |
| 5 | Soil vol.wat cont 25cm | -0.45 | -0.48 | -0.52 | 0.79 | **1.00** | | | | | | | | | | | | | | | | |
| 6 | Soil vol.wat cont 50cm | -0.44 | -0.48 | -0.53 | 0.68 | **0.92** | **1.00** | | | | | | | | | | | | | | | |
| 7 | C Plant AboveGround (1) | 0.13 | 0.14 | 0.15 | -0.20 | -0.27 | -0.30 | **1.00** | | | | | | | | | | | | | | |
| 8 | C Plant Roots (1) | 0.15 | 0.17 | 0.19 | -0.21 | -0.28 | -0.32 | **1.00** | **1.00** | | | | | | | | | | | | | |
| 9 | C total plant | 0.14 | 0.15 | 0.17 | -0.21 | -0.28 | -0.31 | **1.00** | **1.00** | **1.00** | | | | | | | | | | | | |
| 10 | C Total Plant AboveG | 0.13 | 0.14 | 0.15 | -0.20 | -0.27 | -0.30 | **1.00** | **0.99** | **1.00** | **1.00** | | | | | | | | | | | |
| 11 | C Total Roots | 0.16 | 0.17 | 0.19 | -0.21 | -0.28 | -0.32 | **1.00** | **1.00** | **1.00** | **0.99** | **1.00** | | | | | | | | | | |
| 12 | CTotSoil Humus | -0.13 | -0.14 | -0.15 | 0.20 | 0.27 | 0.30 | **-0.98** | **-0.99** | **-0.98** | **-0.98** | **-0.99** | **1.00** | | | | | | | | | |
| 13 | CTotSoil Litter1 | -0.53 | -0.51 | -0.47 | 0.05 | -0.01 | -0.03 | 0.38 | 0.37 | 0.38 | 0.38 | 0.37 | -0.35 | **1.00** | | | | | | | | |
| 14 | CTotSoilOrg | -0.18 | -0.18 | -0.19 | 0.21 | 0.27 | 0.31 | **-0.97** | **-0.98** | **-0.98** | **-0.97** | **-0.98** | **1.00** | -0.28 | **1.00** | | | | | | | |
| 15 | Evapo-transpiration | 0.78 | 0.76 | 0.72 | -0.47 | -0.41 | -0.39 | 0.26 | 0.28 | 0.27 | 0.25 | 0.28 | -0.27 | -0.31 | -0.30 | **1.00** | | | | | | |
| 16 | Soil resp no roots | 0.38 | 0.39 | 0.35 | 0.36 | 0.21 | 0.11 | -0.03 | -0.02 | -0.03 | -0.03 | -0.02 | 0.05 | -0.15 | 0.04 | 0.13 | **1.00** | | | | | |
| 17 | Soil respiration | **0.89** | **0.87** | **0.81** | -0.16 | -0.21 | -0.24 | 0.09 | 0.11 | 0.10 | 0.09 | 0.11 | -0.08 | -0.48 | -0.12 | 0.62 | 0.70 | **1.00** | | | | |
| 18 | Total Photosynt | 0.65 | 0.55 | 0.42 | -0.10 | -0.08 | -0.07 | -0.01 | -0.02 | -0.01 | -0.01 | -0.02 | 0.00 | -0.50 | -0.04 | 0.48 | 0.36 | 0.75 | **1.00** | | | |
| 19 | Total respiration | **0.93** | **0.89** | **0.81** | -0.27 | -0.28 | -0.28 | 0.14 | 0.15 | 0.15 | 0.15 | 0.16 | -0.14 | -0.49 | -0.18 | 0.71 | 0.55 | **0.97** | **0.80** | **1.00** | | |
| 20 | Snow depth | -0.28 | -0.28 | -0.27 | 0.17 | 0.15 | 0.14 | -0.11 | -0.12 | -0.11 | -0.11 | -0.12 | 0.11 | 0.10 | 0.12 | -0.23 | -0.11 | -0.27 | -0.24 | -0.29 | **1.00** | |
| 21 | Precipitation | 0.03 | 0.03 | 0.02 | 0.33 | 0.08 | 0.03 | -0.02 | -0.02 | -0.02 | -0.02 | -0.02 | 0.02 | -0.04 | 0.02 | 0.07 | 0.12 | 0.07 | 0.05 | 0.05 | 0.06 | **1.00** |
| 22 | Air temp | **0.84** | **0.82** | 0.78 | -0.49 | -0.40 | -0.38 | 0.15 | 0.18 | 0.16 | 0.15 | 0.18 | -0.16 | -0.39 | -0.20 | 0.78 | 0.16 | 0.67 | 0.51 | 0.76 | -0.35 | -0.08 |

## CLM – Grassland

| | Variable | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Soil temp 5cm | **1.00** | | | | | | | | | | | | | | | | | | | | |
| 2 | Soil temp 25cm | **0.95** | **1.00** | | | | | | | | | | | | | | | | | | | |
| 3 | Soil temp 50cm | **0.83** | **0.95** | **1.00** | | | | | | | | | | | | | | | | | | |
| 4 | Soil vol.wat cont 5cm | -0.70 | -0.67 | -0.59 | **1.00** | | | | | | | | | | | | | | | | | |
| 5 | Soil vol.wat cont 25cm | -0.71 | -0.75 | -0.73 | **0.85** | **1.00** | | | | | | | | | | | | | | | | |
| 6 | Soil vol.wat cont 50cm | -0.60 | -0.69 | -0.73 | 0.70 | **0.91** | **1.00** | | | | | | | | | | | | | | | |
| 7 | C Plant AboveGround (1) | -0.09 | -0.10 | -0.11 | 0.06 | 0.12 | 0.14 | **1.00** | | | | | | | | | | | | | | |
| 8 | C Plant Roots (1) | 0.00 | 0.00 | 0.01 | 0.05 | 0.08 | 0.09 | 0.61 | **1.00** | | | | | | | | | | | | | |
| 9 | C total plant | 0.37 | 0.49 | 0.59 | -0.29 | -0.40 | -0.44 | 0.07 | -0.09 | **1.00** | | | | | | | | | | | | |
| 10 | C Total Plant AboveG | 0.15 | 0.21 | 0.27 | -0.15 | -0.22 | -0.25 | -0.04 | -0.38 | **0.86** | **1.00** | | | | | | | | | | | |
| 11 | C Total Roots | 0.50 | 0.63 | 0.75 | -0.33 | -0.45 | -0.48 | 0.19 | 0.35 | 0.71 | 0.25 | **1.00** | | | | | | | | | | |
| 12 | CTotSoil Humus | 0.19 | 0.21 | 0.24 | -0.16 | -0.24 | -0.28 | -0.56 | -0.37 | 0.41 | 0.54 | 0.02 | **1.00** | | | | | | | | | |
| 13 | CTotSoil Litter1 | -0.11 | -0.04 | 0.07 | -0.04 | -0.15 | -0.26 | 0.16 | -0.16 | 0.61 | 0.72 | 0.17 | 0.46 | **1.00** | | | | | | | | |
| 14 | CTotSoilOrg | 0.18 | 0.21 | 0.23 | -0.16 | -0.25 | -0.29 | -0.52 | -0.37 | 0.44 | 0.58 | 0.03 | **1.00** | 0.52 | **1.00** | | | | | | | |
| 15 | Evapo-transpiration | **0.80** | 0.68 | 0.48 | -0.50 | -0.44 | -0.30 | -0.03 | -0.01 | 0.13 | 0.04 | 0.19 | 0.09 | -0.22 | 0.09 | **1.00** | | | | | | |
| 16 | Soil resp no roots | 0.10 | 0.12 | 0.14 | 0.40 | 0.26 | 0.14 | 0.10 | 0.01 | 0.28 | 0.26 | 0.18 | 0.12 | 0.22 | 0.13 | 0.15 | **1.00** | | | | | |
| 17 | Soil respiration | 0.47 | 0.36 | 0.20 | -0.14 | -0.11 | -0.06 | 0.05 | 0.12 | 0.07 | 0.08 | 0.03 | 0.22 | -0.06 | 0.22 | 0.57 | 0.39 | **1.00** | | | | |
| 18 | Total Photosynt | 0.19 | 0.02 | -0.16 | -0.04 | 0.06 | 0.14 | -0.01 | 0.02 | -0.26 | -0.09 | -0.36 | 0.15 | -0.16 | 0.15 | 0.41 | 0.10 | **0.86** | **1.00** | | | |
| 19 | Total respiration | 0.54 | 0.40 | 0.21 | -0.28 | -0.21 | -0.12 | -0.01 | 0.03 | 0.05 | 0.09 | -0.04 | 0.26 | -0.07 | 0.26 | 0.63 | 0.21 | **0.97** | **0.88** | **1.00** | | |
| 20 | Snow depth | -0.26 | -0.24 | -0.21 | 0.14 | 0.13 | 0.11 | 0.05 | 0.02 | -0.12 | -0.08 | -0.11 | -0.12 | -0.01 | -0.11 | -0.27 | -0.10 | -0.22 | -0.16 | -0.24 | **1.00** | |
| 21 | Precipitation | 0.00 | 0.01 | 0.00 | 0.29 | 0.12 | 0.07 | 0.02 | 0.01 | -0.01 | -0.02 | 0.00 | -0.03 | -0.02 | -0.03 | 0.11 | 0.10 | 0.04 | 0.02 | 0.03 | 0.06 | **1.00** |
| 22 | Air temp | **0.90** | 0.80 | 0.66 | -0.67 | -0.63 | -0.51 | -0.10 | -0.05 | 0.31 | 0.15 | 0.37 | 0.21 | -0.07 | 0.21 | 0.77 | 0.01 | 0.43 | 0.24 | 0.54 | -0.34 | -0.08 |

## RCA – Forest

| | Variable | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Soil temp 5cm | **1.00** | | | | | | | | | | | | | | | | | | | | |
| 2 | Soil temp 25cm | **0.99** | **1.00** | | | | | | | | | | | | | | | | | | | |
| 3 | Soil temp 50cm | **0.94** | **0.98** | **1.00** | | | | | | | | | | | | | | | | | | |
| 4 | Soil vol.wat cont 5cm | -0.35 | -0.38 | -0.41 | **1.00** | | | | | | | | | | | | | | | | | |
| 5 | Soil vol.wat cont 25cm | -0.34 | -0.37 | -0.41 | 0.74 | **1.00** | | | | | | | | | | | | | | | | |
| 6 | Soil vol.wat cont 50cm | -0.35 | -0.38 | -0.42 | 0.61 | **0.91** | **1.00** | | | | | | | | | | | | | | | |
| 7 | C Plant AboveGround (1) | 0.15 | 0.16 | 0.17 | -0.12 | -0.23 | -0.28 | **1.00** | | | | | | | | | | | | | | |
| 8 | C Plant Roots (1) | 0.17 | 0.18 | 0.20 | -0.13 | -0.24 | -0.29 | **1.00** | **1.00** | | | | | | | | | | | | | |
| 9 | C total plant | 0.16 | 0.17 | 0.19 | -0.12 | -0.23 | -0.29 | **1.00** | **1.00** | **1.00** | | | | | | | | | | | | |
| 10 | C Total Plant AboveG | 0.15 | 0.16 | 0.17 | -0.12 | -0.23 | -0.28 | **1.00** | **1.00** | **1.00** | **1.00** | | | | | | | | | | | |
| 11 | C Total Roots | 0.17 | 0.19 | 0.20 | -0.13 | -0.24 | -0.29 | **1.00** | **1.00** | **1.00** | **1.00** | **1.00** | | | | | | | | | | |
| 12 | CTotSoil Humus | -0.15 | -0.16 | -0.17 | 0.12 | 0.22 | 0.27 | **-0.97** | **-0.97** | **-0.97** | **-0.97** | **-0.97** | **1.00** | | | | | | | | | |
| 13 | CTotSoil Litter1 | -0.44 | -0.43 | -0.39 | 0.03 | -0.13 | -0.18 | 0.37 | 0.35 | 0.37 | 0.38 | 0.35 | -0.32 | **1.00** | | | | | | | | |
| 14 | CTotSoilOrg | -0.22 | -0.23 | -0.23 | 0.13 | 0.21 | 0.25 | **-0.95** | **-0.95** | **-0.95** | **-0.95** | **-0.95** | **0.99** | -0.17 | **1.00** | | | | | | | |
| 15 | Evapo-transpiration | 0.74 | 0.73 | 0.70 | -0.27 | -0.29 | -0.29 | 0.25 | 0.27 | 0.26 | 0.25 | 0.27 | -0.27 | -0.27 | -0.32 | **1.00** | | | | | | |
| 16 | Soil resp no roots | 0.39 | 0.39 | 0.34 | 0.44 | 0.28 | 0.16 | 0.04 | 0.05 | 0.05 | 0.04 | 0.05 | -0.02 | -0.08 | -0.03 | 0.26 | **1.00** | | | | | |
| 17 | Soil respiration | **0.89** | **0.87** | **0.81** | -0.06 | -0.11 | -0.17 | 0.15 | 0.16 | 0.15 | 0.15 | 0.16 | -0.13 | -0.35 | -0.19 | 0.64 | 0.73 | **1.00** | | | | |
| 18 | Total Photosynt | 0.71 | 0.62 | 0.49 | -0.08 | -0.08 | -0.08 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | -0.04 | -0.43 | -0.10 | 0.54 | 0.37 | 0.75 | **1.00** | | | |
| 19 | Total respiration | **0.93** | **0.90** | **0.83** | -0.14 | -0.18 | -0.22 | 0.20 | 0.21 | 0.20 | 0.20 | 0.21 | -0.18 | -0.36 | -0.24 | 0.69 | 0.60 | **0.98** | **0.81** | **1.00** | | |
| 20 | Snow depth | -0.19 | -0.18 | -0.17 | 0.00 | 0.05 | 0.06 | -0.09 | -0.10 | -0.10 | -0.09 | -0.10 | 0.09 | 0.07 | 0.11 | -0.16 | -0.09 | -0.18 | -0.17 | -0.20 | **1.00** | |
| 21 | Precipitation | 0.04 | 0.02 | 0.01 | 0.37 | 0.10 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | -0.01 | 0.00 | 0.13 | 0.16 | 0.09 | 0.08 | 0.08 | -0.03 | **1.00** |
| 22 | Air temp | **0.87** | **0.85** | **0.81** | -0.29 | -0.31 | -0.32 | 0.15 | 0.18 | 0.16 | 0.15 | 0.18 | -0.16 | -0.36 | -0.22 | 0.68 | 0.25 | 0.71 | 0.58 | 0.79 | -0.27 | 0.11 |

## RCA – Grassland

| | Variable | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Soil temp 5cm | **1.00** | | | | | | | | | | | | | | | | | | | | |
| 2 | Soil temp 25cm | **0.96** | **1.00** | | | | | | | | | | | | | | | | | | | |
| 3 | Soil temp 50cm | **0.83** | **0.95** | **1.00** | | | | | | | | | | | | | | | | | | |
| 4 | Soil vol.wat cont 5cm | -0.48 | -0.50 | -0.45 | **1.00** | | | | | | | | | | | | | | | | | |
| 5 | Soil vol.wat cont 25cm | -0.66 | -0.70 | -0.68 | 0.78 | **1.00** | | | | | | | | | | | | | | | | |
| 6 | Soil vol.wat cont 50cm | -0.56 | -0.63 | -0.67 | 0.63 | **0.91** | **1.00** | | | | | | | | | | | | | | | |
| 7 | C Plant AboveGround (1) | -0.09 | -0.10 | -0.10 | -0.02 | 0.06 | 0.06 | **1.00** | | | | | | | | | | | | | | |
| 8 | C Plant Roots (1) | -0.01 | 0.00 | 0.00 | 0.00 | 0.05 | 0.06 | 0.61 | **1.00** | | | | | | | | | | | | | |
| 9 | C total plant | 0.39 | 0.50 | 0.60 | -0.20 | -0.37 | -0.41 | 0.06 | -0.09 | **1.00** | | | | | | | | | | | | |
| 10 | C Total Plant AboveG | 0.14 | 0.20 | 0.26 | -0.08 | -0.18 | -0.21 | -0.09 | -0.42 | **0.83** | **1.00** | | | | | | | | | | | |
| 11 | C Total Roots | 0.50 | 0.63 | 0.74 | -0.24 | -0.43 | -0.46 | 0.22 | 0.37 | 0.73 | 0.23 | **1.00** | | | | | | | | | | |
| 12 | CTotSoil Humus | 0.19 | 0.21 | 0.23 | -0.04 | -0.16 | -0.19 | -0.55 | -0.37 | 0.29 | 0.44 | -0.03 | **1.00** | | | | | | | | | |
| 13 | CTotSoil Litter1 | -0.18 | -0.14 | -0.05 | 0.01 | -0.06 | -0.18 | 0.39 | -0.09 | 0.48 | 0.60 | 0.11 | 0.10 | **1.00** | | | | | | | | |
| 14 | CTotSoilOrg | 0.18 | 0.21 | 0.23 | -0.05 | -0.17 | -0.21 | -0.52 | -0.37 | 0.32 | 0.48 | -0.03 | **1.00** | 0.17 | **1.00** | | | | | | | |
| 15 | Evapo-transpiration | 0.78 | 0.67 | 0.47 | -0.33 | -0.42 | -0.27 | -0.03 | -0.01 | 0.14 | 0.03 | 0.21 | 0.06 | -0.25 | 0.06 | **1.00** | | | | | | |
| 16 | Soil resp no roots | 0.20 | 0.20 | 0.17 | 0.49 | 0.29 | 0.19 | 0.07 | 0.01 | 0.26 | 0.19 | 0.22 | 0.05 | 0.12 | 0.06 | 0.26 | **1.00** | | | | | |
| 17 | Soil respiration | 0.52 | 0.42 | 0.27 | -0.01 | -0.11 | -0.04 | -0.02 | 0.11 | 0.07 | 0.04 | 0.08 | 0.23 | -0.20 | 0.23 | 0.59 | 0.44 | **1.00** | | | | |
| 18 | Total Photosynt | 0.23 | 0.08 | -0.09 | 0.00 | 0.02 | 0.12 | -0.09 | 0.01 | -0.26 | -0.11 | -0.32 | 0.21 | -0.25 | 0.20 | 0.42 | 0.11 | **0.86** | **1.00** | | | |
| 19 | Total respiration | 0.57 | 0.44 | 0.26 | -0.13 | -0.20 | -0.10 | -0.08 | 0.02 | 0.03 | 0.05 | -0.01 | 0.27 | -0.22 | 0.27 | 0.64 | 0.28 | **0.97** | **0.90** | **1.00** | | |
| 20 | Snow depth | -0.20 | -0.17 | -0.14 | 0.01 | 0.10 | 0.09 | 0.04 | 0.04 | -0.12 | -0.08 | -0.11 | -0.10 | -0.01 | -0.10 | -0.20 | -0.12 | -0.18 | -0.12 | -0.19 | **1.00** | |
| 21 | Precipitation | 0.06 | 0.02 | 0.00 | 0.30 | 0.12 | 0.08 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | -0.01 | 0.01 | -0.01 | 0.16 | 0.15 | 0.07 | 0.04 | 0.05 | -0.04 | **1.00** |
| 22 | Air temp | **0.91** | **0.81** | 0.67 | -0.42 | -0.59 | -0.49 | -0.10 | -0.05 | 0.30 | 0.13 | 0.38 | 0.20 | -0.16 | 0.20 | 0.76 | 0.13 | 0.48 | 0.27 | 0.56 | -0.29 | 0.11 |

## REGCM3 – Forest

| | Variable | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Soil temp 5cm | **1.00** | | | | | | | | | | | | | | | | | | | | |
| 2 | Soil temp 25cm | **0.99** | **1.00** | | | | | | | | | | | | | | | | | | | |
| 3 | Soil temp 50cm | **0.94** | **0.98** | **1.00** | | | | | | | | | | | | | | | | | | |
| 4 | Soil vol.wat cont 5cm | -0.63 | -0.65 | -0.65 | **1.00** | | | | | | | | | | | | | | | | | |
| 5 | Soil vol.wat cont 25cm | -0.67 | -0.70 | -0.73 | **0.85** | **1.00** | | | | | | | | | | | | | | | | |
| 6 | Soil vol.wat cont 50cm | -0.63 | -0.67 | -0.71 | 0.76 | **0.94** | **1.00** | | | | | | | | | | | | | | | |
| 7 | C Plant AboveGround (1) | 0.12 | 0.13 | 0.14 | -0.16 | -0.20 | -0.22 | **1.00** | | | | | | | | | | | | | | |
| 8 | C Plant Roots (1) | 0.14 | 0.15 | 0.17 | -0.18 | -0.22 | -0.24 | **1.00** | **1.00** | | | | | | | | | | | | | |
| 9 | C total plant | 0.13 | 0.14 | 0.15 | -0.17 | -0.22 | -0.23 | **1.00** | **1.00** | **1.00** | | | | | | | | | | | | |
| 10 | C Total Plant AboveG | 0.12 | 0.12 | 0.14 | -0.16 | -0.21 | -0.22 | **1.00** | **0.99** | **1.00** | **1.00** | | | | | | | | | | | |
| 11 | C Total Roots | 0.14 | 0.16 | 0.17 | -0.18 | -0.23 | -0.24 | **1.00** | **1.00** | **1.00** | **0.99** | **1.00** | | | | | | | | | | |
| 12 | CTotSoil Humus | -0.12 | -0.13 | -0.14 | 0.15 | 0.19 | 0.20 | **-0.97** | **-0.97** | **-0.97** | **-0.97** | **-0.97** | **1.00** | | | | | | | | | |
| 13 | CTotSoil Litter1 | -0.45 | -0.41 | -0.34 | 0.17 | 0.12 | 0.08 | 0.47 | 0.46 | 0.47 | 0.48 | 0.46 | -0.39 | **1.00** | | | | | | | | |
| 14 | CTotSoilOrg | -0.17 | -0.18 | -0.18 | 0.17 | 0.21 | 0.22 | **-0.96** | **-0.96** | **-0.96** | **-0.96** | **-0.96** | **0.99** | -0.29 | **1.00** | | | | | | | |
| 15 | Evapo-transpiration | 0.76 | 0.73 | 0.68 | -0.51 | -0.52 | -0.48 | 0.23 | 0.25 | 0.24 | 0.23 | 0.25 | -0.24 | -0.29 | -0.28 | **1.00** | | | | | | |
| 16 | Soil resp no roots | 0.22 | 0.23 | 0.21 | 0.36 | 0.16 | 0.07 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | -0.02 | 0.09 | -0.01 | 0.09 | **1.00** | | | | | |
| 17 | Soil respiration | **0.87** | **0.85** | 0.78 | -0.35 | -0.44 | -0.45 | 0.14 | 0.15 | 0.14 | 0.14 | 0.15 | -0.12 | -0.33 | -0.16 | 0.63 | 0.57 | **1.00** | | | | |
| 18 | Total Photosynt | 0.63 | 0.54 | 0.41 | -0.29 | -0.29 | -0.25 | -0.01 | -0.02 | -0.01 | -0.01 | -0.02 | 0.00 | -0.50 | -0.05 | 0.51 | 0.17 | 0.74 | **1.00** | | | |
| 19 | Total respiration | **0.91** | **0.87** | 0.79 | -0.45 | -0.50 | -0.48 | 0.18 | 0.19 | 0.19 | 0.18 | 0.19 | -0.17 | -0.37 | -0.22 | 0.71 | 0.40 | **0.97** | **0.80** | **1.00** | | |
| 20 | Snow depth | -0.31 | -0.31 | -0.29 | 0.25 | 0.27 | 0.26 | -0.14 | -0.15 | -0.14 | -0.14 | -0.15 | 0.13 | 0.12 | 0.15 | -0.25 | -0.05 | -0.30 | -0.27 | -0.32 | **1.00** | |
| 21 | Precipitation | 0.01 | 0.02 | 0.02 | 0.29 | 0.06 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.04 | 0.16 | 0.07 | 0.01 | 0.04 | 0.08 | **1.00** |
| 22 | Air temp | **0.86** | **0.84** | 0.79 | -0.58 | -0.56 | -0.52 | 0.12 | 0.14 | 0.13 | 0.11 | 0.14 | -0.12 | -0.36 | -0.16 | 0.73 | 0.08 | 0.69 | 0.55 | 0.78 | -0.36 | -0.10 |

## REGCM3 – Grassland

| | Variable | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Soil temp 5cm | **1.00** | | | | | | | | | | | | | | | | | | | | |
| 2 | Soil temp 25cm | **0.96** | **1.00** | | | | | | | | | | | | | | | | | | | |
| 3 | Soil temp 50cm | **0.83** | **0.95** | **1.00** | | | | | | | | | | | | | | | | | | |
| 4 | Soil vol.wat cont 5cm | -0.70 | -0.66 | -0.55 | **1.00** | | | | | | | | | | | | | | | | | |
| 5 | Soil vol.wat cont 25cm | -0.74 | -0.75 | -0.69 | **0.84** | **1.00** | | | | | | | | | | | | | | | | |
| 6 | Soil vol.wat cont 50cm | -0.66 | -0.72 | -0.71 | 0.70 | **0.91** | **1.00** | | | | | | | | | | | | | | | |
| 7 | C Plant AboveGround (1) | -0.06 | -0.06 | -0.06 | -0.01 | 0.02 | 0.01 | **1.00** | | | | | | | | | | | | | | |
| 8 | C Plant Roots (1) | 0.02 | 0.04 | 0.05 | 0.02 | 0.04 | 0.03 | 0.61 | **1.00** | | | | | | | | | | | | | |
| 9 | C total plant | 0.34 | 0.45 | 0.55 | -0.23 | -0.31 | -0.35 | 0.19 | 0.05 | **1.00** | | | | | | | | | | | | |
| 10 | C Total Plant AboveG | 0.09 | 0.14 | 0.19 | -0.10 | -0.14 | -0.16 | 0.07 | -0.32 | **0.82** | **1.00** | | | | | | | | | | | |
| 11 | C Total Roots | 0.47 | 0.60 | 0.72 | -0.27 | -0.36 | -0.40 | 0.25 | 0.45 | 0.76 | 0.25 | **1.00** | | | | | | | | | | |
| 12 | CTotSoil Humus | 0.14 | 0.15 | 0.17 | -0.06 | -0.10 | -0.11 | -0.64 | -0.40 | 0.07 | 0.17 | -0.09 | **1.00** | | | | | | | | | |
| 13 | CTotSoil Litter1 | -0.20 | -0.16 | -0.08 | 0.04 | -0.01 | -0.10 | 0.55 | 0.02 | 0.54 | 0.67 | 0.14 | -0.16 | **1.00** | | | | | | | | |
| 14 | CTotSoilOrg | 0.14 | 0.15 | 0.16 | -0.06 | -0.11 | -0.13 | -0.60 | -0.40 | 0.11 | 0.23 | -0.08 | **1.00** | -0.08 | **1.00** | | | | | | | |
| 15 | Evapo-transpiration | **0.83** | 0.72 | 0.52 | -0.56 | -0.53 | -0.42 | -0.02 | 0.01 | 0.14 | 0.01 | 0.22 | 0.05 | -0.24 | 0.05 | **1.00** | | | | | | |
| 16 | Soil resp no roots | 0.23 | 0.26 | 0.28 | 0.30 | 0.14 | 0.02 | 0.14 | 0.07 | 0.35 | 0.25 | 0.31 | 0.00 | 0.18 | 0.01 | 0.23 | **1.00** | | | | | |
| 17 | Soil respiration | 0.49 | 0.40 | 0.27 | -0.18 | -0.18 | -0.14 | 0.06 | 0.18 | 0.02 | -0.07 | 0.11 | 0.11 | -0.19 | 0.11 | 0.55 | 0.37 | **1.00** | | | | |
| 18 | Total Photosynt | 0.21 | 0.07 | -0.09 | -0.09 | -0.01 | 0.06 | -0.03 | 0.04 | -0.31 | -0.22 | -0.28 | 0.11 | -0.26 | 0.10 | 0.38 | 0.05 | **0.86** | **1.00** | | | |
| 19 | Total respiration | 0.55 | 0.43 | 0.26 | -0.30 | -0.26 | -0.19 | 0.00 | 0.09 | -0.03 | -0.06 | 0.02 | 0.15 | -0.22 | 0.15 | 0.62 | 0.23 | **0.97** | **0.89** | **1.00** | | |
| 20 | Snow depth | -0.29 | -0.27 | -0.23 | 0.16 | 0.17 | 0.16 | 0.04 | 0.00 | -0.08 | -0.01 | -0.12 | -0.12 | 0.07 | -0.12 | -0.32 | -0.11 | -0.24 | -0.17 | -0.26 | **1.00** | |
| 21 | Precipitation | -0.01 | 0.01 | 0.02 | 0.29 | 0.11 | 0.05 | -0.01 | 0.00 | 0.02 | 0.00 | 0.03 | 0.00 | 0.00 | 0.00 | 0.03 | 0.11 | 0.04 | 0.00 | 0.01 | 0.09 | **1.00** |
| 22 | Air temp | **0.90** | **0.80** | 0.67 | -0.64 | -0.63 | -0.54 | -0.08 | -0.01 | 0.26 | 0.08 | 0.35 | 0.15 | -0.18 | 0.15 | **0.82** | 0.17 | 0.46 | 0.26 | 0.54 | -0.38 | -0.10 |

# Personal declaration

I hereby declare that the submitted thesis is the result of my own, independent work.
All external sources are explicitly acknowledged in the thesis.

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