Universität Zürich[UZH]

Effects of CO_2 and Soil Characteristics as Drivers of Root Derived Carbon in Soils

GEO 511 Master Thesis

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Abstract

The terrestrial carbon pool is the largest sink of CO_2 and contains more carbon than vegetation and the atmosphere combined. Atmospheric CO_2 concentration is rising and leads to changes of carbon fluxes between the carbon pools. Root derived carbon in soil is more stable than shoot derived. Little is known about the variability of root derived carbon input into soils throughout soil depths and under changing physical and climatic soil properties. In order to investigate root derived carbon production and carbon input into soils, two experiments were conducted. Soil with different clay and soil organic carbon contents were sampled and filled up into 40 columns with a capacity of 319 cm^3. One barley seed was planted in each column. For experiment in the Multi Isotope labelling in a controlled Environment-facility (MICE-facility), 20 columns were placed in chamber 1 and 20 were placed in chamber two. Atmospheric CO_2 was elevated in chamber 2, according to the IPPC scenario of the year 2100. CO_2 in both chambers was labelled with ^{13}C isotope. The experiment in MICE was running for 42 days. When the MICE experiment was over, roots were picked from all columns. Rootless soil samples were used for the subsequent incubation experiment, in order to investigate decomposition of rhizodeposition. Incubation was running for 30 days.

Photosynthetic carbon assimilation increased with high atmospheric CO_2 levels and led to an increase of the above ground biomass but it did not lead to an increase on total root biomass. Where above ground biomass was low, root biomass was high and total amount of rhizodeposits accelerated too. Increased atmospheric CO_2 level might have led to easier decomposable rhizodeposits as the total amount of C CO_2 respired was higher in high CO_2 treatment soils. Furthermore, CO_2 as a driver had an amplifying effect on many significances within different measurements taken (above ground biomass, root biomass, root:shoot ratio, root biomass derived carbon, rhizodeposition, ratio of root biomass C to rhizodeposition C and C CO_2 respired after the incubation).

There was more root biomass and more root biomass derived carbon in low SBD treatments. In soil 2, where clay content and soil organic carbon concentration was higher than in soil 1, root biomass grew less and root biomass derived carbon was lower. The total amount of rhizodeposition was only significant for soil depths and decreased from top to bottom soil layer. However, the factors soil bulk density, CO_2 and soil types seem to control root activity regarding the exudation of rhizodeposits. Root activity was higher in soil type 2, high soil bulk density treatment and low CO_2 treatments. Further, high soil bulk density might have forced roots to excrete lower degradable material.

Overall, soil type 2 led to less root derived carbon input but carbon was more resilient in the soil. Low soil bulk density led to a very high root derived carbon input that was rather resilient than in high soil bulk density and high CO_2 treatments led to more root derived carbon but it was rather unstable. The most root derived carbon was found in top soil layers. The amount of total root derived carbon decreased from top to bottom.

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Abbreviations

AGB	Above ground biomass
C	Carbon
CO_2	Carbon dioxide
°C	Degree Celcius
^{13}C	Stable carbon isotope with atomic mass 13
ha	Hectare
MICE	Multi isotope labelling under controlled environment
MRT	Mean residence time
NaOH	Sodium hydroxide
PE	Priming effect
ppm	parts per million
PVC	Polyvinylchloride
SBD	Soil bulk density
SOC	Soil organic carbon
SOM	Soil organic matter
$SrCl_2$	Strontium chloride
TOC	Total organic carbon

1 Introduction

Soil contains more than twice as much carbon (C) as the vegetation and the atmosphere combined (Brady and Weil, 2016). It is the largest storage of terrestrial carbon, but also a source of carbon dioxide (CO_2) and thus plays an important role in the global carbon cycle (Ciais *et al.*, 2013; van Groenigen *et al.*, 2014). The concentration of carbon in form of CO_2 in the atmosphere is rising as a consequence of burning fossil fuels (Masson-Delmotte *et al.*, 2013; Tans, 2009; van Groenigen *et al.*, 2014). This is leading to changes in plant-soil interaction (van Groenigen *et al.*, 2014). Increased CO_2 may trigger plant growth and productivity, which leads to a higher plant derived soil organic matter (SOM) content in soils. On the other hand, rising levels of atmospheric CO_2 also stimulate soil microbial activity causing soil organic carbon (SOC) mineralisation and a higher rate soil respiration (Rustad *et al.*, 2001; van Groenigen *et al.*, 2014). While the carbon stocks of the ocean and the atmosphere are well defined and understood, little is known about the interaction between the storage and fluxes of the terrestrial carbon pool within the global carbon cycle (Scharlemann *et al.*, 2014). It is rather unclear how long-term storage of C will react to the mentioned climate change induced processes. This depends on the rate of SOM input and decomposition (Hagedorn *et al.*, 2010). Roots play a key role in this as up to 90% of the C induced into soil is root derived (Kätterer *et al.*, 2011). Root derived carbon is not only produced of the living roots, but also of carbon being excreted from living roots (i.e. rhizodeposition) (Jones *et al.*, 2004). Roots improve physical and chemical properties by rearranging and locally binding of soil particles (Pierret *et al.*, 2007). Soil aggregates can be stabilised by the cohesive effect of organic compounds (Boix-Fayos *et al.*, 2001). Soil conditions like a high soil bulk density (SBD) can influence root growth negatively (Huang *et al.*, 2012). Besides SBD, soil texture can affect root biomass as well. Nutrient availability is higher in fine-textured soils as clay is able to absorb them onto their mineral surfaces (Hassink, 1994; Jenny, 1941). Vuuren *et al.* (1997) state that plants with a higher nutrient demand could improve their potential to reach the available nutrients by increasing root biomass and root length. Thus, where nutrients are easily available, roots do not need to increase biomass and root length for nutrient acquisition (Shipley and Meziane, 2002).

This thesis mainly focuses on root-soil interaction under changing climate conditions. Several studies exist that target root and plant parameters (root architecture, plant performance, growth and morphology) under changing climate factors such as rising atmospheric CO_2 and higher temperature (Füllner *et al.*, 2012). Bolinder *et al.* (1997) conducted a study where they estimated the annual C input into soil according to the root to shoot ratio of a plant. Little is known about the variability of root derived C deposition through soil depths and the proportion of rhizodeposition from total root derived C input (Gale *et al.*, 2000; Jones *et al.*, 2004; Rasse *et al.*, 2005). This Master's thesis further targets on the influence of CO_2 as a climate factor on plant-soil interaction, specifically on root derived C deposition through soil depths with different properties regarding soil texture and SBD.

1.1 Dynamics and interactions of terrestrial carbon within the global carbon cycle

The global carbon cycle can be defined as a system consisting of different interacting carbon pools in the earth system. Interactions are happening by fluxes of C between the atmospheric, terrestrial and oceanic reservoirs (Ciais et al., 2013). The terrestrial reservoir is the largest and contains more than twice as much C as the ocean and the atmosphere reservoirs combined (Ciais *et al.*, 2013; van Groenigen *et al.*, 2014). Carbon is stored in soil either as organic or inorganic C. Soil organic matter (SOM) includes dead components such as decomposed plant material, crop residues, litter and dead roots, as well as living components like roots, animals, fungal matter and bacterial matter. In addition to that, living roots excrete carbon compounds which contain sugars, enzymes, amino and organic acids, and mucilage into the soil (Jones *et al.*, 2004; Scharlemann *et al.*, 2014). Soil organic carbon (SOC) refers to the carbon fraction of SOM and functions as C sink in soil (Brady and Weil, 2016; Kong *et al.*, 2005). The geographical location of the soil and soil depth below surface have a major impact on the concentration of SOM (Blume *et al.*, 2010). Recent research state that C content in SOM ranges from 51 to 62% (Pribyl, 2010).

However, C efflux from the soil to the atmosphere is one of the largest fluxes in the entire global carbon cycle (Schlesinger and Andrews, 2000). At this point, several studies suggest that the carbon input and storage exceeds the efflux on a global scale and that the terrestrial C reservoir will increase in a short term perspective (Ciais *et al.*, 2013; Jones *et al.*, 2005; van Groenigen *et al.*, 2014).

Some SOM remains in soils for thousands of years while other SOM decomposes easily (Schmidt *et al.*, 2011).

1.2 Roots and rhizosphere dynamics within the terrestrial carbon cycle

Roots and roots exudates play a crucial role in terrestrial carbon cycle dynamics. Hénin and Dupuis (1945) already showed as early as 1945 that decomposed and more stable SOC consists of roots, rather than of above ground remnants. That means that roots contribute more to SOC stocks than crop residues or fresh leaves do (Rasse *et al.*, 2005; Schmidt *et al.*, 2011). Recent analysis have shown that root derived carbon and root derived molecular structures dominate SOC (Kätterer *et al.*, 2011; Mendez-Millan *et al.*, 2010) and that its MRT is 2.4 times higher than the remaining part of SOC (Rasse *et al.*, 2005). Roots contribute C to the terrestrial carbon pool either by decomposition of biomass after plant death or as root exudates to the rhizosphere (Hirte *et al.*, 2018b; Jones *et al.*, 2004; Kuzyakov and Domanski, 2000). The term *rhizosphere* is based on Lorenz Hiltners work and dates back to the early 20th century. Hiltner defined the rhizosphere as the root-influenced soil around plant roots, where an exclusive population of soil microbes can be found (Hartmann *et al.*, 2008; McNear, 2013). While the process of decomposition of root biomass is widely discussed and well known in literature, knowledge gaps appear regarding understanding and quantification of rhizodeposition (Jones *et al.*, 2004; Kuzyakov and Domanski, 2000; Pausch and Kuzyakov, 2018).

1.2.1 Root derived carbon input into soils – root biomass

Decomposition of root and shoot biomass after plant death provides the accumulation of SOM in soils (Kuzyakov and Domanski, 2000). Thus, total initial carbon input depends on the quantity of root biomass and the vertical and horizontal distribution of C input on root architecture. Root growth and root architecture is influenced by numerous soil properties such as SBD, nutrient availability etc. (Bengough and Mullins, 1990; Dexter, 2004; Rich and Watt, 2013). In return, roots affect chemical as well as physical soil properties (Gregory, 2006). For example, plant roots improve the formation of water-stable microaggregates (Boix-Fayos *et al.*, 2001; Gregory, 2006). Wetting and drying cycles are amplified by the presence of roots, as they take up water to regulate water balance of the plant. These wetting and drying cycles lead to formation of aggregates (Materechera *et al.*, 1992). SOC may stabilize these aggregates due to their cohesive effect (Boix-Fayos *et al.*, 2001).

Roots grow in dependence of the outside conditions and adapt their growth patterns to different soil properties in order to allocate resources or to avoid limiting soil properties (Gregory, 2006; Hirte *et al.*, 2018a; McNear, 2013; Vuuren *et al.*, 1997). The experiment of this thesis focuses, among other factors, on soil bulk density, clay content and SOC content. Relationships between these factors and roots are discussed, all other factors will be neglected, as this would exceed the limits of this thesis.

A high SBD leads to a higher physical impedance and can decrease the elongation of roots. Low soil density may lead to poor mechanical strength what leads to poor anchorage and low plant stability (Bengough and Mullins, 1990; Gregory, 2006). The plant is likely to adjust root biomass in order to adapt to these conditions.

Organic compounds and roots form and stabilize soil aggregates (Boix-Fayos *et al.*, 2001; Traoré *et al.*, 2000). Soil aggregates have a positive effect on carbon storage in soils as fine roots grown into aggregates are protected from microbial degradation (Hassink, 1994; Rasse *et al.*, 2005).

Clay particles absorb nutrients onto their surfaces due to their negative charge (Hassink, 1994; Jenny, 1941). That means nutrients are available where clay content is high.

1.2.2 Root derived carbon input into soils – rhizodeposition

Rhizodeposition is the release of carbon compounds from root to the root surrounding soil (rhizosphere). These compounds are linked to many processes, illustrated in Figure 1, such as the loss of root cap and border cells (1), death and lysis of root cells (2), active release for a specific purpose such as changing the chemical, physical and biological characteristics of the rhizosphere to attract specific organisms (3), gaseous outflow (4), passive diffusion from living cells (5) and insoluble mucilage from living cells (6) (Jones *et al.*, 2004, 2009).

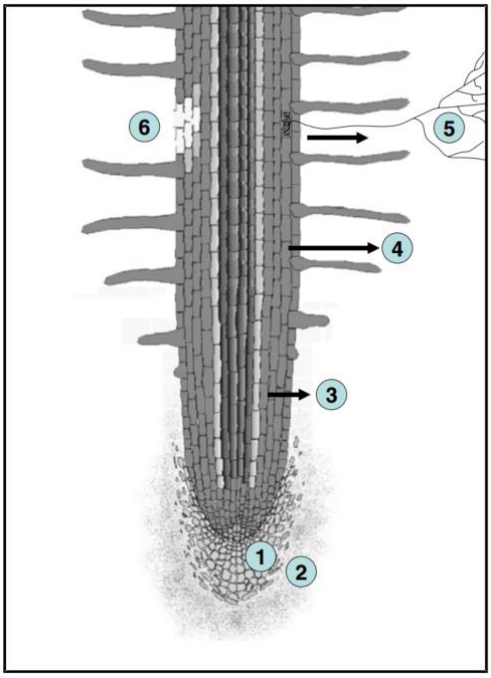


Figure 1: Figure represents a root cross section where numbers from 1 to 6 represent the different types of C loss. 1 is the loss of border cells, 2 is mucilage, 3 are soluble root exudates, 4 is the gaseous outflow, 5 is the passive diffusion of living cells and 6 is loss of the insoluble mucilage of living cells (Jones et al. 2009).

There are several approaches to classify carbon lost from roots (rhizodeposits). Bais *et al.* (2006) divided rhizodeposits according to their molecular structure into a low-molecular and high-molecular group whereas Rasse *et al.* (2005) took water solubility into account and divided the rhizodeposits into water-soluble and water-insoluble groups. Both distinction are similar and contains sugars, amino acids and organic acids in the first group and proteins, cell walls and mucilage in the latter. The first group of rhizodeposits contains rather easily decomposable material and is often referred to as root exudates while the compounds of the second group are more stable (Bais *et al.*, 2006; Rasse *et al.*, 2005). This applies for all components except for mucilage, which is part of the high-molecular and water-insoluble group, respectively. Nevertheless, mucilage is labile and can be decomposed rapidly by soil microbes (Jones *et al.*, 2009).

Notwithstanding the above forms of classifications, the different types of rhizodeposits have various functions and effects on physical soil properties. Sugars, amino acids and organic acids can be rapidly decomposed and converted into inorganic compounds by microorganisms (i.e. mineralisation) (Blume *et al.*, 2010; Chabbi *et al.*, 2001; Rasse *et al.*, 2005). However, Jones (1998) states that this kind of substances are negatively charged and may bind to the mineral phase. Mucilage provides many advantages concerning soil physical properties. Rhizodeposits and mucilage can form or stabilize soil aggregates (Gregory, 2006; Traoré *et al.*, 2000). Mucilage can bind to clay, which improves soil aggregates stability (Oades, 1978), what has a positive effect on soil aeration and root growth (Jones *et al.*, 2009). Furthermore, chemical composition of root exudates can change soil chemical properties and also increase chemical weathering of minerals (Hinsinger, 2001; Paris *et al.*, 1995).

Many studies have been conducted in the last century to gain insight into the process of rhizodeposition (Nguyen, 2003). Recent studies focus on the C fluxes within the plant and the soil (ibid. 2003). However, belowground carbon dynamics remain unclear (Jones *et al.*, 2004). These knowledge gaps are caused by the complexity of belowground carbon dynamics and the lack of unified techniques to examining it (Jones *et al.*, 2004; Pausch and Kuzyakov, 2018). Furthermore, narrowing the zone around the root is difficult and may vary. Some rhizodeposits decompose rapidly, moreover, rhizodeposits contribute very little content compared to the rest of SOC content and the chemical composition of Rhizodeposition can be very similar to other organic substances in the soil (Pausch and Kuzyakov, 2018). Apparently, some information can be gained from a closer look at rhizodeposition inputs into soils.

1.2.3 Priming effect of root derived carbon

It is described in chapter 1.2.1 and 1.2.2 how carbon get into soil by either living root biomass or rhizodeposition. Heterotrophic respiration of microorganisms is the predominate process how soil organic carbon is processed and used as nutrient and energy source in the subsequent (Fontaine *et al.*, 2003).

Quality of SOC controls the decomposition rate. Mining of energy out of initial SOC material is rather slow. As a result, microbes have too little energy available and activity is declining (ibid. 2003). Bingeman *et al.* (1953) introduced the term “priming effect” in the early 1950’s and Dalenberg and Jager (1989) defined it carbon-specifically as an increase in decomposition of organic C after an additional trigger input of easily-decomposable organic material to the soil. Further, rhizodeposition can lead to priming effect (PE), as some rhizodeposits-substances consist of easily decomposable material. Some earlier findings indicate that the trigger materials leads to an increase of the overall soil microbial activity due to the increased availability of energy and nutrients (Bingeman *et al.*, 1953; Sørensen, 1974). However, Fontaine et al. (2003) suggested that the reason for the changes of decomposition rates are modifications in soil microbial community composition rather than just an activation of the population. Anyway, easily-decomposable organic material such as dead root biomass and rhizodeposits stimulate decomposers to degrade initial SOC and substantially boost decomposition rate (see Figure 2) (Fontaine *et al.*, 2004, 2007).

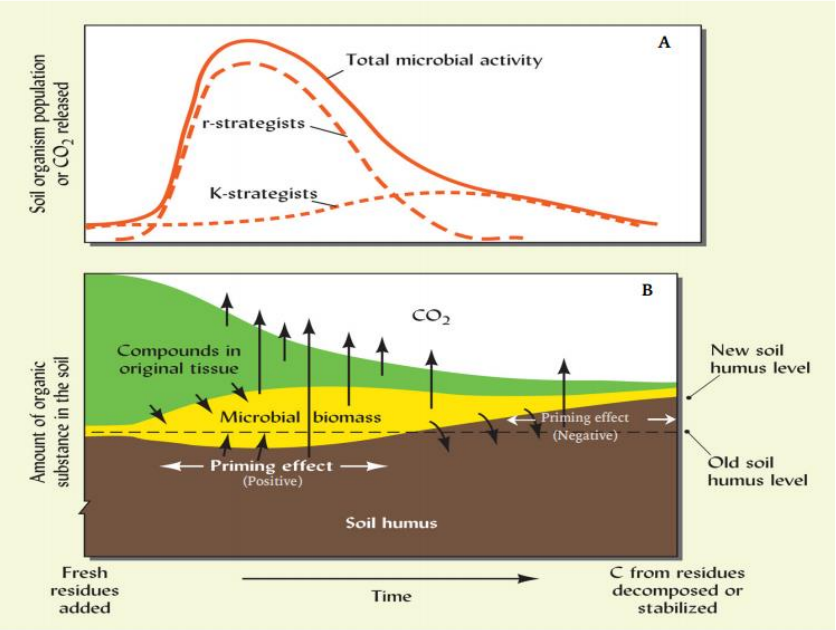


Figure 2: (A) When trigger material is added to soils, a change in soil microbial community and overall soil microbial activity is the consequence. This is represented in orange lines in the above figure. (B) Dynamics between original tissue, microbial biomass and soil humus are represented in the bellow figure. Dashed black horizontal line represents the initial SOM level, the green section shows the amount of trigger material, yellow section the describe over time from litter input on the left side to stabilization of C on the right side. The black arrows describe CO_2 fluxes between the pools (Brady and Weil, 2016).

The addition of trigger carbon material may not only increase the decomposition of initial organic material (i.e. positive PE) but also the opposite (Kuzyakov *et al.*, 2000). The reduction or immobilization of added energy is called negative PE (ibid. et al. 2000). Furthermore and according to the source of CO_2 released through soil respiration, two types of PE can be distinguished. Real PE is the decomposition of SOM derived CO_2 while apparent PE is the result of the turnover of microbial compounds (ibid et al. 2000). These two effects do not influence each other and can therefore be easily distinguished (Westcott and Mikkelsen, 1985). Kuzyakov (2010) states that a differentiation can also be made for the frequency of organic carbon input. While the continuous input is typical for dead biomass SOM such as roots, for aboveground biomass and some rhizodeposits, pulse input is defined consisting of microbial, root and animals cells and root exudates. The decomposition of the latter create a hotspot of increased microbial activity due to the well accessible and soluble energy (Kuzyakov, 2010).

It is biased throughout literature if living roots have a positive or a negative PE on SOM decomposition (Cheng, 1996; Cheng *et al.*, 2003, 2014; Fu and Cheng, 2002; Liljeroth *et al.*, 1994). Information gained out of these studies is that there is a great variability of PE which also can be explained by differences in experimental designs. Factors such as soil type, plant species, growth conditions and soil nutrient concentration affect if PE turns out to be negative or positive (Cheng *et al.*, 2014; Fu and Cheng, 2002; Kuzyakov *et al.*, 2000).

However, Paterson and Sim (2013) suggested that a better understanding of priming effect is needed in order to improve representation of belowground carbon processes in C models.

1.3 Drivers of root derived carbon dynamics

Many drivers influence root derived carbon input and its MRT in soil directly or indirectly. In this thesis CO_2 as climatic factor and SBD as soil property affected by agriculture will be investigated.

Increased CO_2 content enhances biomass growth of plants leading to higher SOM inputs (van Groenigen *et al.*, 2014). These conditions on the other side also trigger soil microbial biomass activity and as a consequence, respiration and mineralisation of SOC increases. (Rustad *et al.*, 2001; van Groenigen *et al.*, 2014).

Agriculture is intensifying as a result of the constantly growing population (UN, 2009) as the agricultural industry branch is supposed to sustain the growth and to feed people (Alexandratos and Bruinsma, 2012). Agriculture intensified due to the use of heavier machinery and increasing fertilization (Barrow, 2012; Hamza and Anderson, 2005). Therefore, the intensification indirectly has a major impact on the physical and chemical properties of soil and thus on plant and root growth.

1.3.1 Increased atmospheric CO_2 as driver of root derived carbon dynamics

CO_2 content in the atmosphere increased by 40% since 1750 and amounted to almost 400 parts per million (ppm) in 2011 (Hartmann *et al.*, 2013). CO_2 concentration is higher in soils than in the atmosphere. Therefore, the predicted elevation of CO_2 in the atmosphere does not have a direct impact on below-ground carbon dynamics (Kandeler *et al.*, 1998). However, changes in carbon dynamics between the atmosphere carbon pool and the soil carbon pool happen as a result of indirect effects of elevated CO_2 (ibid. 1998).

Different climate models have been assessed in the IPCC report of 2013 (Collins *et al.*, 2013). All of them induced further increase of CO_2 until the year 2100 (ibid. 2013). As illustrated in Figure 3, scenarios were conducted where CO_2 in the atmosphere will increase to concentrations between 794 to 1142 ppm by the year of 2100 (ibid. 2013). Further analyses of sensitivity propose uncertainty of -10 to +30% (ibid. 2013).

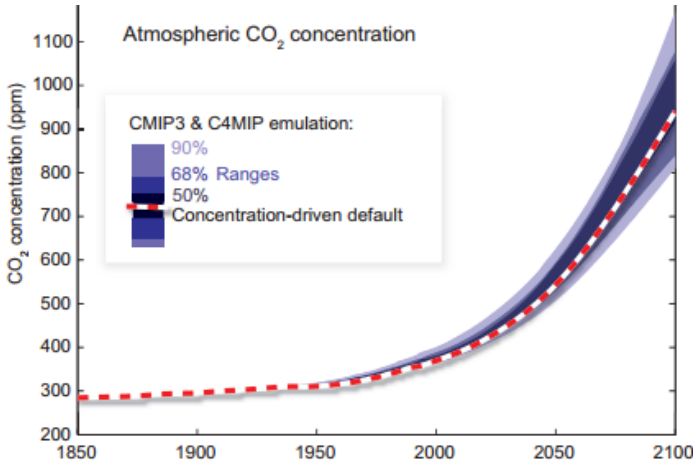


Figure 3: Atmospheric CO_2 concentration is rising. This has been showed in models (CMIP3 or C4MIP). Illustration shows the increase in atmospheric CO_2 until the year 2100. The red and white line illustrates the line of default method used in the specific paper and the sections around default line represent the ranges (Collins et al. 2013).

Photosynthesis, plant respiration and soil respiration are the main mechanisms that control carbon fluxes from the atmosphere to the soil and vice versa (Cao and Woodward, 1998). Increased CO_2 acts as fertilizer and alters photosynthesis and thus root and shoot growth of a plant, resulting in more biomass (Ainsworth and Long, 2005; Cao and Woodward, 1998; Rustad *et al.*, 2001; Vuuren *et al.*, 1997).

Several studies suggest that root growth is stronger under elevated CO_2 conditions than growth of other parts of the plant (Batts *et al.*, 1998; Rogers *et al.*, 1992). An increase of root growth goes along with a greater nutrient demand, in order to sustain the growth. Therefore, roots adapt their architecture and biomass to improve nutrient and water uptake (Pritchard and Rogers, 2000; Vuuren *et al.*, 1997). Rogers et al. (1992) showed an increase in the vertical distribution of soybean roots and stated that more roots in deeper soil layers may imply less vulnerability of a plant to droughts. However, Pritchard and Rogers (2000) proposed that roots will grow larger and, increase horizontal growth directly below soil surface but, also the nutrient and water uptake will be less efficient at the same time. Either way, root growth transitions are also strongly dependent on other parameters such as the plant species, land management technique and soil properties (Pritchard and Rogers, 2000; Vuuren *et al.*, 1997)

Carbon dynamics between the terrestrial carbon pool and the atmospheric carbon pool are very sensitive to environment condition changes. Just small changes in C fluxes may already have a major impact on the CO_2 concentration in the atmosphere (Cox *et al.*, 2000; van Groenigen *et al.*, 2014).

The accumulation of C in the ecosystem biomass increases soil microbial respiration. This causes enhanced microbial respiration and C flux from soil to atmosphere (Cao and Woodward, 1998). Further, higher atmospheric CO_2 can improve water use efficiency as plants lose less water through transpiration. That leads to a higher soil water content inducing higher decomposition rates in dryer ecosystems (Pendall *et al.*, 2003; Wullschleger *et al.*, 2002).

On a global scale and in a long term perspective Jones *et al.* (2005) predicted that carbon stock will not change much before 2060. But in the second half of the 21st century CO_2 fertilization effect will be saturated and the enhanced microbial respiration dominates over the accumulation of C in biomass which results in a large efflux of soil carbon into the atmosphere (Cao and Woodward, 1998; Jones *et al.*, 2005). Either way, it stays rather unclear how changes in atmospheric properties change soil carbon stocks and how root carbon is involved in this process (Schmidt *et al.*, 2011; van Groenigen *et al.*, 2014).

1.3.2 Agriculture as driver of root derived carbon dynamics

Agriculture developed from a labour intensive low-output to a mechanized high output branch of industry since 1880 (Binswanger, 1986). In the second part of the 20th century, high intensity crop varieties established and were used by farmers in developing countries. The subsequent increase of rice and crop yield is known as the “Green Revolution” (Evenson and Gollin, 2003). With the expected population growth (UN, 2009) the need for agricultural products might grow (Alexandratos and Bruinsma, 2012) as agriculture is supposed to foster population growth in order by food supply and security (Alexandratos and Bruinsma, 2012; Rosegrant and Cline, 2003). However, the intensification is also associated with changes in physical and chemical soil properties (Barrow, 2012; Hamza and Anderson, 2005).

To be more precise, intensification of agriculture means increased use of chemical fertilizer, shorter crop rotations or more advanced machines (Barrow, 2012; Hamza and Anderson, 2005). As already explained in section 1.3.2, CO_2 acts as fertilizer and enhances root biomass growth in soils. However, the same does not apply for chemical fertilizer in agriculture. Poeplau *et al.* (2018) demonstrated that there is an increase of SOC stocks with fertilization but that this increase could not be explained with increased root biomass C inputs. Hirte *et al.* (2018a) also pointed out that roots react to site conditions rather than to fertilization intensity. As the impact of chemical fertilizer on root derived C input will not be tested in the experiments, this topic will not be further explained.

Soil compaction is not only discussed as impact on soils throughout literature but mainly as a major problem (De Neve and Hofman, 2000; Hamza and Anderson, 2005). Advanced machines in agriculture in many cases equal heavier machines. This can lead to soil compaction (Hamza and Anderson, 2005). The Soil Science Society of America (2008) defined soil compaction as relative increase of micropores and the subsequent increase of SBD, De Neve and Hofman (2000) examined how compaction influenced decomposition of C input and concluded, that decomposition decreases at high SBD. However, that rate of decomposition is also influenced by quality of SOC. Easily decomposable C is more influenced by higher SBD than the less degradable material. On the other hand, SOM in soil can reduce compaction as SBD of SOM is lower than of mineral soils (Hamza and Anderson, 2005; Martin and Stephens, 2001). But the addition of SOM does not just improve soil physical properties by its low SBD, it is also increases construction and stabilization of aggregates (Martin and Waksman, 1940). Monnier (1965) suggested that SOM input of different composition led to differences in aggregate stability on a time scale up to years after incorporation. Abiven *et al.* (2009) discussed based on Monniers work that the effect of SOM on aggregate stability might also depend on preliminary aggregate stability.

In fact, soil aggregates seem to play an important role. Effects of soil roots and SOM on building and persistence of aggregates and carbon stocks have already been explained in section 1.2.1. Hamza and Anderson (2005) stated that tillage influence soil aggregates negatively by destroying them. Indeed, tillage as agricultural practice is discussed widely as factor that affects SOC stocks. However, results are biased throughout literature. Varvel and Wilhelm (2011) observed an accumulation of SOC in top soil layers and an increase throughout all soil depths under no tillage conditions. Other authors state that there might be changes in top soil but that there are no changes in total SOC considering soil depths up to one meter (Angers and Eriksen-Hamel, 2008; Luo *et al.*, 2010). Furthermore, it is important not to take juts tillage into account as controlling factor but also to have a look on soil properties and air temperature (Ussiri and Lal, 2009).

Agriculture certainly influences physical soil properties and SOC dynamics in soil by compacting, fertilizing and practices such as ploughing. Nevertheless, estimating turnover and persistence of SOC pools also climate factors such as temperature or atmospheric CO_2 (see 1.3), or soil properties such as clay content or initial SBD should be taking into account.

1.4 ^{13}C stable isotope – a method to trace root derived C in soil

Isotopes are atoms whose atomic cores contain different numbers of neutrons. There are three isotopes for carbon: stable ^{12}C, stable ^{13}C and radioactive ^{14}C whereby ^{13}C is heavier than ^{12}C (O'Leary, 1981). CO_2 contains 1.1% of ^{13}C isotope and 98.9% of the ^{12}C isotope (ibid. 1981). This makes clear that a labelling with the less frequent ^{13}C isotope is necessary in order to be able to trace carbon pathways (Dawson *et al.*, 2002). As C itself is naturally abundant in the plant and the isotope is stable and not radioactive, tracing ^{13}C is as gentle and non-invasive method to gain information about plant metabolism and carbon sequestration among plant and soil system (Brüggemann *et al.*, 2011; Dawson *et al.*, 2002). ^{13}C abundance is expressed as $\delta^{13}C$ value in units per mil (‰) throughout literature and indicates the ratio of ^{13}C in CO_2 compared to ^{12}C in CO_2. $\delta^{13}C$ values also indicate state of humification of SOM. The less negative $\delta^{13}C$ values are, the further humification has progressed (Vitorello *et al.*, 1989).

Three methods exist in order to trace $\delta^{13}C$: pulse labelling, continuous labelling and the natural abundance of $\delta^{13}C$ (Kuzyakov and Domanski, 2000). Pulse labelling and continuous labelling are artificial methods where CO_2 is labelled. Both methods can be used in Multi isotope labelling under controlled environment-facility (MICE). When puls labelling is applied, CO_2 is only supplied for a short time while continuous labelling means that CO_2 is used during the whole growing phase (ibid., 2000). This method is useful when the total amount of assimilated C CO_2 is of interest. Pulse labelling is easier to apply but does not provide information about the total amount C CO_2 assimilated but about distribution (ibid., 2000).

1.5 Related work

There are a variety of papers that focus on root properties and factors that control rhizodeposition in soils (Johnson *et al.*, 2006; Jones *et al.*, 2004, 2009; Kuzyakov, 2002; Nguyen, 2003; Pausch and Kuzyakov, 2018). Friedli (2017) and Hirte *et al.* (2018b, 2018a) conducted studies were they focused on how outside conditions and plant genotype influence root derived carbon input into soils. Hirte *et al.* (2018a) observed that fertilization, independent of intensity, had less effect on root biomass derived C than site conditions (Texture, SBD, SOC, plant available water). Furthermore, fertilization had a strong effect on the AGB but root biomass C input and rhizodeposition C input didn't vary much within fertilization types and soil depths (Hirte *et al.*, 2018b). Friedli (2017) demonstrated differences between root derived carbon input of two wheat genotypes, related to root architecture and branching. The genotype that had more root biomass into deeper soil depth and more branching showed more fine roots and thus more rhizodeposition. However, the C input from this genotype was easier decomposable compared to the other genotype. Either way, the amount of rhizodeposition derived C was very high for both genotypes.

2 Objectives

Up to 90% of carbon in soils is root derived (Kätterer *et al.*, 2011). Root derived can either mean root biomass C or rhizodeposition C. Root derived carbon is of importance as it is more stable than carbon from other sources.

Plant and root growth can react sensitively to changing outside conditions such as changing atmospheric CO_2 (Gregory, 2006; Hirte *et al.*, 2018b; McNear, 2013; Vuuren *et al.*, 1997). But little is known about how root derived C, especially the proportion of rhizodeposition to root biomass C change under changing outside conditions (Gale *et al.*, 2000; Jones *et al.*, 2004; Rasse *et al.*, 2005). Therefore, the following research questions and hypotheses were derived:

1. How much does the root derived carbon production increase under an elevated atmospheric CO_2 scenario (82 years)?
    a. Photosynthesis increases with elevated CO_2 resulting in an increase of photosynthetic carbon assimilation.
    b. Root biomass will increase and root vertical distribution will change under elevated atmospheric CO_2 conditions. As a result, rhizodeposition will increase relatively to root biomass.
2. How do soil clay concentration, soil organic carbon content and soil bulk density influence root derived carbon production under an elevated atmospheric CO_2 scenario (82 years)?
    a. A high bulk density reduces root biomass and limits root derived C deposition.
    b. A higher clay and SOC content may lead to a higher nutrient availability and thus to less root biomass, less root exudates and as a consequence to less total root derived C and rhizodeposition relatively to total root derived C in a soil.

3 Material and Methods

In this chapter, material and steps taken are described in order to answer the research questions. In summary, two different soil types with different clay and SOC concentrations were sampled and filled up into columns. Half of the columns were filled with a SBD of 0.9 g/cm^3 and the other half with a SBD of 1.2 g/cm^3. An experiment was conducted in the MICE-facility (**M**ulti-**I**sotope labelling in a **c**ontrolled **E**nvironment) under CO_2 conditions of today (control chamber) and under elevated CO_2 concentration of IPCC scenario of the year 2100 (elevated CO_2 chamber). MICE experiment was conducted in order to estimate shoot growth, root growth and root derived carbon input under different soil types and environmental conditions. Incubations were used to estimate rhizodeposition from root biomass and to measure decomposition of rhizodeposition,

3.1 Study site selection

The experiment in MICE facility and the following incubations were conducted with soil sampled from two different spots. The two spots are both agricultural sites and are cultivated according to a fruit sequence plan, in order to serve the nutritional base of Switzerland (Bundesamt für Raumentwicklung ARE, 1992). Both sites are located within a radius of 3 kilometres in the town Dinhard, in the Canton of Zurich (see Figure 4). On sampling day, soil 1 was cultivated as grassland and winter-barley grew on soil 2.

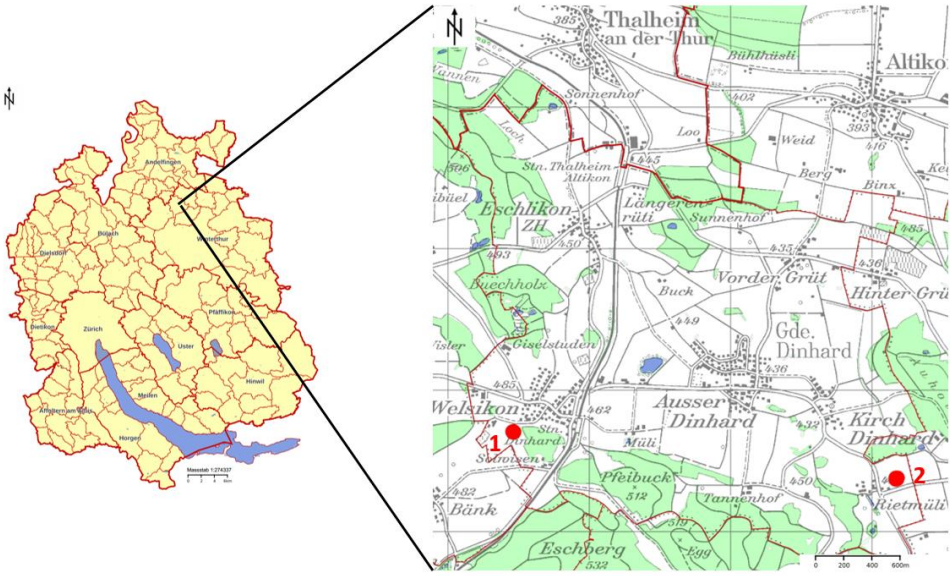


Figure 4: Map of Study site

Sites were selected in order to provide heterogeneity regarding soil properties in order to answer the research questions. Thus, differences in clay content were particularly important. As the content of total organic carbon (TOC) is closely linked to clay content, a logical consequence of a high clay content is also an increased TOC content and vice versa (Greenland, 1971; Martin and Haider, 1986; Wattel-Koekkoek *et al.*, 2001). Every agronomist must carry out soil analyses every 10 years for cultivation plots larger than 1 hectare (ha) in order to receive government support (ÖLN). The analyses include

information about pH, phosphorous, potassium, soil type and SOM. For both plots, the analysis were available and the basis for choosing the study sites. The exact TOC content measured in PICARRO during the experiment. As visible in Table 1, soil 2 shows a high clay content of 31% and also high TOC values of 2.75% whereas soil 1 has a clay content of 11% and a lower TOC content of 1.71%.

Table 1: TOC and clay concentration of soil 1 and soil 2

	TOC	**Clay [%]**	**Cultivation when sampled**
Soil 1	1.71	11	grassland
Soil 2	2.75	31	winter barley

3.2 Soil sample collection

The soil was sampled in October 2017 with a spade to a depth of 15cm. This depth represents a shallow tillage depth (Etana *et al.*, 1999; Reicosky and Archer, 2007). On each spot, 21 samples were taken according to pattern of figure 5 within a range of approximately 15 x 15 m and were mixed subsequently. The samples were air-dried and stored until further processing.

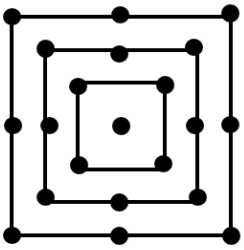


Figure 5: Sampling pattern for soil sampled in spot 1 and 2

3.3 Soil sample preparation

The soil samples from spot 1 and spot 2 were rewetted according to their clay content. Soil 1 was rehydrated to a moisture of 16-20% and soil 2 to 24-30%. Soil was then filled into 40 Polyvinylchlorid (PVC) tubes of 35 cm height and 5.8 mm diameter. The soil in half of the columns was compacted to a SBD of 1.2 g/cm^{3,} the other half to 0.9 g/cm^3. In all of the 40 columns, summer-barley “Sydney” was planted and pregrown for two days before the experiment in MICE started.

3.4 Experimental design

3.4.1 MICE (**M**ulti **I**sotope labelling in a **c**ontrolled **E**nvironment) Facility

The MICE facility consists of two climate chambers, where environmental conditions such as temperature, air humidity and atmospheric CO_2 can be regulated independently (Studer *et al.*, 2017). The climate chamber itself can also be divided into an upper and lower system in order to separately focus on root and shoot respectively (ibid. 2017). There was no division between upper and lower system in this thesis.

20 tubes were placed and fixed in chamber 1 and 20 columns in chamber 2. 10 tubes per chamber were filled with soil 1 and 10 tubes with soil 2. 5 columns per soil type per chamber were compacted to 1.2 g/cm^3 the other 5 columns to 0.9 g/cm^3 (see Figure 6).

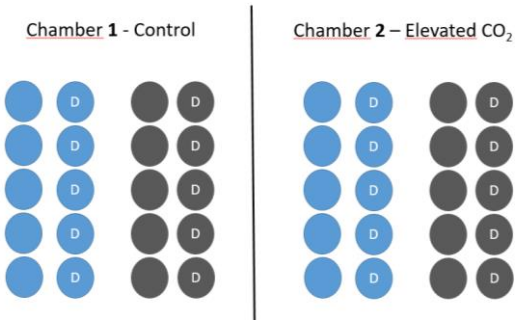


Figure 6: Schematic representation of arrangement of columns in chamber 1 and 2 in MICE. Blue colour represents soil 1 and grey colour soil 2. Columns with a high SBD (1.2g/cm^3) are marked with the letter D, all other columns have SBD of 0.9g/cm^3

Conditions were set in each chamber according to table 2. The average temperature, precipitation, air humidity and day and night cycles were equal in chamber 1 and 2. Regarding CO_2 concentration, chamber 1 was set to control (CO_2 concentration of today) and chamber 2 to elevated CO_2 according to IPCC climate scenario of 2100 (Collins *et al.*, 2013).

Precipitation was adjusted analogous to mean summer precipitation (June, July and August) of the AWEL measuring stations “Winterthur” and “Räterschen” which resulted in 1.97 mm/d. As the value was given for square meter, it had to be adapted to the column surface, which resulted in 0.052 mm/day.

Table 2: Conditions set in MICE chambers 1 and 2

	Chamber 1 control climate scenario	**Chamber 2-future CO_2 scenario**
Average temperature (°C) day	24	24
Average temperature (°C) night	16	16
Duration day (hours)	14	14
Duration night (hours)	10	10
Average precipitation (mm/d)	0.052	0.052
Atmospheric CO_2 (ppm)	400	1000
Average air humidity (%)	18	18

Experiment ran 42 day from 18th of January until 27th of February in order to reach anthesis stage of the barley plant, where flowering begins and the first anthers of cereals are visible (Zadoks *et al.*, 1974). Time when the anthesis would be reached was estimated on the basis of the concept of growing degree-days according to McMaster and Wilhelm (1997) and Miller *et al.* (2001).

3.4.2 Incubation design

Incubation is a method to measure carbon in soil microbial biomass. Respiration of microbial biomass is measured after the addition of an energy source (Anderson and Domsch, 1978). The aim in this thesis was to measure soil respiration in order to estimate the decomposition of rhizodeposition, which acted as energy source.

One jar per treatment, of all repetitions and for soil depth 1 and 3 were prepared (80 jars). Furthermore, some control jars with soil, which were not in MICE, were set up too. In every jar, 20 g of fresh, rootless soil was placed. 5ml of water was added to soil 1 and 10ml to soil 2 in order to reactivate soil microbes. Two additional vials were placed in each jar with 20 ml of 1 molar (M) sodium hydroxide (NaOH) and 20 ml of water respectively (see Figure 7). Jars were put into the incubator at 37 degrees Celsius (°C) for 30 days. Five measurement days have taken place, whereby the NaOH was replaced on the third measurement day. On a measurement day, electrical conductivity was measured in every NaOH vial using a conductivity meter. On sampling day three, conductivity was measured, used vials were removed and new vials with new NaOH solution were placed in the jars. The used vials were closed immediately and stored until further analysis (see 3.5 and 3.6).

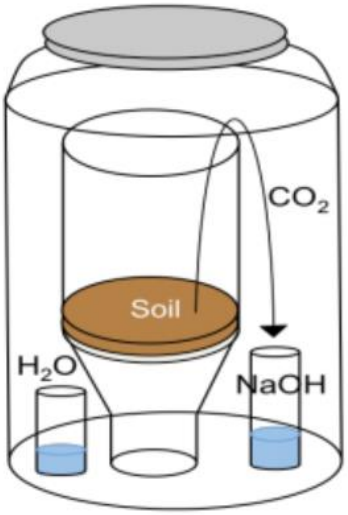


Figure 7: Experimental set up of incubations experiment. Each jar contained a water vial, a NaOH vial and the soil samples where roots had been picked out (adapted figure from Master's Thesis of Jessica Abt, 2017)

3.5 Measuring carbon content

Total amount of aboveground biomass (AGB) and root biomass as well as carbon concentration and $\delta^{13}C$ of AGB, roots and soil were measured in order to reproduce carbon sequestration that happened during the experiment in MICE. The incubation was used in order to estimate the amount of rhizodeposition during the MICE experiment and its subsequent decomposition under consistent conditions.

3.5.1 Measuring carbon sequestration after the MICE experiment

After opening the MICE chambers, above ground barley plants were cut just above the soil surface and oven-dried for 24 hours at 60 °C. After drying, AGB was weighed and stored in a box.
Columns were opened and the soil was cut evenly in three depths (see table 3)

Table 3: Definition of soil depth 1, 2 and 3 in meters below soil surface

	meters below soil surface
Depth 1	0-0.11
Depth 2	0.11-0.23
Depth 3	0.23-0.35

Out of all three soil depths, roots were picked with tweezers, washed and dried in the oven like the AGB, also weighed in and stored in a box. Total weight of AGB biomass with the fruits and root biomass was used to estimate root:shoot ratio.
100 g of fresh and rootless soil substrate was oven dried for 24 hours at 105 °C, the rest was stored in plastic bags and stored in the fridge until it was used for the follow-up incubation experiment.
Dry soil, dry ABG and dry roots were milled and weighed in into tin capsules subsequently. TOC and $\delta^{13}C$ signals were then measured putting the tin caps into Picarro automatic stable isotope analyser (Picarro ^{13}C CM-CRDS System).

3.5.2 Measuring CO_2 efflux and the $\delta^{13}C$ signal of the incubation experiment

As described in chapter 3.4.2, NaOH vials were placed in every incubation jar. The vials worked as CO_2 traps in order to evaluate the soil microbial respiration. Respired CO_2 reacts (see chapter 3.6 calculations) with the NaOH solution in the vials what results in a change of the electrical conductivity of NaOH (González-Domínguez *et al.*, 2017; Wollum and Gomez, 1970). To be more clear, CO_2 respired from to soil leads to an absorption to the NaOH solution. The more CO_2 is absorbed to the NaOH traps, the smaller is the electrical conductivity of the solution (Wollum and Gomez, 1970). Thus, respired CO_2 can be quantified measuring the electrical conductivity using a conductivity meter.
In order to relate respired CO_2 to the amount of root biomass and rhizodeposition and to separate it from the initial SOC, $\delta^{13}C$ signal of CO_2 captured in the NaOH traps was analysed. Analysis was conducted according to Harris *et al.* (1997). There were two sealed NaOH vials for each jar, the one sampled on sampling date three and the other one sampled on the last sampling date. 2.5 ml NaHO each were mixed together with 5 ml (1 M) strontium chloride ($SrCl_2$) in the centrifuge for 5 minutes at a rate of 2500 rpm. After the centrifugation, $SrCO_3$ precipitated in form of a white, solid mass. The remaining water has been drained and the remaining solid $SrCO_3$ was dried for 48 hours at 60 °C. Then, the dry powder was weighted in into tin caps and measured in Picarro analogous root, soil and AGB samples (see also chapter 3.5.1).

3.6 Calculations

Some chemical equation were made in order to quantify soil CO_2 efflux and to powder the trapped CO_2 (see 3.5.2).

$$2NaOH + CO_2 = Na_2CO_3 + H_2O \quad (1)$$

Precipitation of carbon out of NaOH traps was carried out according to the following chemical equation:

$$Na_2CO_3 + SrCl_2 = SrCO_3 + 2NaCl \quad (2)$$

There is always some adhering soil left on root biomass, even if it has been washed before. Therefore, root biomass data was adapted according to Janzen *et al.* (2002).

$$C_t = \frac{M_s}{M_t} C_s + \frac{M_r}{M_t} C_r \quad (3)$$

C_t is the total measured C concentration of the sample (root and soil), C_s and C_r C concentration of the soil fraction and root fraction respectively, whereas M_t, M_r and M_s correspond to mass of total sample (root and soil), root fraction and soil fraction (ibid. 2002). In this thesis, the calculation was made with C_r = 45% according to findings regarding relative plant C allocation of Bolinder *et al.* (2007).
To quantify the PE, the initial SOC concentration was compared to SOC concentration measured after MICE experiment.

$$PE = C_{MICE} - C_{initial} \quad (4)$$

C_{Mice} corresponds to the carbon content of soil samples after experiment in MICE and $C_{initial}$ to the carbon content of soil samples before experiment in MICE. Positive values indicate that an accumulation of SOC has taken place, i.e. negative PE. Negative values mean a depletion of SOC which is the result of increased decomposition, i.e. positive PE.
Initial values for cumulated respiration (C CO_2) were corrected as control soil and samples from the MICE experiment had two different initial SOC values. Soil in MICE was depleted in many cases in C during the experiment whereas control soil was not part of MICE. Difference of TOC between control soil and each sample was added to the cumulated value C CO_2 after incubation. The following equation was done for each sample:

$$g\ C\ CO_{2\ corrected} = g\ C\ CO_{2\ incubation} + (g\ C_{control} - gC_{MICE}) \quad (5)$$

^{13}C abundance is expressed as $\delta^{13}C$ value in units per mil (‰) throughout literature (see 1.4) and indicates the ratio of ^{13}C in CO_2 compared to ^{12}C in CO_2 according to the following equation:

$$\delta^{13}C(‰) = \left(\frac{R(sample)}{R(standard)} - 1\right) x1000 \quad (6)$$

Duration of the Experiment in MICE has been calculated according to growing degree days (GDD):

$$GDD = \left(\frac{T_{MAX}+T_{MIN}}{2}\right) - T_{BASE} \quad (7)$$

where T_{MAX} is maximum daily temperature, T_{MIN} minimum daily temperature and T_{BASE} is the critical temperature below which the barley plant does not grow and was set in this case to 0 °C (McMaster and Wilhelm, 1997; Miller *et al.*, 2001).

3.7 Statistical analysis

Statistical Analysis were made in R (version 3.3.2, 2016-10-16). Visualization of data was conducted with Excel 2013 Pivot Tables.

AGB, root:shoot ratio, root biomass distribution, root derived soil carbon and PE data was checked for range and distribution in Excel 2013. The four factors of importance were soil density, soil depth, CO_2 treatment and soil type. Statistical relevance was then investigated with a multifactorial analysis of variance (ANOVA) in R.

4 Results

4.1 Plant parameters as a factor of the drivers

4.1.1 Above ground biomass

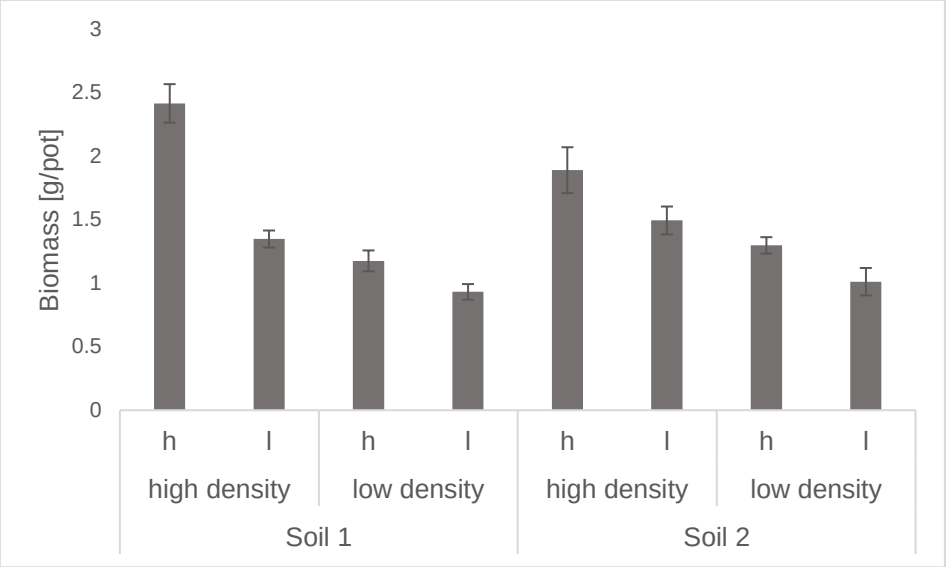


Figure 8: Aboveground biomass of barley plants after MICE experiment. High SBD treatment correspond to 1.2g/cm^3 and low SBD to 0.9g/cm^3. Letter h corresponds to high CO_2 treatment and letter l to low CO_2 treatment in MICE.

Table 4: Results of ANOVA of AGB. Numbers and stars indicate significance level. “n.s” indicates no significance.

	Soil Type	**SBD**	**CO_2**	**SBD:CO2**	**Soil Type: SBD: CO_2**
AGB	n.s	0.001***	0.001***	0.01*	0.05*

Figure 8 shows that the high SBD soil treatment and the increased CO_2 level had a significant effect on the above ground biomass (AGB). The average of the AGB of low SBD treatment was 1.1 g/kg dry soil whereas the high SBD treatment resulted in average of 1.78 g/kg dry soil. The range was similar for the CO_2 treatments (low CO_2: 1.12 g/kg dry soil; high CO_2 : 1.68 g/kg dry soil). No significant difference was detected between soil types (Table 4). Results correspond with other findings that suggested that biomass increases with increased level of atmospheric CO_2 (Cao and Woodward, 1998; Rustad *et al.*, 2001; van Groenigen *et al.*, 2014; Vuuren *et al.*, 1997). An interaction between the factors Soil Type, SBD and CO_2 can be observed.

4.1.2 Root biomass

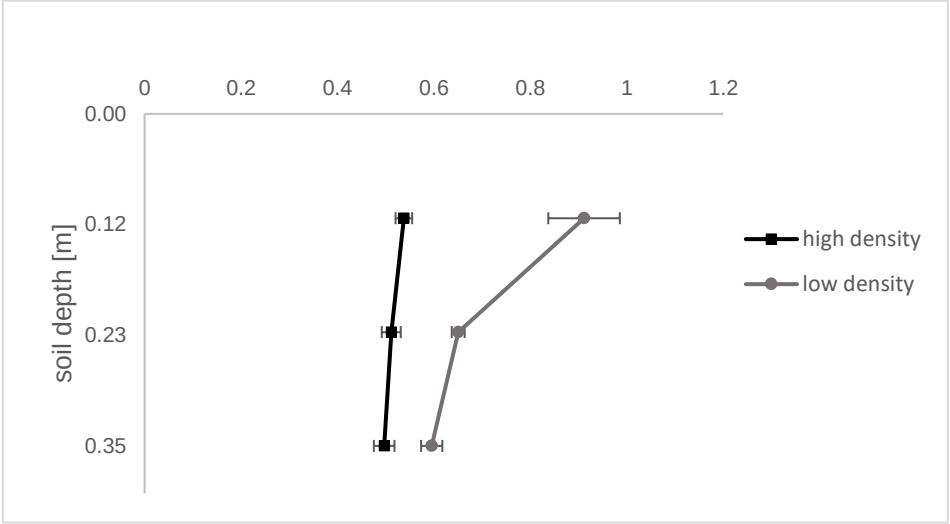


Figure 9: Root biomass distribution among soil depths. Dark grey colour corresponds to high SBD treatment, light grey colour to low SBD treatment.

Table 5: Results of ANOVA of root biomass. Numbers and stars indicate significance level. “n.s” indicates no significance.

	Soil Type	**SBD**	**CO_2**	**Soil Depth**	**Soil Depht: Soil Type**	**Soil Depth: SBD**	**Soil Depht:Soil Type:SBD**	**Soil Depth: Soil Type: CO_2**
Root Biomass	0.001***	0.001***	n.s	0.001***	0.001***	0.001***	0.001***	0.01**

The range of root biomass corresponds with other findings (Yang *et al.*, 2010). Figure 9 illustrates root biomass distribution between soil depths. The result shows significant differences for SBD treatments, soil depths and between soil types. According to the results, CO_2 does not have an impact on the amount of root biomass. High SBD treatments show root biomass of 0.54 g in top layer, 0.51 g in middle layer and 0.5 g in bottom layer. In the low SBD treatment root biomass in first layer is 0.91 g, 0.65 g in middle layer and 0.6 g in bottom soil layer. Root biomass is steadily distributed in high SBD treatments and shows a slight decrease from top to bottom layer. Root biomass is increased in soil 1 (0.64 g) compared to soil 2 (0.6 g). Several interactions occur between the factors such as between soil depth and soil type, soil depth and SBD, soil depth, soil type and SBD and soil depth, soil type and CO_2 treatment (Table 5).

4.1.3 Root:Shoot ratio

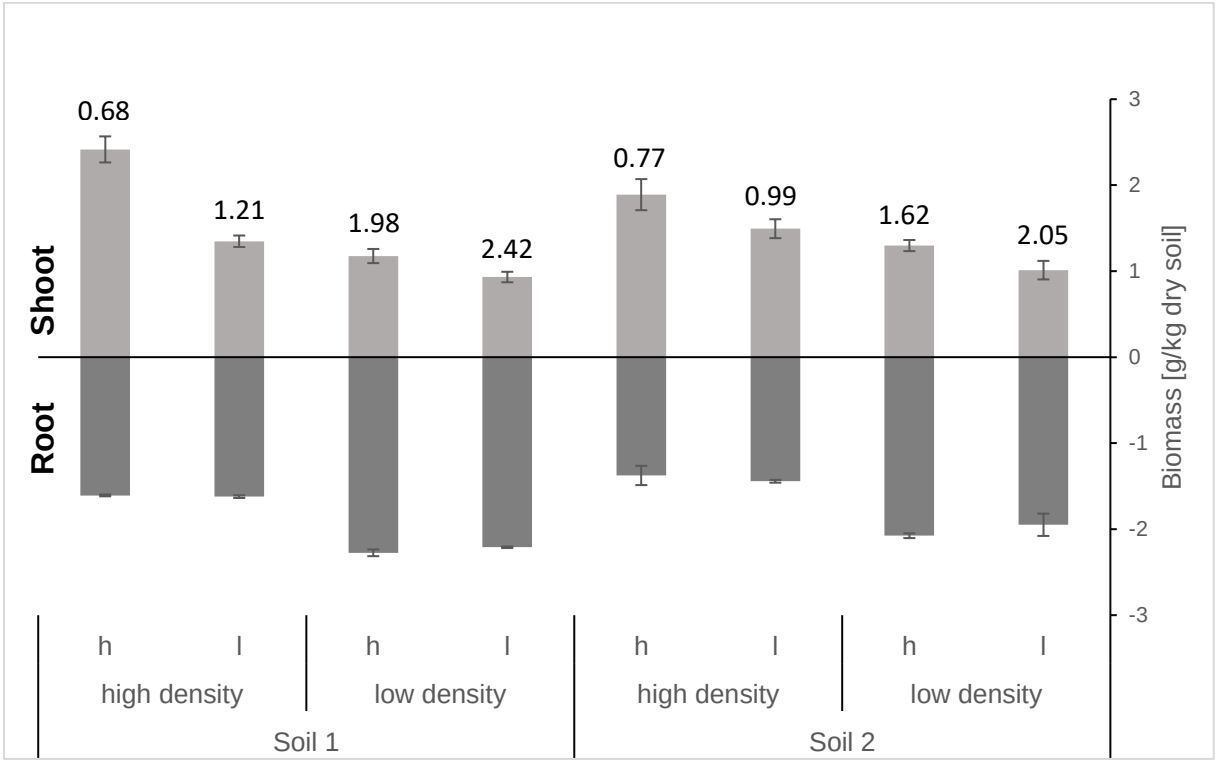


Figure 10: Root:shoot ratio after MICE experiment. High SBD treatment correspond to 1.2g/cm^3 and low SBD to 0.9g/cm^3. Letter h corresponds to high CO_2 treatment and letter l to low CO_2 treatment in MICE.

Table 6: Results of ANOVA of root:shoot ratio. Numbers and stars indicate significance level. "n.s" indicates no significance.

	Soil Type	**SBD**	**CO_2**	**Soil Type: CO_2**
Root:Shoot	0.01**	0.01**	0.05*.	0.001***

Figure 10 shows the root:shoot ratios between the treatments. Root:shoot ratio was measured with the fruits. Even though root and shoots are two different systems with autonomous functions, they are still linked an complement each other (Gregory, 2006). Wilson (1988) suggested that there is an equilibrium between root and above ground plant biomass which can be expressed as root:shoot ratio. Bolinder *et al. (*1997) even stated that below ground C input can be estimated taking root:shoot ratios into account. However, root:shoot ratios can also be influenced by CO_2, temperature or irrigation patterns (Rogers *et al.*, 1995; Yang *et al.*, 2010; Ziska *et al.*, 2004). Large number means more root biomass compared to the AGB. The values of root:shoot ratio of the samples of this thesis are comparable with literature (Bolinder *et al.*, 1997; Friedli, 2017) and are significant between soil types, SBD treatments and CO_2 treatments. Average root:shoot ratio of soil 1 is 1.31 and 1.23 for soil 2. Difference between high and low SBD treatments is more than 1 (high density: 0.85 and low density: 1.92). High CO_2 treatment has a ratio of 1.1 and low CO_2 treatment 1.5. Interaction can be observed between the factors soil type and CO_2 treatment (Table 6).

4.2 Root contribution to the soil carbon as a factor

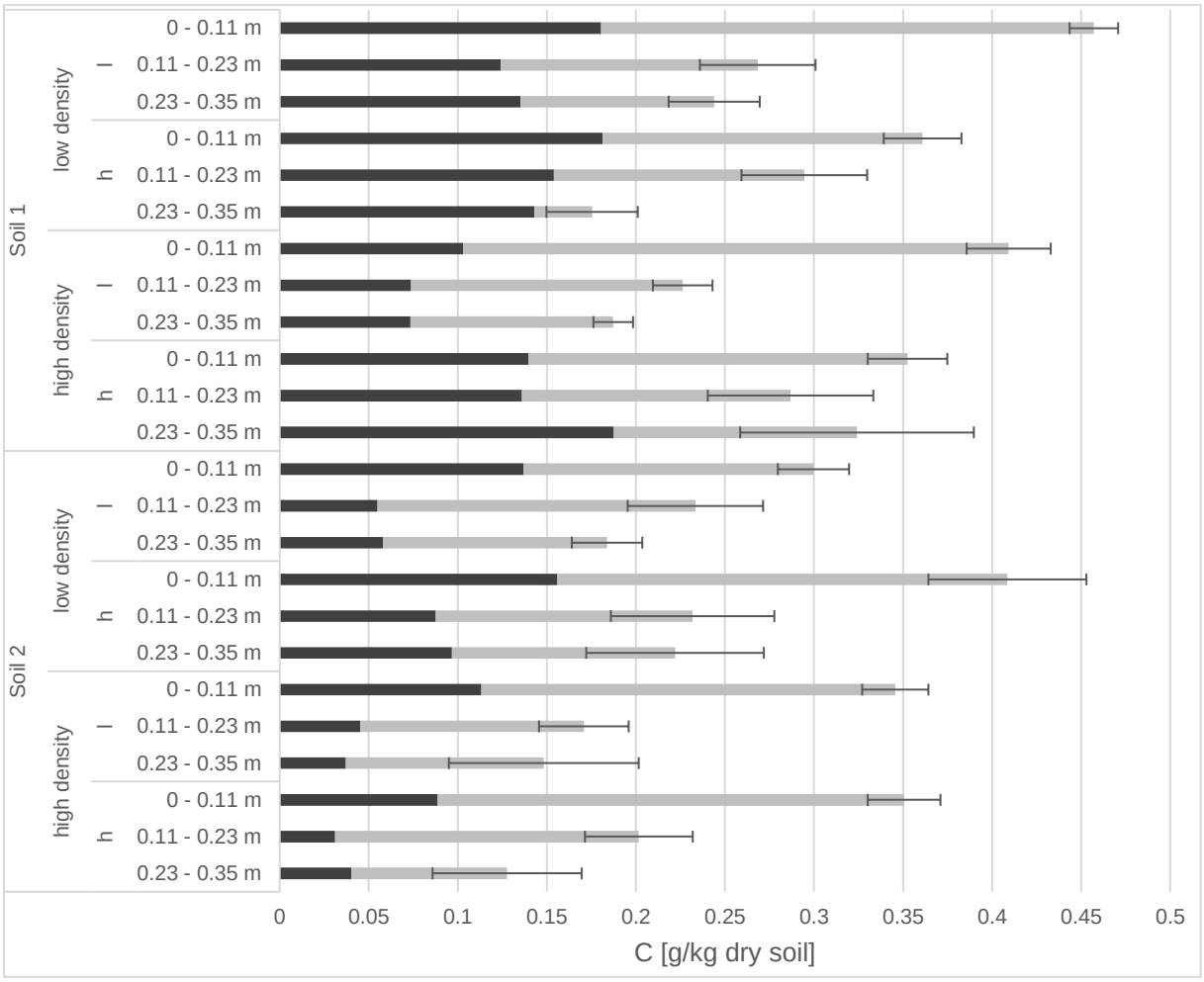


Figure 11: Root derived carbon input into soil. Soil type 1 is addressed to Soil 1 and soil type 2 to Soil 2. High SBD treatment correspond to 1.2g/cm^3 and low SBD to 0.9g/cm^3. Letter h corresponds to high CO_2 treatment and letter l to low CO_2 treatment in MICE.

Table 7: Results of ANOVA of root biomass C and rhizodeposition. Numbers and stars indicate significance level. "n.s" indicates no significance.

	Soil Type	**SBD**	**CO_2**	**Soil Depth**	**Soil Depht: Soil Type**	**Soil Type: CO_2**	**SBD: CO_2:Soil Type**	**Soil Depth: Soil Type:CO_2**
Root Biomass C	0.001***	0.001***	0.001***	0.001***	0.01**	0.05*	0.001***	n.s
Rhizodeposition	n.s	n.s	n.s	0.001***	n.s	0.05*	n.s	0.05*

Root derived carbon input in soils may either come from root biomass or rhizodeposition. Figure 11 shows total root derived C input between the different treatments and dephts. Root biomass C is highly significant for dephts, SBD treatments, CO_2 treatments and soil type. Distribution between soil depths is rather uneven. Greatest root biomass C concentration can be found in the upper soil depth (0.13 g/kg dry soil), decreases in the middle soil layer (0.091 g/kg dry soil) and increases again in the bottom layer (0.098 g/kg dry soil). Further, there is more root biomass C in soil 1 (0.13 g/kg dry soil), low SBD soils (0.12 g/kg dry soil) and high CO_2 treatments (0.12 g/kg dry soil) than in soil 2 (0.08 g/kg dry soil), high

SBD soils (0.09 g/kg dry soil) and low CO2 treatments (0.095 g/kg dry soil). There are interactions between soil depth and soil type, soil type and CO_2 tratment and SBD treatments, CO_2 treatments and soil type (Table 7).

Rhizodeposition derived C is only significantly different between soil dephts and is evenly distributed from top to bottom soil layer. Most rhizodeposition derived C can be found in the upper layer (0.23 g/kg dry soil), less is in the middle layer (0.15 g/kg dry soil) and the least is in the bottom layer (0.10g/kg dry soil) (see Figure 11). Some interaction can be observed for factors soil type and CO_2 treatment and for soil depth, soil type and CO_2 treatment.

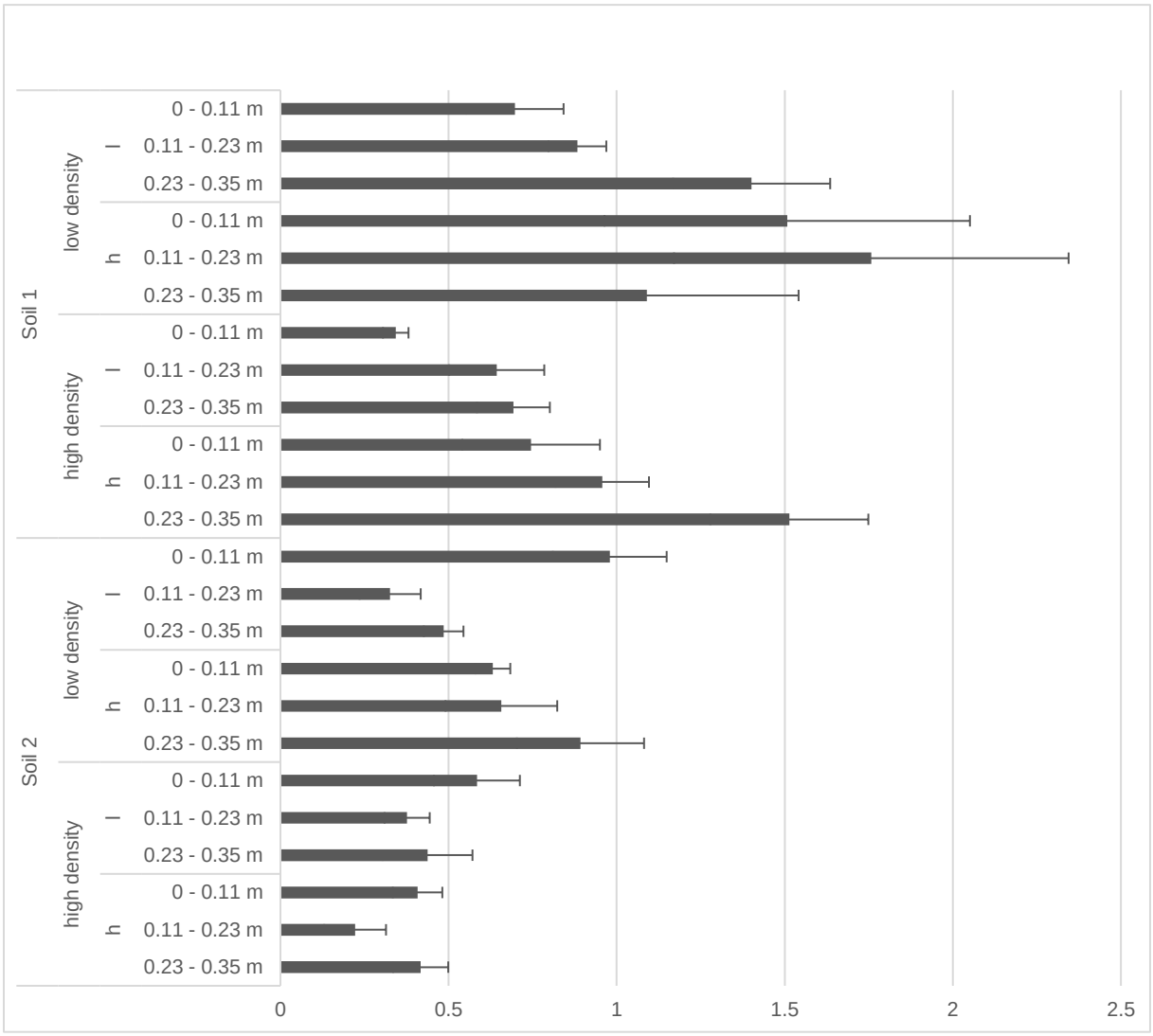


Figure 12: Ratio between root biomass C and rhizodeposition C throughout soil depths. High SBD treatment correspond to 1.2g/cm^3 and low SBD to 0.9g/cm^3. Letter h corresponds to high CO_2 treatment and letter l to low CO_2 treatment in MICE.

Table 8: Results of ANOVA of root biomass C:rhizodeposition C ratio. Numbers and stars indicate significance level. “n.s” indicates no significance.

	Soil Type	**SBD**	**CO_2**	**Soil Depth**	**Soil Type: CO_2**
Root C:Rhizodeposition C	n.s	0.01**	0.01**	0.001***	0.05*

Figure 12 illustrates the ratio of root biomass C to rhizodeposition C. The higher the ratio is, the lower is the rhizodeposition compared to root biomass C and vice versa. The ratio is significant for SBD treatments, CO_2 treatments and soil type. There is a increase of the ratio from top to bottom layer, meaning rhizodeposition decreases compared to total root biomass C, but it is not significiant. Ratios for soil type 1 (1.02) low density SBD (0.95) and the high CO_2 treatment are higher than for soil 2 (0.55), high SBD treatment (0.63) and low CO_2 treatment (0.66). There is an interacton between the two factors soil type and CO_2 treatment (Table 8).

4.3 Priming effect after MICE experiment

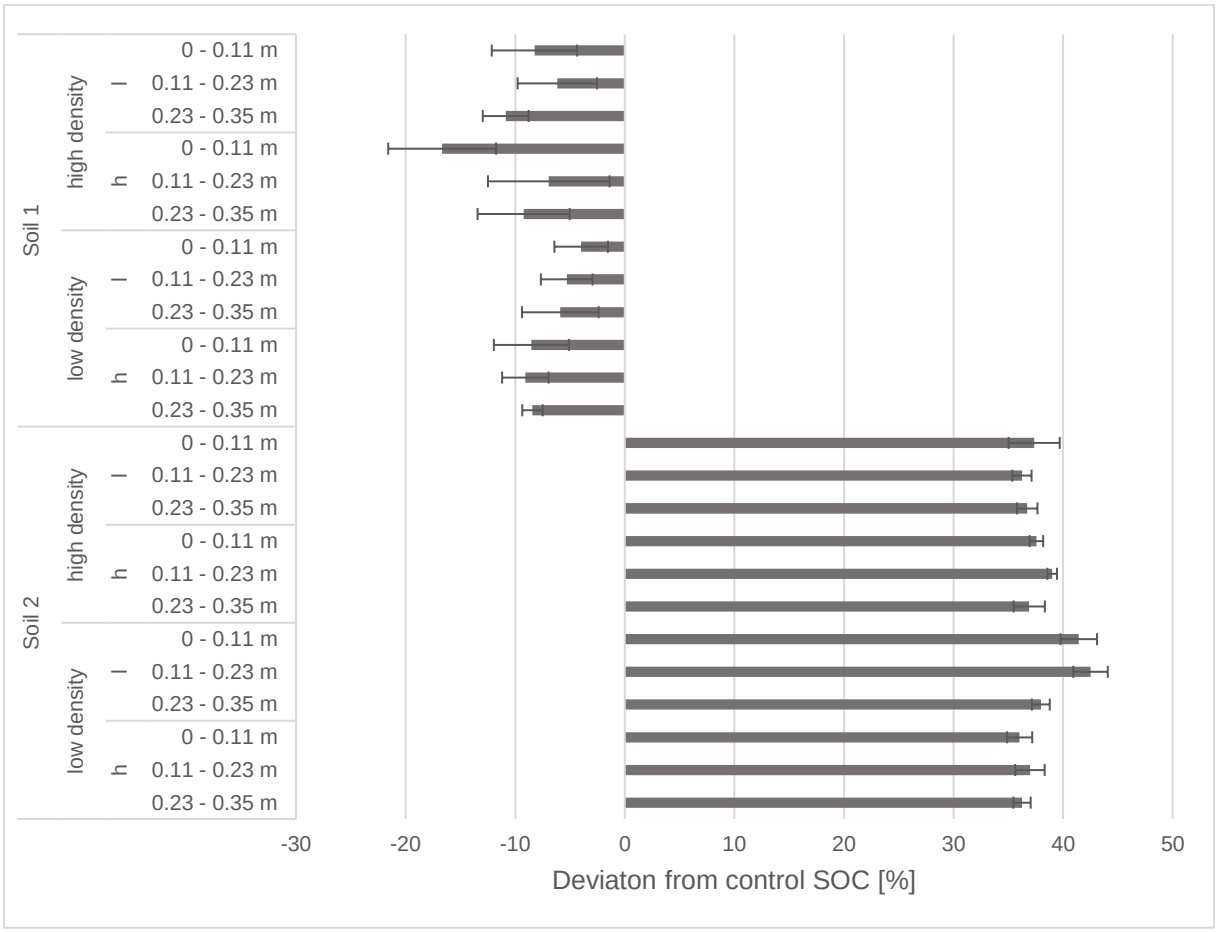


Figure 13: PE after MICE experiment throughout soil depths. High SBD treatment correspond to 1.2g/cm^3 and low SBD to 0.9g/cm^3. Letter h corresponds to high CO_2 treatment and letter l to low CO_2 treatment in MICE.

Table 9: Results of ANOVA of PE. Numbers and stars indicate significance level. “n.s” indicates no significance.

	Soil Type	**SBD**	**CO_2**	**Soil Depth**
Priming effect	0.001***	0.01**	0.01**	n.s

Priming effects are illustrated in Figure 13. Soil 1 and 2 showed contrasting PE. Low negative values, thus positive PE apply for soil 1 and positive values, thus negative PE to a greater extent for soil 2. PE is also significant for SBD treatments and CO_2 treatments. A stronger negative PE can be observed for low SBD treatments (15.82%) than for high SBD treatments (12.54%). The same is true for CO_2 treatments (low CO_2: 15.98%; high CO_2: 12.38%). The different directions of the PE between the soil

type 1 and 2 can have various reasons as PE is affected, among others, by soil type and nutrient concentrations and can be intensified by roots and rhizodeposition (Fontaine *et al.*, 2004, 2007; Fu and Cheng, 2002; Kuzyakov *et al.*, 2000). No interactions occur between factors for PE (Table 9).

4.4 Decomposition of rhizodeposition

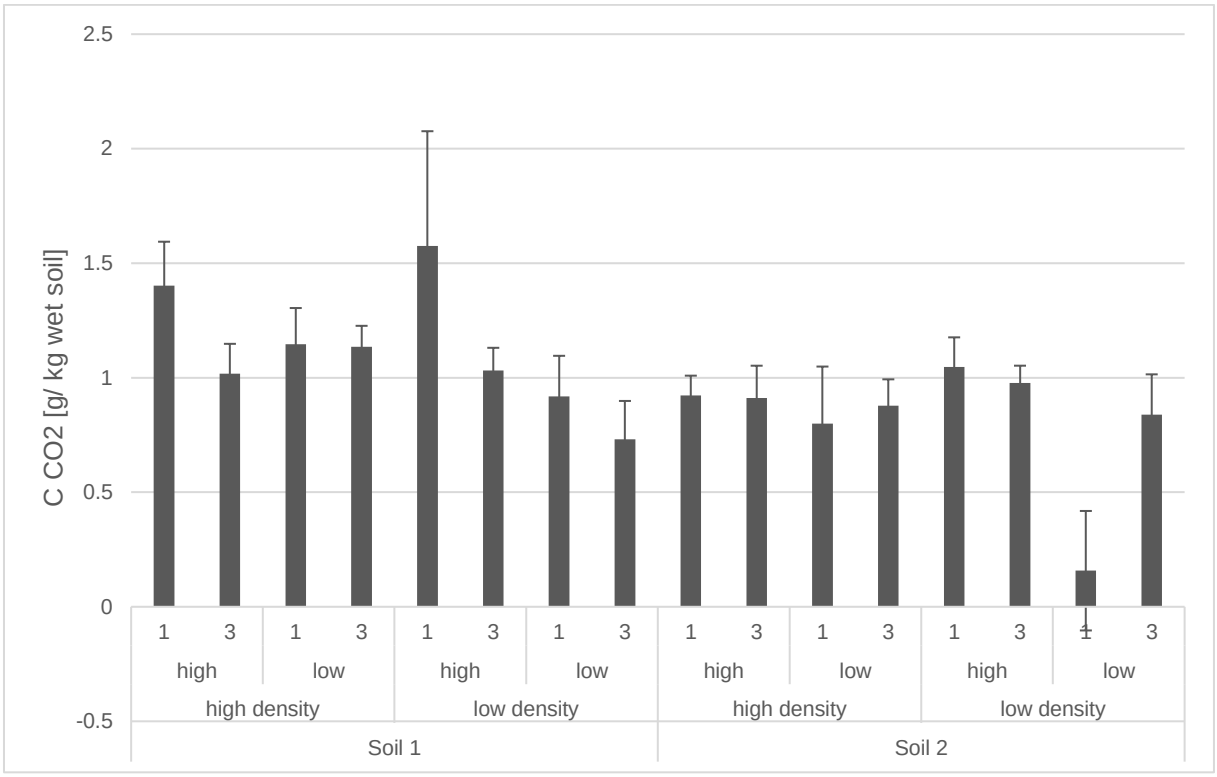


Figure 14: Cumulated respired C CO_2 from root free soil after incuabation experiment. High SBD treatment correspond to 1.2g/cm^3 and low SBD to 0.9g/cm^3. "High" corresponds to high CO_2 treatment and "low" to low CO_2 treatment in MICE.

Table 10: Results of ANOVA of cumulated C CO_2. Numbers and stars indicate significance level. "n.s" indicates no significance.

	Soil Type	**SBD**	**CO_2**	**Soil Depth**	**Soil Type: SBD**	**Soil Type:Soil Depth**
C CO_2	0.01**	n.s	0.01**	n.s	0.05*	0.05*

Figure 14 shows the cumulated C CO_2 of the incubation experiment, measured and calculated according the electrical conductivity (see 3.5.2). Respired C CO_2 significantly differed between CO_2 treatments and soil types. Average C CO_2 respired from soil 1 was 1.12 g/kg wet soil and 0.81 g from soil 2. High SBD treatment samples respired 1.12 g/kg wet soil and low SBD treatments 0.82 g/kg wet soil C CO_2. High CO_2 treatment respired 1.12 g/kg wet soil C CO_2 and low CO_2 treatment respired 0.82 g/kg wet soil C CO_2. Interactions can be observed between the factors soil type, SBD and Soil type, soil depth (Table 10).

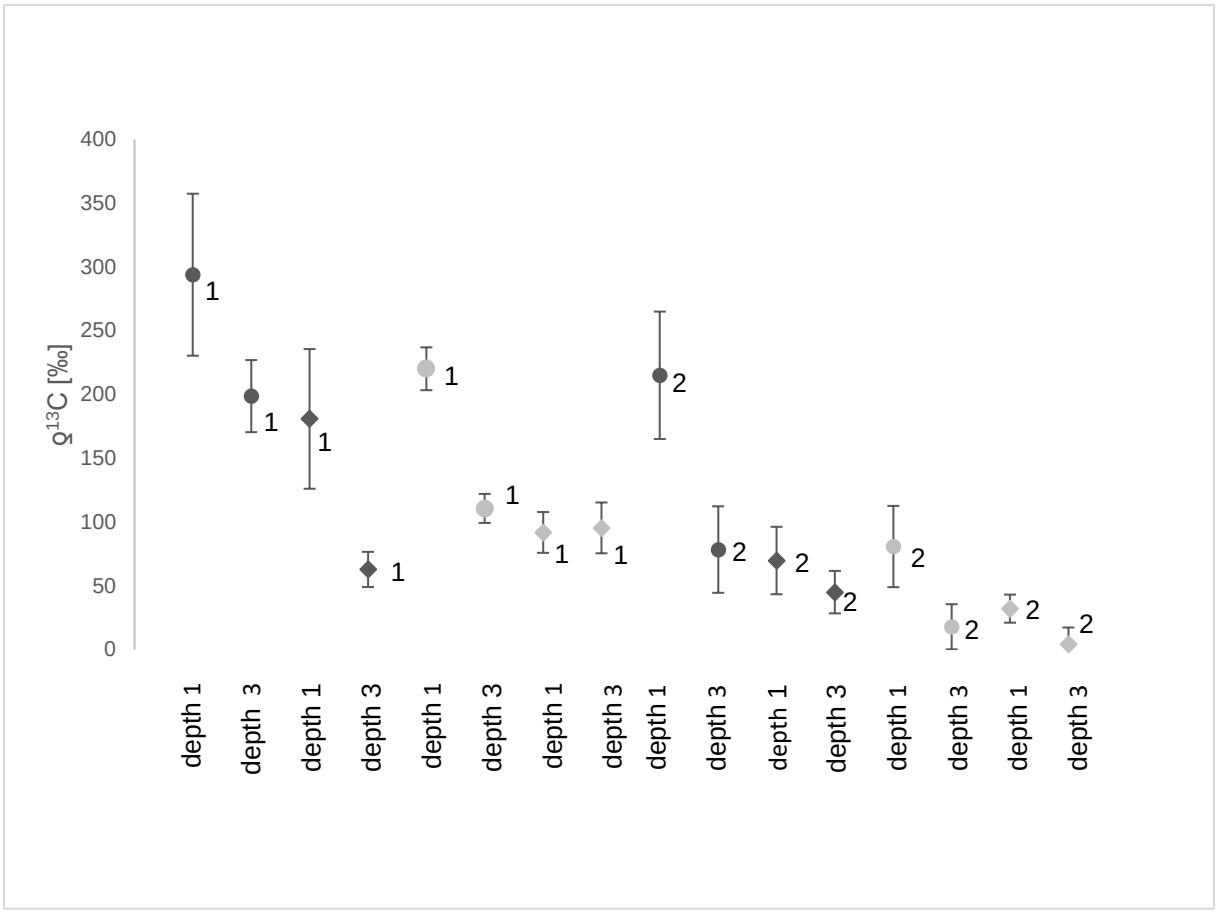


Figure 15: ϱ^{13}C signal of cumulated respired C CO_2 from root free soil after incubation experiment. Dark grey colour corresponds to high density treatment, light grey colour to low density treatment. Dots correspond to high CO_2 treatments, squares to low CO_2 treatments. The numbers correspond to the soil type. Number 1 is soil type 1 and number 2 is soil type 2.

Table 11: Results of ANOVA of ϱ^{13}C signal of C CO_2. Numbers and stars indicate significance level.

	Soil Type	**SBD**	**CO_2**	**Soil Depth**
ϱ^{13}C signal C CO_2	0.001***	0.001***	0.001***	0.001***

Figure 15 represents the ϱ^{13}C signal of C CO_2 trapped in the NaOH vials. Values are highly significant for all parameters such as CO_2 treatments, soil type, SBD treatments and soil depths. The signal of high CO_2 treatment is 153‰ and 73‰ for low CO_2 treatment, 158‰ for soil 1 and 63‰ for soil 2, 143‰ for high SBD treatment and 81‰ low SBD treatment. ϱ^{13}C signal for soil depth 1 is 146‰ and 76‰ for soil depth 3. No interactions occur between factors for the ϱ^{13}C signal of C CO_2 (Table 11).

5 Discussion

5.1 Atmospheric CO_2 influence on above ground biomass, root biomass and rhizodeposition

The results of MICE experiment regarding biomass of plant and root were in line with the literature and the expected increase of AGB with increased atmospheric CO_2 Increase of atmospheric CO_2 concentration has a fertilizing effect on plants and enhances root and biomass growth (Cao and Woodward, 1998; Rustad *et al.*, 2001; Vuuren *et al.*, 1997). Therefore, it is not a surprise that CO_2 has also a significant effect on root:shoot ratio. Low ABG was coincided with a higher amount of root biomass in contrast to high AGB that resulted in less root biomass

Nguyen (2003) states that elevated CO_2 had a positive effect on rhizosphere respiration. Since CO_2 triggers root growth, more root biomass derived C and also rhizosphere derived C could have been expected also for the experiments of this thesis. Results showed that indeed that root biomass derived C increased but an increased atmospheric CO_2 level did not lead to a higher amount of rhizodeposition. Bolinder *et al.* (1997) suggested that belowground C input can be estimated taking shoot biomass into account. Considering Figure 11 the total amount of rhizodeposition cannot directly be related to the total amount of root biomass C. Reason could be that rhizodeposition is affected by many factors such as plant age, the microorganisms, physical and chemical soil properties, soil nutrient availability, temperature or soil pH (Nguyen, 2003). In addition, Nguyen (2003) declares that high CO_2 may have led to an increase in rhizodpeosition. However, increase of rhizodeposition under elevated CO_2 conditions is rather indirectly and due to the effect of CO_2 on root growth. Results of this thesis support these findings as elevated CO_2 affects plant growth but it does not influence rhizodeposition. CO_2 seems to amplify effects of factors as interactions of the ANOVA tests showed. There are significant interactions in measurements of AGB, root biomass, root:shoot ratio, root biomass C, rhizodeposition C, ratio of root biomass C:rhizodeposition and respired C CO_2. Significant effects such as soil type and SBD for AGB are even stronger when combined with CO_2 treatment. CO_2 and soil type as factors are significant for root:shoot ratio (0.01** each) interaction is even of higher significance for these two (0.001***). CO_2 amplifies also the significance of soil depth of rhizodeposition.

5.2 Soil properties influence on biomass and root derived carbon

5.2.1 Influence of soil organic carbon and clay content on biomass and root derived carbon

Results showed that soil type, i.e. SOC and clay content had no effect on the amount of AGB itself. As the plant does not consist only of AGB it makes sense to look at proportion of plant parts (Wilson, 1988). And indeed, considering root:shoot ratio a significant difference between soil type 1 and soil type 2 is visible. The root:shoot values show that shoot biomass does not differ between soil types but root biomass is higher in soil 1 than in in soil 2, leading to a higher ratio for soil 1. These findings are in line

with the expectations as roots adapt to their outside conditions. Soil 2 contains more clay, thus more nutrients bound to clay can be expected. The opposite applies for soil 1. Plants favour growth of the organ where a resource is missing (Shipley and Meziane, 2002). As a result, more root biomass is in soil 1 where less nutrients are directly available.

There is an obvious difference in the PE between the two soil types. Direction of PE differs between the soil types. Positive PE, thus less carbon than originally in stock can be shown for soil 1. Soil 2 shows a strong negative PE, thus more carbon was measured after MICE than originally available. This phenomenon can have various reasons. In literature, positive PE is often associated with roots (Cheng *et al.*, 2014). However, Pausch *et al. (*2016) demonstrated that roots with no root hair led to negative PE. Cheng *et al.* (2014) suggest that negative PE may not be long-lasting as it was just reported from short-term experiments that lasted 38 days maximum. The time-aspect and the biased information throughout literature makes clear that it also important to look at other factors than just roots, such as soil type and soil nutrient concentrations (Cheng *et al.*, 2014; Fu and Cheng, 2002; Kuzyakov *et al.*, 2000). There is positive PE where more root biomass is, i. e. soil 1. Reason for negative PE in soil 2 could be that organic compounds, especially rhizodeposits, bound to the mineral phase (Rasse *et al.*, 2005). As soil 2 has a higher content of clay, more charged minerals are available to bind C to it. Result is that organic C is stabilised and protected against decomposition. The same trend has already been shown by Wang *et al.* (2003) who stated that SOC decomposition is restrained with increasing clay content. These findings are also supported by $\wr^{13}C$ signal of C CO_2 after the incubation (see figure 15). $\wr^{13}C$ signal is significantly higher for soil 1 what could induce the higher degree of decomposition of carbon in this soil. Also total amount C CO_2 respired from soils is smaller in soil 2, where the better protected and immobile SOC is supposed to be (see Figure 14). Interaction between the soil depth, type and depth, SBD and the combination of the three are all highly significant. It seems that soil types explain differences in SBD.

5.2.2 Influence of soil bulk density, soil depths and the combination on biomass and root derived carbon

During the experiment in MICE, SBD changed throughout the soil depths. Soil depth 1 shows initial SBD of 0.91 g/cm^3 for low density treatment and 1.19 g/cm^3 for high density treatment. Low SBD treatment increases steadily from top to bottom soil layer until it reaches 1.04 g/cm^3 at the bottom. High SBD treatment first decreases from top to middle soil layer to 0.05 g/cm^3 and increases from middle to bottom soil layer in the subsequent to 1.26 g/cm^3 (see Figure 16). Fine particles were shifted vertically with irrigation and accumulated at the bottom layer between 0.23 and 0.35 m (Blume *et al.*, 2010). However, the difference in SBD between the two treatments never exceeded 0.3 g/cm^3 throughout all three soil depths. This rather small difference in SBD still had major impact on almost all of the factors investigated.

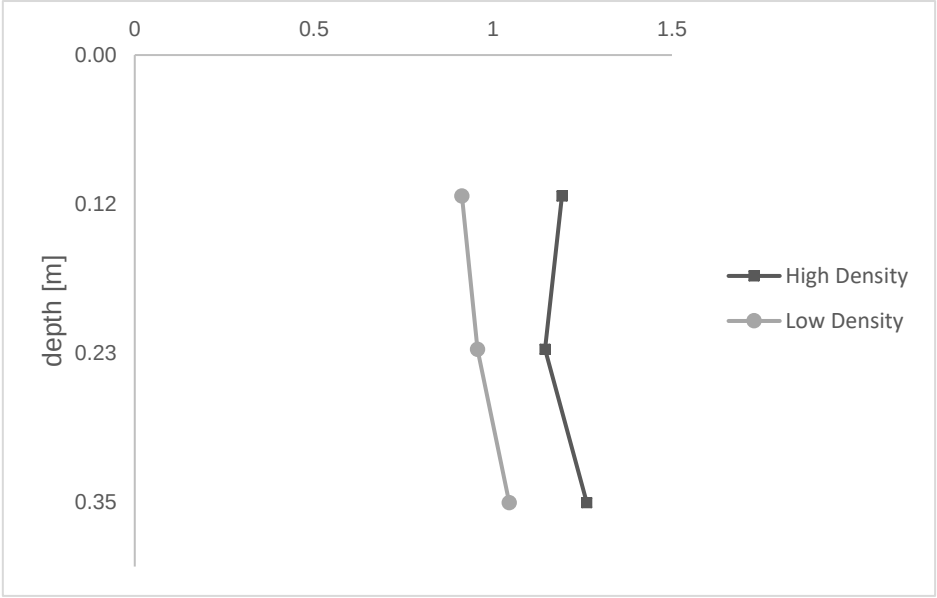


Figure 16: Calculated SBD after MICE experiment.

Soil bulk density had a significant effect on AGB, root biomass, root:shoot ratio, root biomass derived C, PE and $\delta^{13}C$ signal. AGB was significantly increased in the high SBD treatment compared to low SBD treatment. Same applies considering root biomass and root:shoot ratio respectively. There was less root biomass in high SBD treatment compared to low SBD treatment. Consequently, root:shoot ratio resulted in higher values for low SBD treatment compared to high SBD treatment. The explanation for high AGB and low root biomass for high SBD treatment and low AGB and high root biomass for low SBD treatment, respectively lies in the already mentioned equilibrium between root and shoot of a plant. Low SBD soil may not provide enough mechanical strength to provide enough root anchorage and plant stability (Bengough and Mullins, 1990). As roots adapt to limiting factors, plant grows more root biomass to increase stability. To sustain equilibrium, the increased growth goes along with an inhibited growth of AGB.

As there is more root biomass in low SBD soils also more root biomass derived carbon can be expected. Findings of this thesis supports this as there is a significant higher amount of root biomass derived carbon in low SBD soils. However, rhizodeposition derived C does not differ between SBD treatment.

SBD treatments do not differ in direction of PE but in its strength. Low SBD treatment shows more negative PE than high SBD treatment. An explanation for this could be that in low SBD treatment, a high amount of root biomass was reported. This could have led a higher number of soil aggregates, which protected and fixed root derived carbon in the soil (see 1.2.1 & 1.2.2).

Total root biomass, root biomass derived C, rhizodeposition and $\delta^{13}C$ signal of respiration significantly differed between the three soil depths.

What is particularly striking is the very high amount of root biomass in the first soil depth of low SBD treatment, which almost reached 1 g. As visible in Figure 16, SBD did not differ more than 0.1g/cm^3 in all of the three soil depths and between the two SBD treatments. Further, SBD was rather evenly distributed. Similar root biomass distribution pattern could have been expected because many studies have been conducted where adaption of root growth, architecture and branching were studied under changing outside conditions, i.e. biochar amendment (Abiven 2015) or lacking or availability of nutrients

(Hirte *et al.*, 2018a; Lambers *et al.*, 2006; Saengwilai *et al.*, 2014). Roots grew uniformly according to external conditions. However, difference in root biomass the two SBD treatments is much higher in soil depth 1 compared to soil depth 2 and 3. There is much written throughout literature of the last few decades about critical high SBD and its effect on roots (Dexter, 2004; Jones, 1983; Pabin *et al.*, 1998) but nothing about the influence of low SBD under 1 g/cm^3. Dunbabin *et al.* (2003) published a study, where they showed that root biomass maximizes quickly in top soils in order to capture nitrate in sandy and permeable soils. Most likely, same applies for this thesis but the limiting factor was not nitrate but plant stability. SBD may has fallen below a critical threshold in soil depth 1 of low SBD treatment and forced the plant to maximize root growth in top layer to sustain plant stability.
Root biomass C distribution shows the expected pattern and decreases from top to bottom layer.
The decrease from top to the middle and the subsequent increase may be misleading. The capacity of the tubes were limited to 35 cm. Roots could have grown into deeper soil depths but were stopped at 35 cm. That led to an accumulation of roots at the bottom of the column and lead to an increase in root biomass C in the bottom layer.

5.3 Special case rhizodeposition and findings after incubation experiment

Rhizodeposition is only significant between soil depths but did not differ between CO_2 or SBD treatments, even though root biomass and root biomass derived C differed significantly for these treatments. Root biomass and root biomass derived C is significant between soil depths (Figure 17). These findings may induce that the amount of rhizodeposition is linked to the amount of root biomass. Also Hirte *et al.* (2018b) discovered that the ratio between rhizodeposition to total root biomass C input is significant between soil depth due to changes in vertical distribution of root biomass.
As illustrated in Figure 17, the first soil depth shows the highest amount root biomass derived C as well as the highest amount of rhizodeposition. Second depth has slightly less root biomass derived C compared to bottom soil depth but rhizodeposition is greater in soil depth two than three. These findings do not correspond with Friedli (2017) who detected an increase from top to bottom soil depth or rhizodeposition at plant harvest. Explanation for this could be that the different soil properties (21% clay and 0.91% TOC) led to a different composition of rhizodeposits excreted. Soil properties itself or composition of rhizodeposits or combination of both must have been more favourable to transportation in the experiment of Friedli (2017).

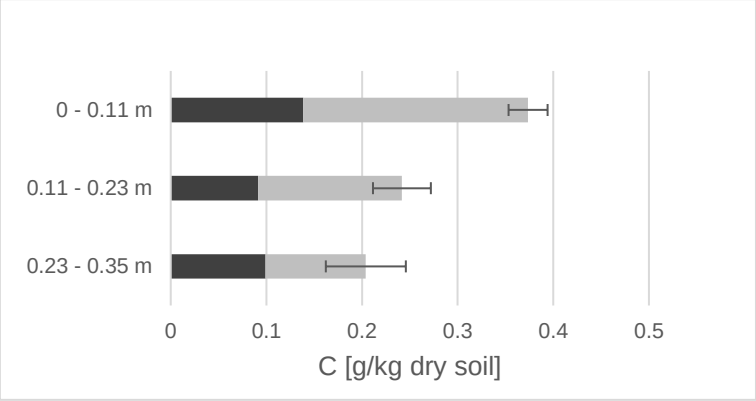


Figure 17: Root derived carbon per soil dephts. Dark grey correspond to root biomass C and light grey corresponds to rhizodeposition C.

Root biomass input in soil type 1 is higher than in soil 2 (Figure 18), the amount of rhizodeposition is higher than root biomass derived C but difference of rhizodeposition between the treatments is negligible. The same applies for CO_2 and SBD treatments (Figure 19 and Figure 20).

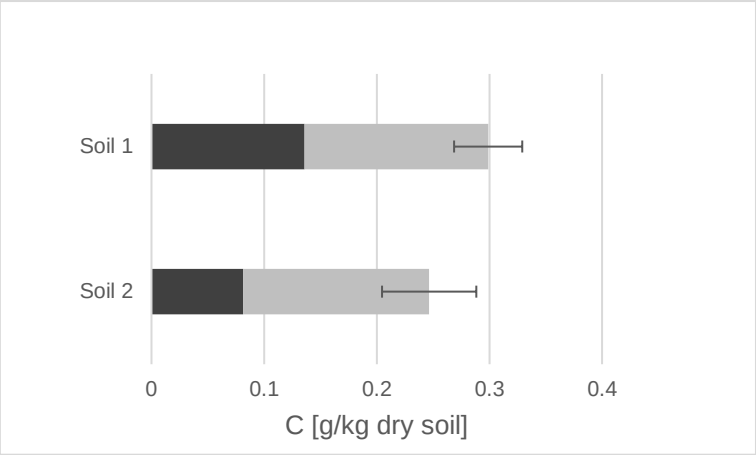


Figure 18:. Root derived carbon of soil type 1 and soil type 2. Dark grey correspond to root biomass C and light grey corresponds to rhizodeposition C.

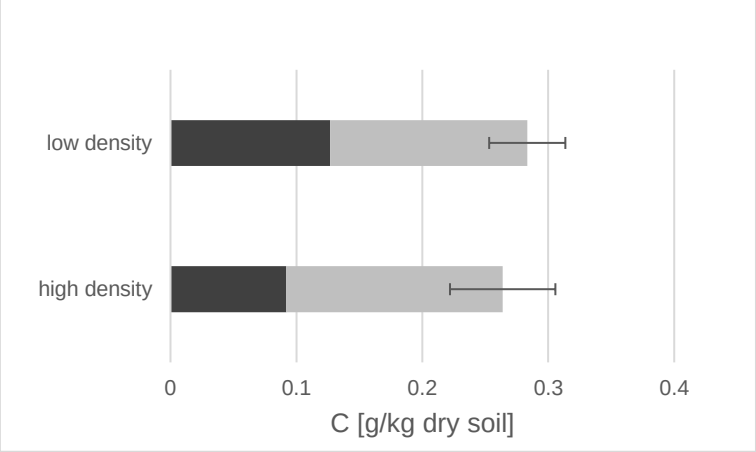


Figure 19: Root derived carbon of high density and low density treatments. Dark grey correspond to root biomass C and light grey corresponds to rhizodeposition C.

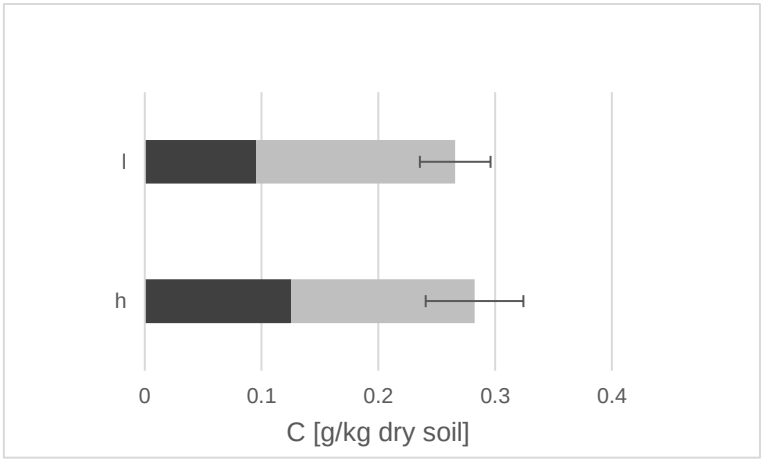


Figure 20: Root derived carbon of high (h) and low (l) CO_2 treatments. Dark grey correspond to root biomass C and light grey corresponds to rhizodeposition C.

In other words, no conclusions regarding the total amount of rhizodeposition derived C can be drawn only by looking at root biomass derived C. Reason could be that that rhizosphere and rhizodeposition is controlled by many soil physical and chemical properties. Results of this thesis show that these properties seem to have greater effect on total amount of rhizodeposition than the amount of root biomass and root biomass derived C content have.

In order to investigate activity of root rhizodeposits production, it is better to put it in relation to root C production. Comparing root biomass C to rhizodeposition C makes clear that there is more root activity in soil 2, high SBD treatment and low CO_2 treatment. Results are inversely proportional to root biomass C and root:shoot ratio respectively. That means, wherever high shoot biomass, low root biomass and low root derived biomass C occur, root activity is higher than where root biomass and root biomass derived C is high and shoot biomass is low. Where SBD is high, roots might have increased activity in order to exudate mucilage and root cap cells what improves root growth (Bengough and McKenzie, 1997). Wherever root growth is limited, root activity is increased. It might be that roots offset limiting root growth conditions by enhanced root activity.

According to the difference of rhizodeposition also signal of $\varrho^{13}C$ of respired C CO_2 differed between the soil depths. The signal was constantly lower for bottom soil depth than for top soil depth. Furthermore, $\varrho^{13}C$ CO_2 differed highly significant between soil types, SBD and CO_2 treatments. ϱ^{13} signal of C CO_2 and the total amount of the respired C CO_2 are influenced by rhizodeposition C and SOC. $\varrho^{13}C$ signal of rhizodeposition is affected by factors such as the decomposition level of rhizodeposits, how strongly roots have been labelled where the rhizodeposits originate from and the total amount of the rhizodeposition. Labelling of roots will be neglected in the discussion as all roots were highly labelled. There are significant differences in ϱ^{13} C CO signal between all factors (SBD, soil types, soil depths and CO_2 treatment). Furthermore, there are significant differences between for soil types and CO_2 treatments of total respired C CO_2 after the incubation. There is just a significant difference between rhizodeposition between soil depths. These facts tell us a lot about the composition of the rhizodeposits. As learned in section 1.2.2, rhizodeposits consists of a wide range of components which ones are easier degradable than the others are. The easier rhizodeposits are degradable, the more energy is available and as a

result, the higher is soil microbial activity and soil respiration. The amount of rhizodeposition was significantly higher in soil depth 1 compared to depth 3. Therefore, ϱ^{13}C signal is higher too.

High SBD treatment showed significantly less root biomass and no significant difference of rhizodeposition. A higher ϱ^{13}C signal was measured in high SBD treatment, what leads to the assumption that high SBD treatment must have caused roots to excrete easier decomposable rhizodeposits compared to the low SBD treatment. The same applies for CO_2 treatments. Incubated soils from the high CO_2 treatment excreted easier decomposable rhizodeposits. As CO_2 acts as fertilizer and enhances plant growth, assumption is plausible that the rhizodeposits excreted from those treatments were not supposed to acquire nutrients. The ϱ^{13}C signal of soil 1 is elevated compared to soil 2. As already discussed, clay content favour building of aggregates, which can protect C from decomposition. Results supported this as the higher ϱ^{13}C values in soil 1 could induce a higher level of decomposition of the available C. Nutrients may not be so well available in soil 1 than in soil 2 as result of the lower clay content. That could have led to the difference in rhizodeposition compounds.

Indeed, the total measured respired C CO_2 from the decomposition of rhizodeposition significantly differed between soil type and CO_2 treatment and was higher for soil type 1 and for high CO_2 treatment. However, respiration was not significant for SBD treatments and soil depths. Both of the not significant factors interacted with soil type inducing that they explain part of soil type significance.

5.4 Persistence and storage of root derived carbon in agricultural soils

Roots contribute to SOC by building aggregates. Fine roots may grow into the aggregates where they are protected from decomposition. It is widely discussed throughout literature how much rhizodeposition contribute to SOC (Chabbi *et al.*, 2001; Gregory, 2006; Kandeler *et al.*, 1998; Rasse *et al.*, 2005; Traoré *et al.*, 2000). Results above showed that growth of root biomass, root derived C input, rhizodeposition and its decomposition is influenced by many things such as physical and chemical soil properties. It would therefore be of advantage in terms of storing as much C as possible in soils to enhance root biomass input and to create as favourable soil physical and chemical conditions as possible to preserve it. However, the discussion about root derived C input, storage and preservation into soils becomes more complex referring it to agriculture. As mentioned in the introduction, agriculture influences soil physical and chemical properties by enhanced nutrients input, compaction and agricultural processes such as ploughing. Critical SBD may suppress root growth (see 1.2.1) what limits root C input but at a certain level, it also stops decomposition of SOC (De Neve and Hofman, 2000). Especially ploughing is mentioned as cause of short-term loss of SOC throughout literature (Chan *et al.*, 2002; Clapp *et al.*, 2000; Reicosky and Archer, 2007). Effect of fertilizer will not be further discussed, as it was not assessed as a driver of root derived C input into soils in this thesis.

In a short-term perspective, results of root biomass growth in the low density treatments of top soil depth show that at the very beginning of growing phase root derived C input can be maximized. Even though no differences of rhizodeposition between the factors SBD, CO_2 treatment and soil type could be detected, there was a significant higher amount of rhizodeposition where the more root biomass was. Furthermore, results have shown that on one hand, soil with low clay and low SOC content favour root

growth and root biomass C input. On the other hand, soil with high clay and high SOC concentrations are favourable in terms of C storage and preservation.

Where root biomass is high, also rhizodeposition is high. However, rhizodeposits are more likely to decompose. On the other hand, they are also more mobile and may be transported to lower soil depths where they are more protected and microbial activity is lower (Rasse *et al.*, 2005). On a long-term scale, ploughing does not affect turnover of C (Ussiri and Lal, 2009). Results of this thesis even suggest on the short-term view that ploughing and the resulting low SBD in the upper soil layers might increase root biomass growth at the beginning of the growing phase. The estimation of beneficing effects of clay content and concentration of SOC regarding root derived C input and C preservation is a balancing act as low levels of clay favour root growth and root biomass C input. Nevertheless, increased but too high levels may cause more compaction (Hamza and Anderson, 2005). Compaction can reduce decomposition of C but it also decreases root growth and root derived C input. However, SBD seems to be the game-changing factor as it is rather possible to affect SBD than clay content in soils with agricultural practices.

In order to maximize root derived C input it would make sense to sow crops in soil where SBD is as low as possible and to keep SBD low in the beginning of plant growth. So if careful to plow when the conditions are right in order to avoid compaction, ploughing as agricultural practice might be very favourable in terms of root derived carbon input into agricultural soils.

5.5 Climate change contribution to changes in global carbon dynamics

Climate change is a complex term and includes many dynamic interactions between all global C pools. As learned in section 1.3, atmospheric CO_2 concentration is rising. As factor of climate change, increasing atmospheric CO_2 and its influence on root derived C in soils was investigated. It is widely discussed that elevated atmospheric CO_2 leads to an increase of root and shoot biomass and other changes in root growth patterns (see 1.3.2). This leads to either more SOM input into soils but also to enhanced soil microbial respiration and decomposition.

Results of this thesis suggest that elevated CO_2 concentration is not favourable in terms of SOC input by roots. Atmospheric CO_2 concentration has a significant effect on AGB but increased AGB goes along with less root biomass as root:shoot biomass data revealed. Root biomass alone is not significant for CO_2 but root biomass C is. That leads to the assumption that the roots are at advantage when it comes to increased CO_2 during C partioning. Nevertheless, high atmospheric CO_2 levels also lead to low root activity regarding exudation of rhizodeposits.

$\delta^{13}C$ signal of C CO_2 after the incubation was significantly higher for the elevated CO_2 scenario. Reason for that may be the stronger labelling of root biomass, which led to a stronger signal of the decomposed rhizodeposits. Total respired C CO_2 was higher for high CO_2 treatment than for low CO_2 treatment. That indicates that either the microbial community changed during high CO_2 treatment in MICE or that the root exudates are of low stable quality and are easily decomposable or both. Either way, elevated atmospheric CO_2 concentration seems not to have a positive influence on MRT of C. Increase of AGB and its contribution to SOC may be so high that it offsets negative aspects shown for root derived C under elevated CO_2. Literature suggest that the fertilizing effect of CO_2 is exhausted by 2060 (Jones *et*

al., 2005). As soon as that happens, effects mentioned above come to bear and soil may turn from C sink to C source. This effect of root derived C loss and preservation of root derived C respectively, could be slowed down trying to maximize total root biomass input into soils. As results suggested, roots are in favour of C partioning under elevated CO_2. Increased root biomass may result in increased root biomass C. Maximizing root biomass input as suggested in 5.4 could lead to a net enhancement of root derived C in soils and to a deceleration of root derived C loss.

6 Conclusion

Results of this thesis suggest that changes in climatic properties and soil properties lead to modifications in plant and root growth. However, estimation of root derived C input remains difficult, as rhizodeposition is not dependent on root biomass derived C. As hypothesized, photosynthetic carbon assimilation increased with high atmospheric CO_2 levels and led to an increase of the AGB. Nevertheless, high atmospheric CO_2 levels and high amounts of AGB did not automatically lead to an increase in root biomass input. Rather the opposite was the case and with increasing AGB, a decrease of root biomass input was observed leading to low root:shoot. Where ABG was low, root biomass was high and total amount of rhizodeposits accelerated too. Rhizodeposition was not significant for CO_2 treatments but it was significantly different between soil types and decreased from top soil layer to bottom soil layer, as total root biomass did too. Assumption can be made that total amount of rhizodeposition is controlled by the amount of root biomass rather than by atmospheric CO_2 concentration. Nevertheless, increased atmospheric CO_2 level might have led to easier decomposable rhizodeposits as the total amount of C CO_2 respired was higher in high CO_2 treatment soils. Interaction between CO_2 and the other factors investigated (SBD, soil type and soil depth) revealed that atmospheric CO_2 as a driver had an amplifying effect on many significances within different measurements taken (AGB, root biomass, root:shoot ratio, root biomass C, rhizodeposition, ratio of root biomass C to rhizodeposition C and C CO_2 respired after the incubation).

As assumed, there was less root biomass in the high SBD treatment than in the low SBD treatment. This was the case rather due to enhanced growth in the very low SBD treatment in order to sustain plant stability than due limiting effects of a high SBD. Because of less total root biomass in high SBD treatments, root biomass C was lower too. In soil 2, where clay content and SOC concentration was higher than in soil 1, root biomass grew less and root biomass C was lower which fits the hypothesis. Contrary to what was hypothesized is that there is no difference of amount of rhizodeposition between the two soil types, even though root biomass C is significantly lower in soil 2. SBD treatments showed no significant effect on total amount of rhizodeposition. Total amount of rhizodeposition is not controlled by the factors SBD, CO_2 treatments or soil type but they seem to control root activity regarding the exudation of rhizodeposits. Root activity was higher in soil type 2, high SBD treatment and low CO_2 treatments. More C CO_2 was respired in soil type 1 and where high CO_2 treatment was applied in MICE. Overall, soil type 2 led to less root derived C input but C was more resilient against soil microbial decomposition, low SBD led to a very high root derived C input that was rather resilient compared to C in high SBD treatment and high CO_2 treatment led to more root derived C but it was rather unstable. The most root derived C was produced in top soil layer due to the significantly higher amounts of root biomass and the higher amount of total amount of rhizodeposition. The amount of root derived C decreased from top to bottom.

Results suggest that agricultural management might be able to affect production and storage of root derived C in soils by maximizing root biomass at the beginning of grain growing phase.

However, the absence of significant differences of the amount of rhizodeposition between many factors tested reveals that there are still uncertainties concerning drivers of rhizodeposition. Furthermore, more

information should be gained about processes influencing transportation and storage of rhizodeposition derived C in soils.

7 Limitations

Several limitations appear regarding this thesis. Rhizodeposition dynamics is the scientific field where the greatest uncertainties occur (Kuzyakov and Domanski, 2000). The comparability to real field conditions is a limitation of this thesis as there are only a few rhizosphere and rhizodeposition studies under field conditions (Pausch and Kuzyakov, 2018). The pot density of soil in columns of approximately 319 cm^3 is not directly comparable to real field SBD as in the field SBD can be very heterogeneous within small distances (Brady and Weil, 2016). Furthermore, conditions in MICE cannot adapted to the field in full extent. It was technically not possible to cool down the climate chambers of MICE facility below 18°C. These day-night temperature cycles with high night temperatures may have enhanced the process of growing which would have been much slower in the field. That means that one day in MICE does not correspond to one day in the field. In addition, two experiments were conducted in this thesis, where roots have been picked in between. The results of the second experiment, the incubation, refer to root-free soil. However, wherever roots are picked, some leftovers remain in the soil what might lead to an over or underestimation of the incubation results in some cases. As a result, the root picking error may have also influenced results of root biomass and root biomass C values at the end of MICE experiment. Furthermore, many calculations with corrected values were made to get cumulated C CO_2 values for the incubation experiment, what may have disturbed the result to a small extent.

8 Outlook

There are still many uncertainties regarding root derived C production in soils. Especially the process of rhizodeposition remains difficult to assess. The drivers of excreted rhizodeposits related to the amount of root biomass C remains rather unclear and needs to be further investigated. In this thesis, factors SBD, atmospheric CO_2 concentration, clay content and SOC content were investigated. Other physical, chemical and climatic properties may provide more insight into root derived C production and storage and could improve terrestrial C pool modelling.

It is a matter of time until terrestrial C pool turns from sink to source of C. Further research could target the adaption of findings of laboratory studies to real field conditions as this may help to improve estimation when this change is going to happen.

9 Bibliography

9.1 List of references

Abiven, S. Menasseri, S. and Chenu, C. (2009). The effects of organic inputs over time on soil aggregate stability – A literature analysis. *Soil Biology and Biochemistry* 41(1): 1–12.

Abt, J. (2017). Mineralisation of carbon from root residues in agricultural and grassland soils of Switzerland. Assessment of carbon mineralisation by laboratory incubation and isotopic analysis. Master Thesis, University of Zurich.

Ainsworth, E. A. and Long, S. P. (2005). What have we learned from 15 years of free-air CO2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO2. *New Phytologist* 165(2): 351–372-

Alexandratos, N. and Bruinsma, J. (2012). World agriculture towards 2030/2050: the 2012 revision. *ESA Working paper NO. 12-03*. Rome, FAO.

Anderson, J. P. E. and Domsch, K. H. (1978). A physiological method for the quantitative measurement of microbial biomass in soils. *Soil Biology and Biochemistry* 10(3): 215–221.

Angers, D.A. and Eriksen-Hamel, N. S. (2008). Full-Inversion Tillage and Organic Carbon Distribution in Soil Profiles: A Meta-Analysis. *Soil Science Society of America Journal* 72(5): 1370-1374.

Bais, H.P., Weir, T. L., Perry, L.G., Gilroy, S. and Vivanco, J. M. (2006). The Role of Root Exudates in Rhizosphere Interactions with Plants and Other Organisms. *Annual Review of Plant Biology* 57(1): 233–266.

Barrow, C.J. (2012). Biochar: Potential for countering land degradation and for improving agriculture. *Applied Geography* 34: 21–28.

Batts, G.R., Ellis, R.H., Morison, J. I. L., Nkemka, P. N., Gregory, P. J. and Hadley, P. (1998). Yield and partitioning in crops of contrasting cultivars of winter wheat in response to CO2 and temperature in field studies using temperature gradient tunnels. *The Journal of Agricultural Science* 130(1): 17–27.

Bengough, A. G. and McKenzie, B. M. (1997). Sloughing of root cap cells decreases the frictional resistance to maize (Zea mays L.) root growth. *Journal of Experimental Botany* 48(4): 885–893.

Bengough, A.G. and Mullins, C.E. (1990). Mechanical impedance to root growth: a review of experimental techniques and root growth responses. *Journal of Soil Science* 41(3): 341–358.

Bingeman, C. W., Varner, J. E. and Martin, W. P. (1953). The Effect of the Addition of Organic Materials on the Decomposition of an Organic Soil 1. *Soil Science Society of America Journal* 17(1): 34–38.

Binswanger, H. (1986). Agriculutral mechanization Comparative Historical Perspective. *The World Bank Research Observer* 1(1): 27–56.

Blume, H. P., Brümmer, G., Horn, G., Kandeler, E., Kögel-Knabner, I., Kretzschmar, R., Stahr, K. and Wilke, B. M. (2010). *Scheffer/Schachtschabel: Lehrbuch der Bodenkunde*. Springer: Berlin.

Boix-Fayos, C., Calvo-Cases, A., Imeson, A. C. and Soriano-Soto, M.D. (2001). Influence of soil properties on the aggregation of some Mediterranean soils and the use of aggregate size and stability as land degradation indicators. *CATENA* 44(1): 47–67.

Bolinder, M. A., Angers, D. A. and Dubuc, J. P. (1997). Estimating shoot to root ratios and annual carbon inputs in soils for cereal crops. *Agriculture, Ecosystems & Environment* 63(1): 61–66.

Bolinder, M. A., Janzen, H. H., Gregorich, E. G., Angers, D. A. and VandenBygaart, A. J. (2007). An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. *Agriculture, Ecosystems & Environment* 118(1): 29–42.

Brady, N. C. and Weil, R. R. (2016). *The Nature and Properties of Soil*. Pearson Education, Harlow.

Brüggemann, N., Gessler, A., Kayler, Z., Keel, S. G., Badeck, F., Barthel, M., Boeckx, P., Buchmann, N., Brugnoli, E., Esperschütz, J., Gavrichkova, O., Ghashghaie, J., Gomez-Casanovas, N., Keitel, C., Knohl, A., Kuptz, D., Palacio, S., Salmon, Y., Uchida, Y. and Bahn, M. (2011). Carbon allocation and carbon isotope fluxes in the plant-soil-atmosphere continuum: a review. *Biogeosciences* 8(11): 3457–3489.

Bundesamt für Landwirtschaft (1999). Richtlinien für den ökologischen Leistungsnachweis (ÖLN). *Koordinationsgruppe Richtlinien Deutschschweiz (KIP) c/o Landwirtschaftliche Beratungszentrale*, Eschikon.

Bundesamt für Raumentwicklung (1992). Sachplan Fruchtfolgeflächen FFF. Bern: ARE.

Cao, M. and Woodward, F. I. (1998). Dynamic responses of terrestrial ecosystem carbon cycling to global climate change. *Nature* 393(6682): 249–252.

Chabbi, A., Hines, M. E. and Rumpel, C. (2001). The role of organic carbon excretion by bulbous rush roots and its turnover and utilization by bacteria under iron plaques in extremely acid sediments. *Environmental and Experimental Botany* 46(3): 237–245.

Chan, K. Y., Heenan, D. P. and Oates, A. (2002). Soil carbon fractions and relationship to soil quality under different tillage and stubble management. *Soil and Tillage Research* 63(3–4): 133–139.

Cheng, W. (1996). Measurement of rhizosphere respiration and organic matter decomposition using natural $\delta^{13}C$. *Plant and Soil* 183(2): 263–268.

Cheng, W., Johnson, D. W. and Fu, S. (2003). Rhizosphere Effects on Decomposition. *Soil Science Society of America Journal* 67(5): 1418–1427.

Cheng, W., Parton, W. J., Gonzalez-Meler, M. A., Phillips, R., Asao, S., McNickle, G. G., Brzostek, E. and Jastrow, J. D. (2014). Synthesis and modeling perspectives of rhizosphere priming. *New Phytologist* 201(1): 31–44.

Ciais, P., Sabine, C., Bala, L., Brovkin, V., Canadell, J. G., Chhabra, R., DeFries, R., Galloway, J., Heimann, M., Jones, C., Le Quéré, C., Myneni, R. B., Piao, S. L. and Thornton, P. (2013). Carbon and Other Biogeochemical Cycles. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Campridge, United Kindom and New York, NY, USA.

Clapp, C., Allmaras, R., Layese, M., Linden, D. and Dowdy, R. (2000). Soil organic carbon and ^{13}C abundance as related to tillage, crop residue, and nitrogen fertilization under continuous corn management in Minnesota. *Soil and Tillage Research* 55(3–4): 127–142.

Collins, M., Arblaster, J., Dufresne, J. L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W. J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A. J. and Wehner, M. (2013). Long-term Climate Change: Projections, Commitments and Irreversibility. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Campridge, United Kindom and New York, NY, USA.

Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A. and Totterdell, I. J. (2000). Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. 408(6809), 184.

Dalenberg, J. W. and Jager, G. (1989). Priming effect of some organic additions to 14C-labelled soil. *Soil Biology and Biochemistry* 21(3): 443–448.

Dawson, T. E., Mambelli, S., Plamboeck, A. H., Templer, P. H. and Tu, K. P. (2002). Stable Isotopes in Plant Ecology. *Annual Review of Ecology and Systematics* 33(1): 507–559.

De Neve, S. and Hofman, G. (2000). Influence of soil compaction on carbon and nitrogen mineralization of soil organic matter and crop residues. *Biology and Fertility of Soils* 30(5): 544–549.

Dexter, A. R. (2004). Soil physical quality: Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. *Geoderma* 120(3): 201–214.

Dunbabin, V., Diggle, A. and Rengel, Z. (2003). Is there an optimal root architecture for nitrate capture in leaching environments? *Plant, Cell & Environment* 26(6): 835–844.

Etana, A., Håkansson, I., Zagal, E. and Bučas, S. (1999). Effects of tillage depth on organic carbon content and physical properties in five Swedish soils. *Soil and Tillage Research* 52(3): 129–139.

Evenson, R. E. and Gollin, D. (2003). Assessing the Impact of the Green Revolution, 1960 to 2000. *Science* 300(5620): 758–762.

Fontaine, S., Bardoux, G., Abbadie, L. and Mariotti, A. (2004). Carbon input to soil may decrease soil carbon content. *Ecology Letters* 7(4): 314–320.

Fontaine, S., Barot, S., Barré, P., Bdioui, N., Mary, B. and Rumpel, C. (2007). Stability of organic carbon in deep soil layers controlled by fresh carbon supply. *Nature* 450(7167): 277–280.

Fontaine, S., Mariotti, A. and Abbadie, L. (2003). The priming effect of organic matter: a question of microbial competition? *Soil Biology and Biochemistry* 35(6): 837–843.

Friedli, C. N. (2017). One century of Swiss wheat selection and its effect on drought adaptation and carbon input into soil. Ph.D. Dissertation, ETH Zurich.

Fu, S. and Cheng, W. (2002). Rhizosphere priming effects on the decomposition of soil organic matter in grassland soils. *Plant and Soil* 238(2): 289–294.

Füllner, K., Temperton, V. M., Rascher, U., Jahnke, S., Rist, R., Schurr, U. and Kuhn, A. J. (2012). Vertical gradient in soil temperature stimulates development and increases biomass accumulation in barley. *Plant, Cell & Environment* 35(5): 884–892.

Gale, W. J., Cambardella, C.A. and Bailey, T. B. (2000). Root-Derived Carbon and the Formation and Stabilization of Aggregates. *Soil Science Society of America Journal* 64(1): 201–207.

González-Domínguez, B., Studer, M. S., Hagedorn, F., Niklaus, P. A. and Abiven, S. (2017). Leaching of soils during laboratory incubations does not affect soil organic carbon mineralisation but solubilisation. *PloS one* 12(4): e0174725.

Greenland, D. J. (1971). Interactions between humic and fulvic acids and clays. *Soil Science* 111(1): 34-41.

Gregory, P. J. (2006). Growth, Activity and Interaction with Soils. *Blackwell Publishing Ltd.,* Oxford.

Hagedorn, F., Moeri, A., Walthert, L. and Zimmermann, S. (2010). Kohlenstoff in Schweizer Waldböden – bei Klimaerwärmung eine potenzielle CO_2-Quelle | Soil organic carbon in Swiss forest soils – a potential CO_2 source in a warming climate. *Schweizerische Zeitschrift fur Forstwesen* 161(12): 530–535.

Hamza, M. A. and Anderson, W. K. (2005). Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil and Tillage Research* 82(2): 121–145.

Harris, D., Porter, L. K. and Paul, E. A. (1997). Continuous flow isotope ratio mass spectrometry of carbon dioxide trapped as strontium carbonate. *Communications in Soil Science and Plant Analysis* 28(9–10): 747–757.

Hartmann, A., Rothballer, M. and Schmid, M. (2008). Lorenz Hiltner, a pioneer in rhizosphere microbial ecology and soil bacteriology research. *Plant and Soil* 312(1–2): 7–14.

Hartmann, D. L., Klein Tank, A. M. G., Rusticucci, M., Alexander, L. V., Brönimann, S., Charabi, Y., Dentener, F. J., Dlugokenchy, E. J., Easterling, D. R., Kaplan, A., Soden, B. J., Thorne, P. W., Wild, M. and Zhai, P. M. (2013). Observations: Atmosphere and Surface. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fith Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press: Campridge, United Kindom and New York, NY, USA.

Hassink, J. (1994). Effects of soil texture and grassland management on soil organic C and N and rates of C and N mineralization. *Soil Biology and Biochemistry* 26(9): 1221–1231.

Hénin, S. and Dupuis, M. (1945). Essai de bilan de la matière organique du sol. Dudod.

Hinsinger, P. (2001). Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review. *Plant and Soil* 237(2): 173–195.

Hirte, J., Leifeld, J., Abiven, S. and Mayer, J. (2018a). Maize and wheat root biomass, vertical distribution, and size class as affected by fertilization intensity in two long-term field trials. *Field Crops Research* 216: 197–208.

Hirte, J., Leifeld, J., Abiven, S., Oberholzer, H. R. and Mayer, J. (2018b). Below ground carbon inputs to soil via root biomass and rhizodeposition of field-grown maize and wheat at harvest are independent of net primary productivity. *Agriculture, Ecosystems & Environment* 265: 556–566.

Huang, G., Chai, Q., Feng, F. and Yu, A. (2012). Effects of Different Tillage Systems on Soil Properties, Root Growth, Grain Yield, and Water Use Efficiency of Winter Wheat (Triticum aestivum L.) in Arid Northwest China. *Journal of Integrative Agriculture* 11(8): 1286–1296.

Janzen, H. H., Entz, T. and Ellert, B. H. (2002). Correcting mathematically for soil adhering to root samples. *Soil Biology and Biochemistry* 34(12): 1965–1968.

Jenny, H. (1941). Factors of soil formation: a system of quantitative pedology. *McGraw-Hill Book Company Inc.*, New York and London.

Johnson, J. M. F., Allmaras, R. R. and Reicosky, D. C. (2006). Estimating Source Carbon from Crop Residues, Roots and Rhizodeposits Using the National Grain-Yield Database. *Agronomy Journal* 98(3): 622–636.

Jones, C., McConnell, C., Coleman, K., Cox, P., Falloon, P., Jenkinson, D. and Powlson, D. (2005). Global climate change and soil carbon stocks; predictions from two contrasting models for the turnover of organic carbon in soil. *Global Change Biology* 11(1): 154–166.

Jones, C. A. (1983). Effect of Soil Texture on Critical Bulk Densities for Root Growth 1. *Soil Science Society of America Journal* 47(6): 1208–1211.

Jones, D. L. (1998). Organic acids in the rhizosphere – a critical review. *Plant and Soil* 205(1): 25–44.

Jones, D. L., Hodge, A. and Kuzyakov, Y. (2004). Plant and mycorrhizal regulation of rhizodeposition. *New Phytologis* 163(3): 459–480.

Jones, D. L., Nguyen, C. and Finlay, R. D. (2009). Carbon flow in the rhizosphere: carbon trading at the soil-root interface. *Plant and Soil* 321(1–2): 5–33.

Kandeler, E., Tscherko, D., Bardgett, R. D., Hobbs, P. J., Kampichler,.C. and Jones, T. H. (1998). The response of soil microorganisms and roots to elevated CO_2 and temperature in a terrestrial model ecosystem. 12. *Plant and Soil 202(2)*: 251-262.

Kätterer, T., Bolinder, M. A., Andrén, O., Kirchmann, H. and Menichetti, L. (2011). Roots contribute more to refractory soil organic matter than above-ground crop residues, as revealed by a long-term field experiment. *Agriculture, Ecosystems & Environment* 141(1): 184–192.

Kong, A. Y. Y., Six, J., Bryant, D. C., Denison, R. F. and van Kessel, C. (2005). The Relationship between Carbon Input, Aggregation, and Soil Organic Carbon Stabilization in Sustainable Cropping Systems. *Soil Science Society of America Journal* 69(4): 1078-1085.

Kuzyakov, Y. (2002). Review: Factors affecting rhizosphere priming effects. Journal of Plant of Nutrition and Soil Science 165(4): 382-396.

Kuzyakov, Y. (2010). Priming effects: Interactions between living and dead organic matter. *Soil Biology and Biochemistry* 42(9): 1363–1371.

Kuzyakov, Y. and Domanski, G. (2000), Carbon input by plants into the soil. Review. *Journal of Plant Nutrition and Soil Science* 163(4): 421–431.

Kuzyakov, Y., Friedel, J. K. and Stahr, K. (2000). Review of mechanisms and quantification of priming effects. *Soil Biology and Biochemistry* 32(11): 1485–1498.

Lambers, H., Shane, M. W., Cramer, M. D., Pearse, S. J. and Veneklaas, E. J. (2006). Root Structure and Functioning for Efficient Acquisition of Phosphorus: Matching Morphological and Physiological Traits. *Annals of Botany* 98(4): 693–713.

Liljeroth, E., Kuikman, P. and Veen, J. A. V. (1994). Carbon translocation to the rhizosphere of maize and wheat and influence on the turnover of native soil organic matter at different soil nitrogen levels. *Plant and Soil* 161(2): 233–240.

Luo, Z., Wang, E. and Sun, O. J. (2010). Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. *Agriculture, Ecosystems & Environment* 139(1–2): 224–231.

Martin, J. and Waksman, S. A. (1940). Influence of microorganisms on soil aggregation and erosion I. *Soil Science* 50(1):29-48.

Martin, J. P. and Haider, K. (1986). Influence of Mineral Colloids on Turnover Rates of Soil Organic Carbon. In: Huang, P. M., Shnitzer, M. (eds). *Interactions of soil minerals colloids on turnover rates of soil organic carbon.* SSSA Special Pub. No 17. SSSA, Madison, WI.

Martin, P. J. and Stephens, W. (2001). The potential for biomass production on restored landfill caps. *Aspects of Applied Biology* (65): 337–344.

Masson-Delmotte, V., Abe-Ouchi, A., Gonzàles Ruoco, J. F., Schulz, M., Beer, J., Ganopolski, A., Jansen, E., Lambeck, K., Luterbacher, J., Naish, T., Osborn, T., Otto-Bliesner, B., Quinn, T., Ramesh, R., Rojas, M., Shao, X. and Timmermann, A. (2013). Information from Paleoclimate Archives. In: Stocker, T. F., Qin, D., Plattner, G. K., Tignor, M., Allen, S. K., Boschung, A., Nauels, A., Xia, Y., Bex, V. and Midgley, P. M. (eds). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fith Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press: Campridge, United Kindom and New York, NY, USA, 82.

Materechera, S. A., Dexter, A. R. and Alston, A. M. (1992). Formation of aggregates by plant roots in homogenised soils. *Plant and Soil* 142(1): 69–79.

McMaster, G. S. and Wilhelm, W. W. (1997). Growing degree-days: one equation, two interpretations. *Agricultural and forest meteorology* 87(4): 291–300.

McNear, D. H. (2013). The Rhizosphere - Roots, Soil and Everything In Between. *Nature Education Knowledge* 4(3): 1.

Mendez-Millan, M., Dignac, M. F., Rumpel, C., Rasse, D. P. and Derenne, S. (2010). Molecular dynamics of shoot vs. root biomarkers in an agricultural soil estimated by natural abundance 13C labelling. *Soil Biology and Biochemistry* 42(2): 169–177.

Miller, P., Lanier, W. and Brandt, S. (2001). Using Growing Degree Days to Predict Plant Stages. *Ag/Extension Communications Coordinator, Communications Services, Montana State University-Bozeman, Bozeman, MO*.

Monnier, G, (1965). Action des matieres organiques sur la stabilite structurale du sol. *African Soils 1 (10), 5-42.*

Nguyen, C. (2003). Rhizodeposition of organic C by plants: mechanisms and controls. *Agronomie,* 23(5–6): 375–396.

Oades, J. M. (1978). Mucilages at the Root Surface. *Journal of Soil Science* 29(1): 1–16.

O'Leary, M. H. (1981). Carbon isotope fractionation in plants. *Phytochemistry* 20(4): 553–567.

Pabin, J., Lipiec, J., Włodek, S., Biskupski, A. and Kaus, A. (1998). Critical soil bulk density and strength for pea seedling root growth as related to other soil factors. *Soil and Tillage Research* 46(3): 203–208.

Paris, F., Bonnaud, P., Ranger, J., Robert, M. and Lapeyrie, F. (1995). Weathering of ammonium- or calcium-saturated 2:1 phyllosilicates by ectomycorrhizal fungi in vitro. *Soil Biology and Biochemistry* 27(10): 1237–1244.

Paterson, E. and Sim, A. (2013). Soil-specific response functions of organic matter mineralization to the availability of labile carbon. *Global Change Biology* 19(5): 1562–1571.

Pausch, J. and Kuzyakov, Y. (2018). Carbon input by roots into the soil: Quantification of rhizodeposition from root to ecosystem scale. *Global Change Biology* 24(1): 1–12.

Pausch, J., Loeppmann, S., Kühnel, A., Forbush, K., Kuzyakov, Y. and Cheng, W. (2016). Rhizosphere priming of barley with and without root hairs. *Soil Biology and Biochemistry* 100: 74–82.

Pendall, E., Grosso, S. D., King, J. Y., LeCain, D. R., Milchunas, D. G., Morgan, J. A., Mosier, A. R., Ojima, D. S., Parton, W. A., Tans, P. P. and White, J. W. C. (2003). Elevated atmospheric CO_2 effects and soil water feedbacks on soil respiration components in a Colorado grassland. *Global Biogeochemical Cycles* 17(2).

Pierret, A., Doussan, C., Capowiez, Y., Bastardie, F. and Pagès, L. (2007). Root functional architecture: a framwork for modeling the interplay between roots and soil. *Vadose Zone Journal* 6(2): 269–281.

Poeplau, C., Zopf, D., Greiner, B., Geerts, R., Korvaar, H., Thumm, U., Don, A., Heidkamp, A. and Flessa, H. (2018). Why does mineral fertilization increase soil carbon stocks in temperate grasslands? *Agriculture, Ecosystems & Environment* 265: 144–155.

Pribyl, D. W. (2010). A critical review of the conventional SOC to SOM conversion factor. *Geoderma* 156(3–4): 75–83.

Pritchard, S. G. and Rogers, H. H. (2000). Spatial and temporal deployment of crop roots in CO2-enriched environments. *New Phytologist* 147(1): 55–71.

Rasse, D. P., Rumpel, C. and Dignac, M. F. (2005). Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. *Plant and Soil* 269(1–2): 341–356.

Reicosky, D. C. and Archer, D. W. (2007). Moldboard plow tillage depth and short-term carbon dioxide release. *Soil and Tillage Research* 94(1): 109-121.

Rich, S. M. and Watt, M. (2013). Soil conditions and cereal root system architecture: review and considerations for linking Darwin and Weaver. *Journal of Experimental Botany* 64(5): 1193–1208.

Rogers, H. H., Peterson, C. M., McCrimmon, J. N. and Cure, J. D. (1992). Response of plant roots to elevated atmospheric carbon dioxide. *Plant, Cell and Environment* 15(6): 749–752.

Rogers, H. H., Prior, S. A., Runion, G. B. and Michell, R. J. (1995). Root to shoot ratio of crops as influenced by CO_2. *Plant and Soil* 187(2): 229.248.

Rosegrant, M. W. and Cline, S. A. (2003). Global Food Security: Challenges and Policies. *Science* 302(5652): 1917–1919.

Rustad, L., Campbell, J., Marion, G., Norby, R., Mitchell, M., Hartley, A., Cornelissen, J. and Gurevitch, J. (2001). A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. *Oecologia* 126(4): 543–562.

Saengwilai, P., Tian, X. and Lynch, J. (2014). Low crown root number enhances nitrogen acquisition from low nitrogen soils in maize (Zea mays L.). *Plant Physiology*: 1190-1201.

Scharlemann, J. P., Tanner, E. V., Hiederer, R. and Kapos, V. (2014). Global soil carbon: understanding and managing the largest terrestrial carbon pool. *Carbon Management* 5(1): 81–91.

Schlesinger, W. H. and Andrews, J. (2000). Soil respiration and the global carbon cycle. *Biogeochemistry* 48(1): 7–20.

Schmidt, M. W., Torn, M. S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I. A., Kleber, M., Kögel-Knabner, I., Lehmann, J. and Manning, D. A. (2011). Persistence of soil organic matter as an ecosystem property. *Nature* 478(7367): 49-56.

Shipley, B. and Meziane, D. (2002). The balanced-growth hypothesis and the allometry of leaf and root biomass allocation. *Functional Ecology* 16(3): 326–331.

Soil Science Society of America (2008). Glossary of Soil Science Terms. Madions, WI, USA.

Sørensen, L. H. (1974). Rate of decomposition of organic matter in soil as influenced by repeated air drying-rewetting and repeated additions of organic material. *Soil Biology and Biochemistry* 6(5): 287–292.

Studer, M. S., Künzli, R., Maier, R., Schmidt, M. W. I., Siegwolf, R. T. W., Woodhatch, I. and Abiven, S. (2017). The MICE facility – a new tool to study plant–soil C cycling with a holistic approach. *Isotopes in Environmental and Health Studies* 53(3): 286–297.

Tans, P. (2009). An accounting of the observed increase in oceanic and atmospheric CO2 and an outlook for the future. *Oceanography* 22(4): 26–35.

Traoré, O., Groleau-Renaud, V., Plantureux, S., Tubeileh, A. and Boeuf-Tremblay, V. (2000). Effect of root mucilage and modelled root exudates on soil structure. *European Journal of Soil Science* 51(4): 575–581.

United Nations (2009). World Population Prospects: The 2008 Revision.

Ussiri, D. A. N. and Lal, R. (2009). Long-term tillage effects on soil carbon storage and carbon dioxide emissions in continuous corn cropping system from an alfisol in Ohio. *Soil and Tillage Research* 104(1): 39–47.

van Groenigen, K. J., Qi, X., Osenberg, C. W., Luo, Y. and Hungate, B. A. (2014). Faster Decomposition under Increased Atmospheric CO_2 Limits Soil Carbon Storage. *Science* 344(6183), 508-509.

van Vuuren, I. M., Robinson, D., Fitter, A. H., Chasalow, S. D., Williamson, L. and Raven, J. A. (1997). Effects of elevated atmospheric CO_2 and soil water availability on root biomass, root length, and N, P and K uptake by wheat. *New Phytologist* 135(3): 455–465.

Varvel, G. E. and Wilhelm, W. W. (2011). No-tillage increases soil profile carbon and nitrogen under long-term rainfed cropping systems. *Soil and Tillage Research* 114(1): 28–36.

Vitorello, V. A., Cerri, C. C., Victória, R. L., Andreux, F. and Feller, C. (1989). Organic Matter and Natural Carbon-13 Distribution in Forested and Cultivated Oxisols. *Soil Science Society of America Journal* 53(3): 773–778.

Wang, W. J., Dalal, R. C., Moody, P. W. and Smith, C. J. (2003). Relationships of soil respiration to microbial biomass, substrate availability and clay content. *Soil Biology and Biochemistry* 35(2): 273–284.

Wattel-Koekkoek, E. J. W., van Genuchten, P. P. L., Buurman, P. and van Lagen, B. (2001). Amount and composition of clay-associated soil organic matter in a range of kaolinitic and smectitic soils. *Geoderma* 99(1): 27–49.

Westcott, M. P. and Mikkelsen, D .S. (1985). Comparative Effects of an Organic and Inorganic Nitrogen Source in Flooded Soils 1. *Soil Science Society of America Journal* 49(6): 1470–1475.

Wilson, J. B. (1988). A Review of Evidence on the Control of Shoot: Root Ratio, in Relation to Models. *Annals of Botany* 61(4): 433–449.

Wollum, A. G. and Gomez, J. E. (1970). A Conductivity Method for Measuring Microbially Evolved Carbon Dioxide. *Ecology* 51(1): 155–156.

Wullschleger, S. D., Tschaplinski, T. J. and Norby, R. J. (2002). Plant water relations at elevated CO2–implications for water-limited environments. *Plant, Cell & Environment* 25(2): 319–331.

Yang, C. H., Chai, Q. and Huang, G. B. (2010). Root distribution and yield responses of wheat/maize intercropping to alternate irrigation in the arid areas of northwest China. *Plant, Soil and Environment* 56(No. 6): 253–262.

Zadoks, J. C., Chang, T. T. and Konzak, C. F. (1974). A decimal code for the growth stages of cereals. *Weed research* 14(6): 415–421.

Ziska, L. H., Faulkner, S. and Lydon, J. (2004). Changes in biomass and root:shoot ratio of field-grown Canada thistle (Cirsium arvense), a noxious, invasive weed, with elevated CO_2: implications for control with glyphosate. *Weed Science* 52(4): 584–588.

9.2 List of internet sources

AWEL Amt für Abfall, Wasser, Energie und Luft / Jahrbücher Niederschlag. Accessible online at: https://awel.zh.ch/internet/baudirektion/awel/de/wasser/messdaten/niederschlag.html#jahrb-cher (Access: 3.9.2018).

10 Annex

10.1 Excerpt from ÖLN

■ **Bodenanalysen**

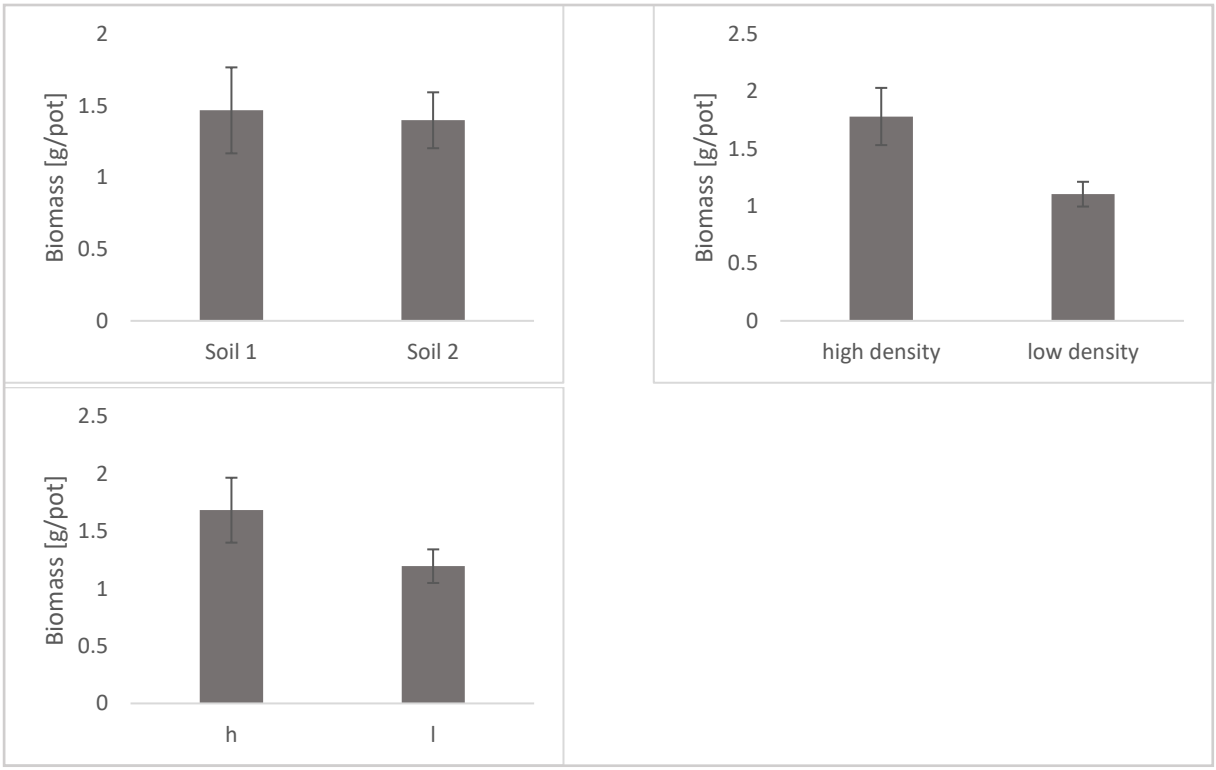
Sie müssen auf allen Bewirtschaftungsparzellen, die grösser als 1 ha sind (maximal 5 ha pro Analyse) mindestens alle 10 Jahre eine Bodenanalyse durchführen. Davon ausgenommen sind alle Flächen mit Düngeverbot, wenig intensiv genutzte Wiesen sowie Dauerweiden. Für Obst- und Rebbauflächen gelten die Anforderungen auf ↘ Seite 30 bzw. ↘ 34. Mehrere nebeneinander liegende Grundstücke mit den gleichen Bodeneigenschaften und mit analoger Bewirtschaftung (Kultur, Düngung) können bei der Probenahme für Bodenanalysen zusammengefasst werden. Die Analysen müssen von einem Labor ausgeführt werden, das vom Bundesamt für Landwirtschaft BLW anerkannt ist, siehe www.agroscope.ch ➜ Themen Umwelt und Ressourcen ➜ Boden, Gewässer, Nährstoffe ➜ Verbesserung der Nährstoffeffizienz ➜ Bodenuntersuchung und Laborzulassung. Die Analysen müssen die Werte für pH, Phosphor, Kalium, Bodenart nach Fühlprobe und für Acker- und Obstflächen auch die organische Substanz, geschätzt nach Farbskala enthalten. Es sind sowohl die AAE10-, die CO_2- als auch die H_2O10-Methode zulässig.

Sie müssen keine Bodenanalysen machen, wenn Sie keine N- oder P-haltigen Dünger zuführen und seit dem 1. Januar 1999 keine Parzelle die Versorgungsklasse D oder E aufweist, und wenn der Viehbesatz pro Hektare düngbare Fläche folgende Werte nicht überschreitet:

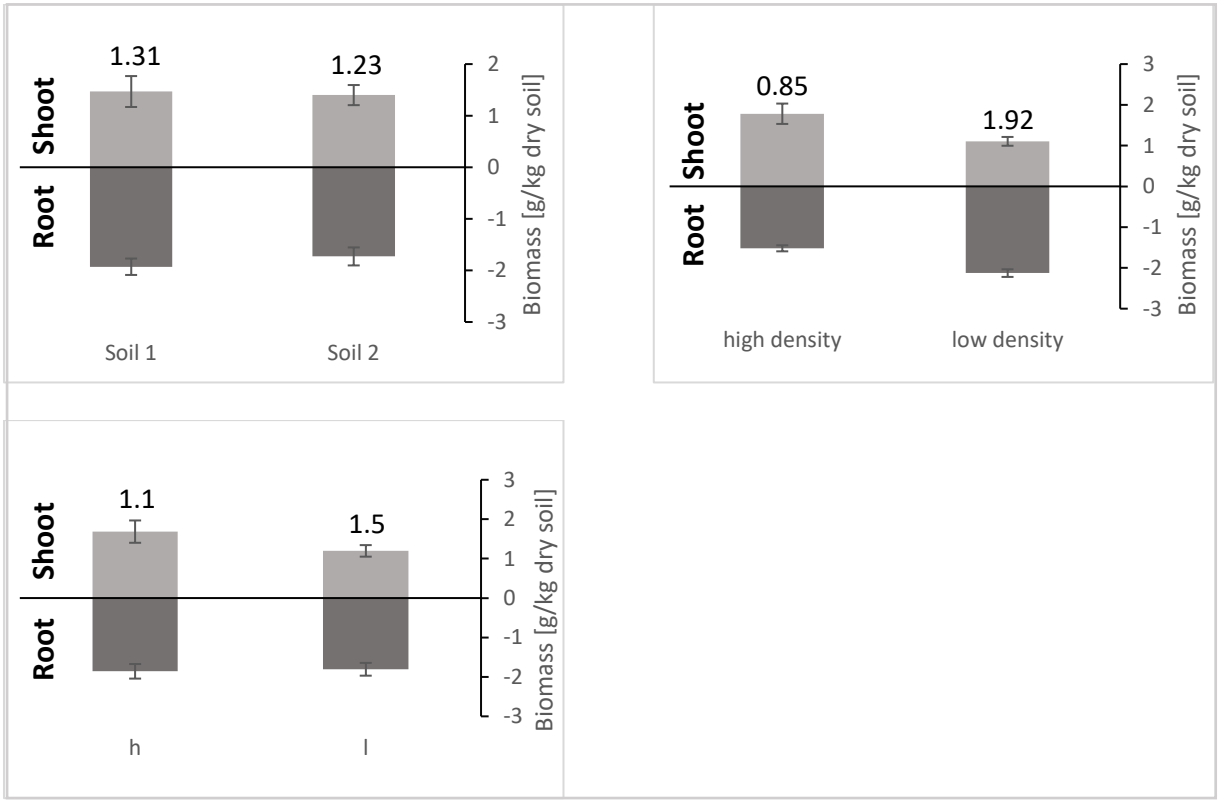
max. 2,0 Düngergrossvieheinheiten (DGVE)/ha	Talzone
max. 1,6 Düngergrossvieheinheiten (DGVE)/ha	Hügelzone
max. 1,4 Düngergrossvieheinheiten (DGVE)/ha	Bergzone I
max. 1,1 Düngergrossvieheinheiten (DGVE)/ha	Bergzone II
max. 0,9 Düngergrossvieheinheiten (DGVE)/ha	Bergzone III
max. 0,8 Düngergrossvieheinheiten (DGVE)/ha	Bergzone IV

Excerpt from ÖLN concerning soil analysis in order to get support payments from the government

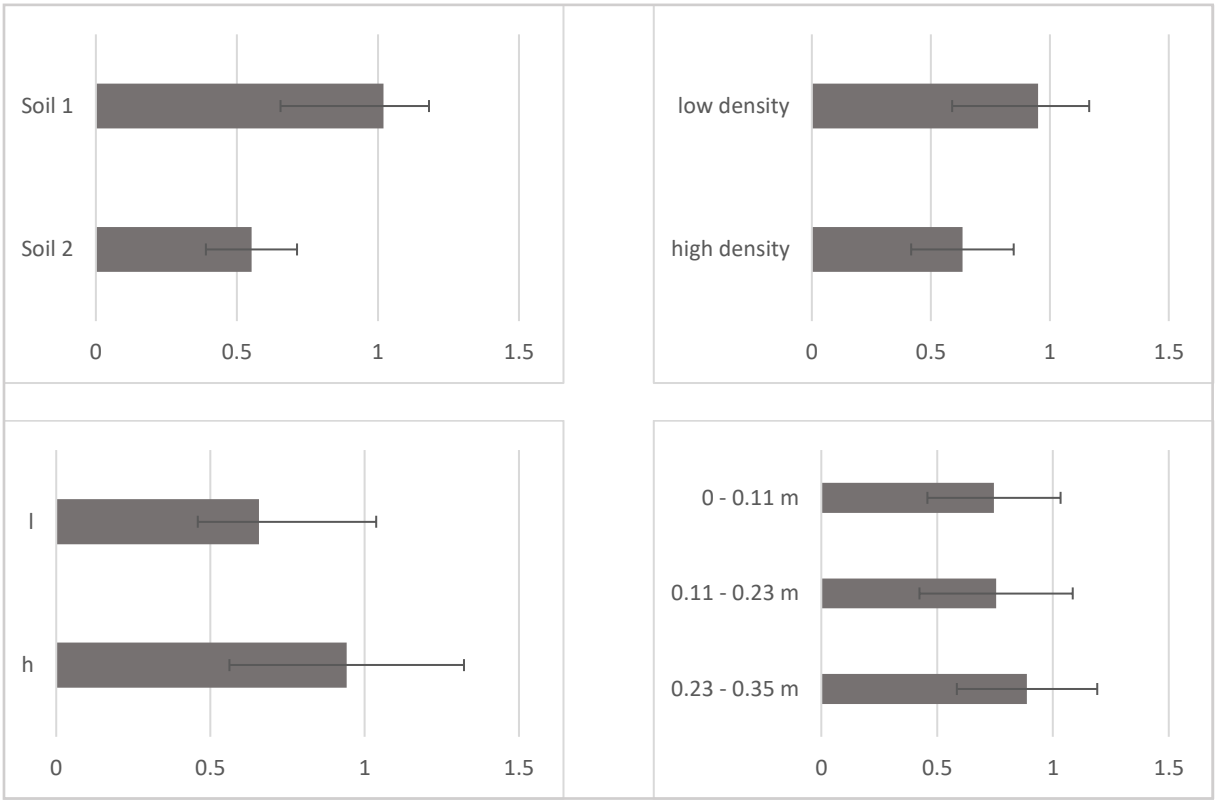
10.2 Additional Figures



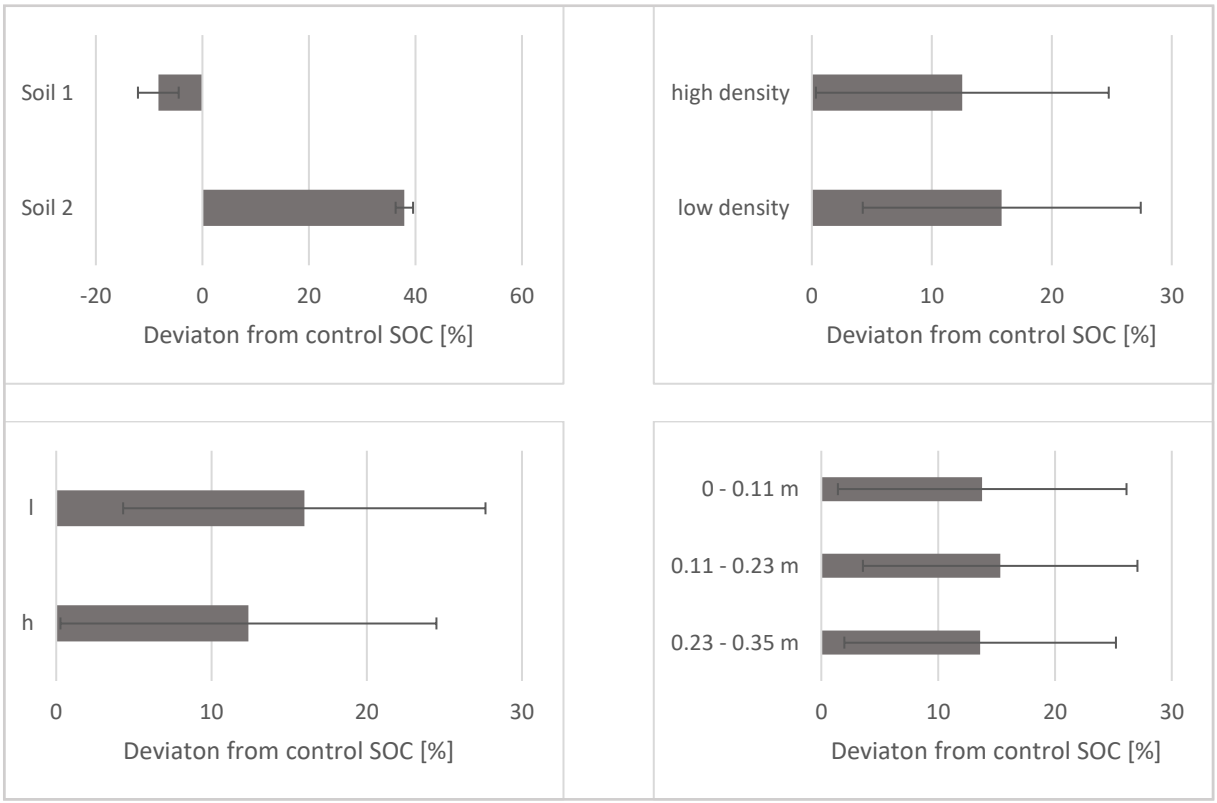
Aboveground biomass of barley plants after MICE experiment of soil 1 and soil 2, high SBD and low SBD and high CO_2 and low CO_2 treatments. High SDB treatment correspond to 1.2g/cm^3 and low SBD to 0.9g/cm^3. Letter h corresponds to high CO_2 treatment and letter l to low CO_2 treatment in MICE.



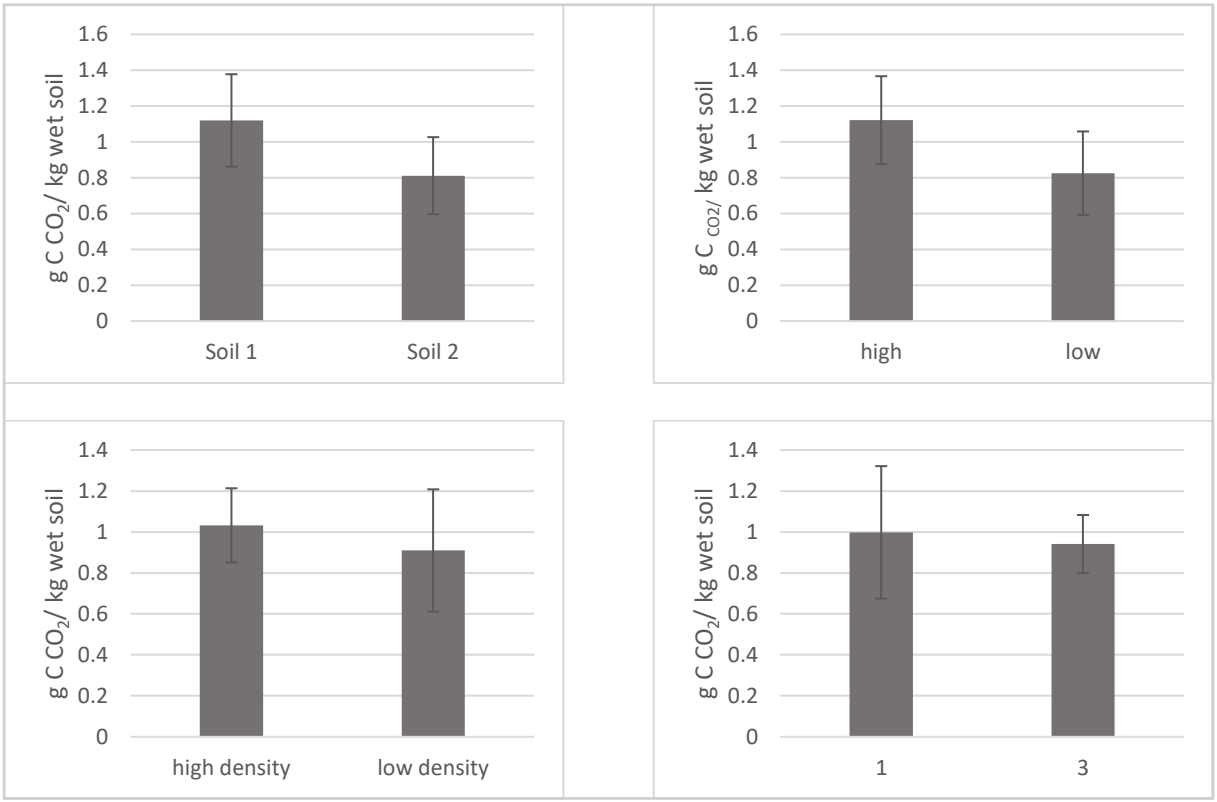
Root:shoot ratio after MICE experiment of soil 1 and soil 2, high SBD and low SBD and high CO_2 and low CO_2 treatments. High SDB treatment correspond to 1.2g/cm^3 and low SBD to 0.9g/cm^3. Letter h corresponds to high CO_2 treatment and letter l to low CO_2 treatment in MICE.



Ratio between root biomass C and rhizodeposition C of soil 1 and soil 2, high SBD and low SBD and high CO_2 and low CO_2 treatments and between soil depths. High SDB treatment correspond to 1.2g/cm^3 and low SBD to 0.9g/cm^3. Letter h corresponds to high CO_2 treatment and letter l to low CO_2 treatment in MICE.



Priming effect after MICE experiment of soil 1 and soil 2, high SBD and low SBD and high CO_2 and low CO_2 treatments and between soil depths. High SDB treatment correspond to 1.2g/cm^3 and low SBD to 0.9g/cm^3. Letter h corresponds to high CO_2 treatment and letter l to low CO_2 treatment in MICE.

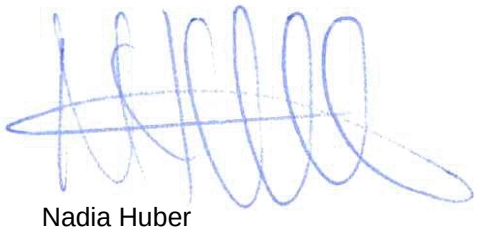


Cumulated respired C CO_2 from root free soil after the incubations of soil 1 and soil 2, high SBD and low SBD and high CO_2 and low CO_2 treatments and between soil depths. High SDB treatment correspond to 1.2g/cm^3 and low SBD to 0.9g/cm^3. Letter h corresponds to high CO_2 treatment and letter l to low CO_2 treatment in MICE.

11 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.

Zurich, 25th of September



Nadia Huber