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Consequences of Climate Change for Soil Water in Pre-Alpine Grassland Soils

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Consequences of Climate Change for Soil Water in Pre-Alpine Grassland Soils

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Abstract

Stable water isotopes (δ^2H and $\delta^{18}O$) serve as ideal tracers of hydrological processes in the critical zone. The isotopic composition of soil water is altered by the processes of evaporation and mixture with waters from other sources. Montane regions are expected to be hotspots of global change and endure particular exposure to future climate changes. For pre-alpine soils, this means higher evaporation rates in summer and increased freezing in winter due to diminished snow cover insulation. This is expected to lead to changes in soil water balance and the isotopic composition of the soil water. This thesis focuses on these. Lysimeters of undisturbed soil cores were translocated to a less elevated location to simulate climate change. The soil water was monitored in the transferred lysimeters as well as the reference lysimeters in both locations. The lysimeters were covered in grassland, which is the typical land cover management in this region. Half of the lysimeters were managed intensively, while the other half was manged extensively. The results indicate that climate change will lead to alterations in the soil water of pre-alpine grassland soils. They further suggest that the type of agricultural management of the grassland does not interfere with the isotopic composition of soil water. Increased evaporation rates due to warmer temperatures and less precipitation are expected to be measurable in the isotopic composition of soil water, even in deep soil layers. The volumetric soil water content, however, appears to be affected by global change in the upper soil layer only (top 10 cm of the soil). This study does not allow for long-term conclusions to be drawn about the effects of climate change. Further research is needed for this purpose.

Keywords: climate change, critical zone, lysimeter, mobile soil water, soil water, stable water isotopes, TERENO, δ^2H, $\delta^{18}O$

Zusammenfassung

Stabile Wasserisotope (δ^2H und $\delta^{18}O$) gelten als ideale Tracer für hydrologische Prozesse in der kritischen Zone. Die Isotopenzusammensetzung des Bodenwassers wird durch Prozesse wie Verdunstung oder das Mischen mit Wasser aus anderen Quellen verändert. Gebirge werden Hotspots des Globalen Wandels sein und damit besonders stark von Klimaveränderungen in der Zukunft betroffen sein. Für voralpine Böden bedeutet das höhere Verdunstungsraten im Sommer und vermehrtes Gefrieren aufgrund der fehlenden schützenden Schneedecke im Winter. Dies wird zu Veränderungen im Bodenwasserhaushalt und in der Isotopenzusammensetzung des Bodenwassers führen. Die vorliegende Arbeit beschäftigt sich mit diesen durch den Klimawandel verursachten Veränderungen des Bodenwassers. Lysimeter mit ungestörten Bodenkernen wurden von einem Standort an einen tiefer gelegenen Standort verlegt. Die Verlagerung der Lysimeter diente dabei als Simulation des Klimawandels. Das Bodenwasser in den transferierten Lysimetern sowie in Kontroll-Lysimetern an beiden Standorten wurde regelmäßig beprobt und hinsichtlich der isotopischen Signatur analysiert. Die Lysimeter sind mit Grünland bedeckt, was die typische Landnutzungsform in den Alpen und Voralpen ist. Eine Hälfte der Lysimeter wird intensiv, die andere extensiv bewirtschaftet. Die Ergebnisse deuten darauf hin, dass der Klimawandel zu Veränderungen im Bodenwasser der voralpinen Grünlandböden führen wird. Sie deuten außerdem darauf hin, dass die Bewirtschaftungsform (intensiv oder extensiv) keinen Einfluss auf das Bodenwasser hat. Es wird erwartet, dass höhere Verdunstungsraten aufgrund wärmerer Temperaturen und weniger Niederschlag auch in tiefen Bodenschichten in der Isotopenzusammensetzung des Bodenwassers messbar sein werden, während der volumetrische Bodenwassergehalt nur in der oberen Bodenschicht (oberste 10 cm des Bodens) vom Klimawandel betroffen sein wird. Aussagen über die Langzeitfolgen des Globalen Wandels sind mit dieser Studie jedoch nicht möglich, weshalb weiterhin Forschungsbedarf besteht.

Keywords: Bodenwasser, Klimawandel, kritische Zone, Lysimeter, mobiles Bodenwasser, stabile Wasserisotope, TERENO, $\delta^{18}O$, δ^2H

1 Introduction

1.1 State of Research

1.1.1 Introduction to Isotope Hydrology

Atoms of one element all have the same number of protons, yet they may differ in the number of neutrons in their cores and thus in their masses. These atoms carrying a different amount of neutrons are called isotopes (Kendall and Caldwell 1998). A distinction is made between radioactive (unstable) and stable isotopes (Kendall and Caldwell 1998). The stable isotopes of water are protium (^{1}H) and deuterium (^{2}H) as stable isotopes of hydrogen, and ^{16}O, ^{17}O, ^{18}O of oxygen, respectively. In nature, water molecules occur in three combinations of these five isotopes: $^{1}H_2{}^{16}O$, $^{1}H_2{}^{18}O$ and $^{1}H^{2}H^{16}O$ (Mook et al. 2001; Ingraham 1998).

The isotopic composition of water is changed by fractionation processes. The equilibrium fractionation, firstly described by Urey (1947), is a reversible process that occurs in a closed system when isotopes are exchanged between two phases in equilibrium. Equilibrium fractionation arises due to the difference in the strength of the bond between molecules, which is dependent on the atomic masses of molecules (Sharp 2017). The bond of a heavy isotope is slightly stronger than that of a light one, which is why light isotopes leave a more condensed phase quicker than heavy isotopes. Hence, in phase transitions, the heavy isotopes are enriched in the phase with greater density (solid > liquid > gaseous) and vice versa (Sharp 2017; Ingraham 1998). Equilibrium fractionation is dependent on temperature: at high temperatures, fractionation is less pronounced than at low temperatures (Leibundgut et al. 2009; Sharp 2017; Urey 1947).

Kinetic (non-equilibrium) fractionation occurs in open systems and is irreversible. It depends on the reaction rate, the reaction pathway, and the strength of the bond between the isotopes (Kendall and Caldwell 1998; Sharp 2017): generally, the bonds between lighter isotopes are weaker than those between heavy isotopes (Kendall and Caldwell 1998). Consequently, isotopes differ in their reaction velocity: as less energy is needed to break the bonds between the molecules with lighter isotopes, they react more quickly to changes (e.g. change in temperature) than molecules with heavier isotopes (Sharp 2017; Kendall and Caldwell 1998). Thus, during evaporation, for instance, lighter isotopes diffuse out of the liquid into the gaseous phase before the heavier isotopes do, which leads to the enrichment of heavy isotopes (and the depletion of light isotopes) in the remaining water and the enrichment of light isotopes in the water vapour (Sharp 2017). This process is called diffusive fractionation (Leibundgut et al. 2009). Another important kinetic fractionation process is Rayleigh fractionation or Rayleigh distillation which is characterised by the continuous removal of the resulting water vapour from the water source (Gat 1996; Sharp 2017). This means that isotopes cannot be interchanged once the phases have been separated. Thereby, Rayleigh distillation often results in very light precipitation as the depletion of heavy isotopes from the precipitation continues to progress (Sharp 2017; Gat 1996). In conclusion, it can be noted that the isotopic composition of (precipitation) water relates deeply to fractionation processes caused by phase changes between liquid water, vapour, and ice.

The isotopic signature of precipitation is determined by the so-called *isotopic effects,* which are crucial for the interpretation of isotope data (Leibundgut et al. 2009). The most important of these effects will be presented shortly. Full explanation goes beyond the scope of this thesis. For more details, the reader is referred to Leibundgut et al. (2009) and Sharp (2017).

The most important factor for determining the isotopic composition of local precipitation may be the **temperature** as it influences the fractionation severely. As mentioned above, equilibrium fractionation is more effective at low temperatures. Consequently, the precipitation in warm regions is characterised by less negative δ-signatures than the precipitation in cold regions. In other words, rainfall is more enriched in heavy isotopes in warm regions than in colder ones (Leibundgut et al. 2009).

The **altitude effect** also has a major impact on the isotopic signal of precipitation. It is based on a combination of the temperature effect and the decrease of humidity through adiabatic cooling and leads to the fact that the rainfall gets lighter with increasing altitude (Leibundgut et al. 2009; Sharp 2017). With increasing altitude, temperatures further decrease, leading to incrementally efficient fractionation. Moreover, adiabatic cooling occurs when air masses are transported upwards, leading to a decrease in humidity in these air masses due to (possibly repeated) orographic rainfall which may even cause Rayleigh distillation (Leibundgut et al. 2009).

Finally, **seasonal effects** on the δ-signatures must be mentioned. These effects are caused by the seasonal variability of temperatures, which is why the seasonal course of the isotopic composition of rainfall is closely related to the seasonal course of air temperatures (Leibundgut et al. 2009). Besides temperatures, seasonal air circulation patterns also contribute to the seasonal course of the isotopic composition as they transport humidity from other origins and thereby change the isotopic signature of the original local moisture (Leibundgut et al. 2009). Lastly, the seasonal effect is caused by the variation of the phase of the precipitation water (i.e. rain or snow) and the seasonally changing surrounding conditions like air humidity (Leibundgut et al. 2009). The seasonal effects intensify with increasing continentality of a location (Leibundgut et al. 2009). This leads typically to more enriched precipitation waters in summer and lighter precipitation in winter (Gat 1996).

1.1.2 Stable Water Isotopes in Soil Water

In recent years, the so-called critical zone has become a major field of interest in the earth sciences. The critical zone is the outer layer of the Earth’s terrestrial surface where dynamics between the Earth’s subsurface and atmosphere occur, e.g. in form of interactions between the soil water and climate or vegetation (Brooks et al. 2015; Sprenger et al. 2017a). Stable water isotopes are often considered ideal tracers for hydrological processes occurring in the critical zone. Being part of the water molecule, they behave like water: their composition is not modified by the water passing through soil (Zimmermann et al. 1967), nor when being absorbed by plant roots (Wershaw et al. 1966; Sprenger et al. 2017a), yet it is modified by mixing with water from other origins and by evaporation processes (Zimmermann et al. 1967), as described above. Recently, some studies found differences in the isotopic composition of plant water and soil water (Tetzlaff et al. 2021; Barbeta et al. 2020), but the fractionation appears to happen within the plant, not during the plant water uptake (Zhao et al. 2016). Consequently, plant water uptake does not appear to alter the isotopic composition of soil water. Another concept is the two water worlds hypothesis by McDonnell (2014), which is based on the observation that bulk soil water and mobile soil water differ in their isotopic composition. While mobile water is isotopically similar to the local precipitation, the tightly bound soil water plots below the Local Meteoric Water Line (LMWL) in a dual-isotope plot (Sprenger et al. 2018; McDonnell 2014). Streams and groundwater mostly show similar isotopic values as the LMWL, while plant water samples are similar to the bulk soil water. Therefore, the mobile soil water seems to serve as groundwater recharge or as input in rivers, while plants seem to take their water from the tightly bound water (McDonnell 2014).

Zhou et al. (2008) found that different soils show significantly different soil hydraulic properties. However, their study indicates that soil properties are more greatly affected by seasonal effects than soil type.

In previous studies, effects of influencing factors on soil water or soil properties were almost exclusively detected in the upper soil layers. As an example, Sprenger et al. (2017a) found effects of evaporation as well as effects of different vegetation in soil water only in the upper 15 cm of the soil profile. Stumpp et al. (2012) found that strong differences in soil properties (e.g. water content) disappeared within the upper 25 to 30 cm of the soil, while in a study by Schwartz et al. (2003), land use effects on soil properties like pore structure could only be detected up to a soil depth of 20 cm. Schwartz et al. (2003) also found that soil type has a stronger influence on the soil hydraulic properties than vegetation does.

1.1.3 Consequences of Global Change on Soil Water

In montane regions, the consequences of climate change are expected to be more severe than in lower areas (Kunstmann et al. 2004; Smiatek et al. 2009). Their vulnerability to climate change has already been observed: Kiese et al. (2018) mention that, for instance, the mean temperature at Mount Hohenpeißenberg increased by 1.5 °C from 1880 to 2012, while at the same time, the global land temperature increased by 1.17 °C, and the global mean temperature of land and ocean surfaces combined increased by only 0.78 °C. This already shows that the climate in the pre-alpine area has been more exposed to changes than the global average. According to Kunstmann et al. (2004), the mean annual temperature in the area of the Pre-Alpine Observatory will have increased by up to 4 °C by the 2030s. Moreover, their climate models predicted increasing precipitation for the area. Not only will the amount of precipitation change but also its intensity and, due to the higher temperatures, so will the form in which precipitation falls. Snowfall will be rarer and contained in a shorter period, leading to thinner layers than today (Schädler et al. 2012). Since a closed snow layer serves to protect soil from freezing in winter, this will have crucial consequences for soils: they will experience more variability in temperatures over the year and experience an increase in freezing, which will lead to an alteration of their hydrological processes due to the changes in soil temperature and soil moisture, which effects both hydrological and biological processes in the soil (Schuerings et al. 2014; Hardy et al. 2001). Groffman et al. (2001) coined the phrase "colder soils in a warmer world" to summarise the consequences of climate change on soils.

Wang et al. (2016) analysed the influences of climate change on the nitrogen balance of pre-alpine grassland soils in the same experimental set-up where the data for this present study originate from. They reached the conclusion that the effects of climate change on the soil nitrogen balance will be primarily limited to the topsoil (2 - 6 cm depth), as climate change impacts were only found in exceptional cases at a maximum soil depth of 16 cm. Overall, they found that climate change will alter the soils' nitrogen balance severely, especially in winter when – due to the decreased snow cover – soil freezing will take place (Wang et al. 2016).

Global change includes both climate and land use changes (Kiese et al. 2018). A study by Wang et al. (2018) clearly differentiated these two factors and estimated the severity of their separate impacts. To do so, data from a boreal catchment in Scotland were analysed with a one-dimensional hydrological model (Hydrus-1D). Climate parameters were adjusted to fit predictions for the climate in the study area, and the impact of shrubs and trees on soil hydrology (which are the predominant vegetation types in the catchment) was assessed. Results indicated that land cover changes have a bigger influence on soil hydrology than the expected change in climate in this region (Wang et al. 2018). On a long-term basis, the water balance will be altered especially in the months of April until October, whilst the colder, wetter season (November - March) will sustain relatively less change. An increase in temperature and thus in evapotranspiration, however, is expected for all months. It should be noted that Wang et al. (2018) did not consider the intensity of rainfall in their calculations. Nevertheless, rainfall intensity would likely be a culprit in interfering with soil water balance due to the expected increased intensity summer rainfall, which would in turn decrease interception during precipitation events in summer(Soulsby et al. 2017; Wang et al. 2018).

1.2 TERENO and the Study Area

The data used in this study originate from TERENO (Terrestrial Environmental Observatories) which is a network for integrated environmental research in Germany. Its aim is to gain insights into the impact of climate and land cover change on ecosystems (Zacharias et al. 2011). It was initiated in 2008 and since then, data have been collected in four observatories which are distributed all over Germany to cover a variety of ecosystems. The data for this thesis were collected at the Bavarian Alps/ Pre-Alps Observatory in the South of Germany which is displayed in detail in Figure 1. The Pre-Alps Observatory is operated by the Karlsruhe Institute of Technology (KIT). It covers parts of the Bavarian Alps and their foothills, with the Ammer and Rott catchments being the central part of the observed area (Kiese et al. 2018). The most elevated point of the study area lies in the southern part at 2185 m a.s.l. The terrain becomes flatter towards the north, the lowest point of the investigation area is at 540 m a.s.l. (Kiese et al. 2018). The three main sites of the observatory are, from north to south, Fendt (DE-Fen) in the lower part of the Ammer catchment, Rottenbuch (DE-Rbw) in the central part, and Graswang (DE-Gwg) in the upper part of the catchment. For this thesis, only Graswang and Fendt are taken into consideration. Their locations are marked with a yellow square in Figure 1. The lysimeter network in the observatory was established in 2010 (Pütz et al. 2016).

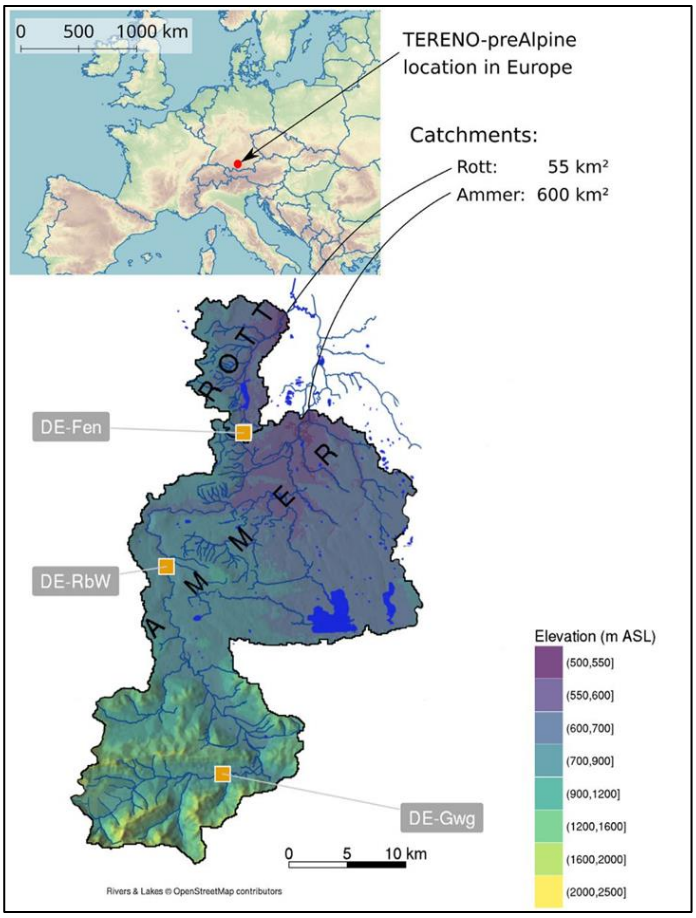

Figure 1. Overview of the Pre-Alps Observatory.
Source: Kiese et al. 2018 (modified).

In this thesis, the locations DE-Fen and DE-Gwg are compared on the basis of stable isotope and soil moisture data observed there. In Fendt, cambic Stagnisols are the mostly found soils. Their upper layer (top 10 cm) consists mainly of clay and loam, is slightly acidic (pH = 5.7) and has a bulk density of 1.1 g/cm^3 (Kiese et al. 2018). In Graswang, fluvic calceric Cambisols are the predominant soils, where the upper soil layer has a high clay content, a pH of 6.4 and a bulk density of 0.8 g/cm^3 (Kiese et al. 2018). More details regarding the soils can be found in Table A 1. Both test sites are covered in grassland, which in Fendt is managed intensively, i.e. the grass is cut up to six times a year and manure is applied up to five times a year. In Graswang, farmers manage their grasslands extensively, that means the grass is cut up to three times per year and manure is applied up to twice a year (Kiese et al. 2018). The lysimeters where the isotope and soil moisture data originate from were managed both intensively and extensively to enable a comparison of the consequences of management of grasslands.

A key property of mountain areas is the steep topography and the climate gradients that go along with it. According to Kunstmann et al. (2004) the temperature gradient in the Ammer catchment is 0.6 °C/100 m in summer and 0.45 °C/100 m in winter. Since climate is connected to elevation, the three main sites of the observatory differ clearly. The mean annual temperature decreases with increasing height, whereas the mean annual precipitation increases with increasing elevation (Kiese et al. 2018). For more detailed information about climate and geographical location of the sites, see Table 1.

Table 1. Station meta information and mean values for annual air temperature (MAT), global radiation (MAR) and total precipitation (MAP) for the years 2014 to 2017.

Station acronym	Coordinates [lon, lat]	Elevation [m a.s.l.]	MAT [°C]	MAP [mm]	MAR [W/m²]
DE-Fen	11.06111, 47.83243	595	8.9	956	132
DE-Gwg	11.03189, 47.57026	864	6.9	1347	119

Source: Kiese et al. 2018.

Figure 2 shows the precipitation and evaporation in Fendt and Graswang in 2019. The graph illustrates that Graswang receives more precipitation throughout the whole year. The maximum rainfall in 2019 was on May 20th with almost 80 mm/d at both locations. In total, Graswang received ca. 1500 mm of precipitation in 2019, Fendt ca. 1000 mm (calculated based on the weight changes of the lysimeters). The difference between the precipitation amount at the two testing sites is overall strongest in summer and weakest in winter (Table 2). For an exact depiction of the difference in precipitation amount per day see Figure A 1. With regard to the evaporation it is noticeable that in January and February, the evaporation at both locations is 0, thus evaporation effects on the soil water can be ruled out.

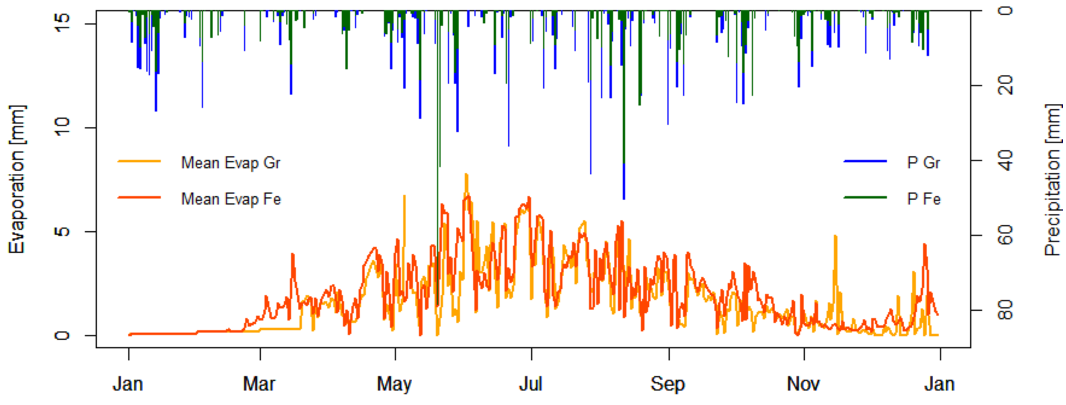

Figure 2. Precipitation and evaporation in Fendt and Graswang over the year. Evaporation was calculated as the daily average of evaporation rates calculated per lysimeter by weight change. Precipitation was measured on site.

Table 2. Precipitation in Fendt and Graswang in 2019.

Station	Total [mm]	Spring [mm]	Summer [mm]	Fall [mm]	Winter [mm]
Fe	967.43	319.03	254.00	228.30	166.11
Gr	1499.12	418.08	436.10	341.24	303.49
Difference (Gr – Fe)	531.69	99.05	182.31	112.94	137.38

1.3 Motivation and Goals of this Study

Global change is one of the major challenges for humanity in the 21st century and gaining as much knowledge as possible about it is one of the top priorities of today's earth sciences. Since mountain areas are considered to be hotspots of global change and will be particularly exposed to its consequences, research focussing on climate change in the mountains is a crucial part of general research on global change. Since soil has been understood to be the connecting zone between the atmosphere, vegetation, and subsurface processes (e.g. Brooks et al. 2015), the investigation of soil hydraulics will further improve the understanding of ecohydrological processes. Using the isotopic composition of soil water as a tracer of evaporation and to analyse the soil water flow has proven to be effective in various studies before (Benettin et al. 2019; Sprenger et al. 2017a; Stumpp et al. 2012; Yong et al. 2020; Gaj et al. 2016). In this master thesis, this approach is extended by a comparison of lysimeters located in different climates to investigate the consequences of climate change on soil water in pre-alpine grassland soils under current and future climate conditions. To do so, the control lysimeters in Graswang and Fendt are compared to the relocated lysimeters in Fendt based on data obtained in 2019. Graswang and Fendt were chosen as the main sites of the experiment because of the altitude-related climate gradient between them.

The following hypotheses are to be analysed by this study:

I. Climate change affects the isotopic composition of the soil water in the lysimeters transferred from Graswang to Fendt.
II. The isotopic composition of the upper soil layers will be most affected by climate change effects.
III. Soil moisture dynamics will be affected by the lysimeter translocation and change in climatic conditions. This has a knock-on effect on the isotopic composition.

2 Methods

2.1 Experimental Set Up

In Graswang, which lies at 864 m a.s.l., undisturbed soil monoliths in lysimeters were extracted from the ground and relocated to the lower-lying location Fendt (595 m a.s.l.). Thus, they were transferred to a location with less precipitation and higher mean annual temperatures (Table 1), following the “space for time concept” to simulate climate change (Pütz et al. 2016). Due to climate change, temperatures in the Alps are expected to rise. Precipitation is expected to decrease and to change in temporal distribution (Smiatek et al. 2009; Kunstmann et al. 2004). Therefore, the re-location of the soil cores serves as a vague climate change simulation.

Each lysimeter unit contains six lysimeters which have a surface area of 1.0 m^2 with a length of 1.5 m (Zacharias et al. 2011). They are distributed in a hexagonal structure around a service device where data recording and analytical devices are stored. By aligning them in a hexagonal design, each lysimeter is equally distant from the service device in the centre, thus equal conditions, and therefore comparable results, are guaranteed. Each lysimeter unit contains three intensively managed lysimeters, and three extensively managed ones (Figure 3).

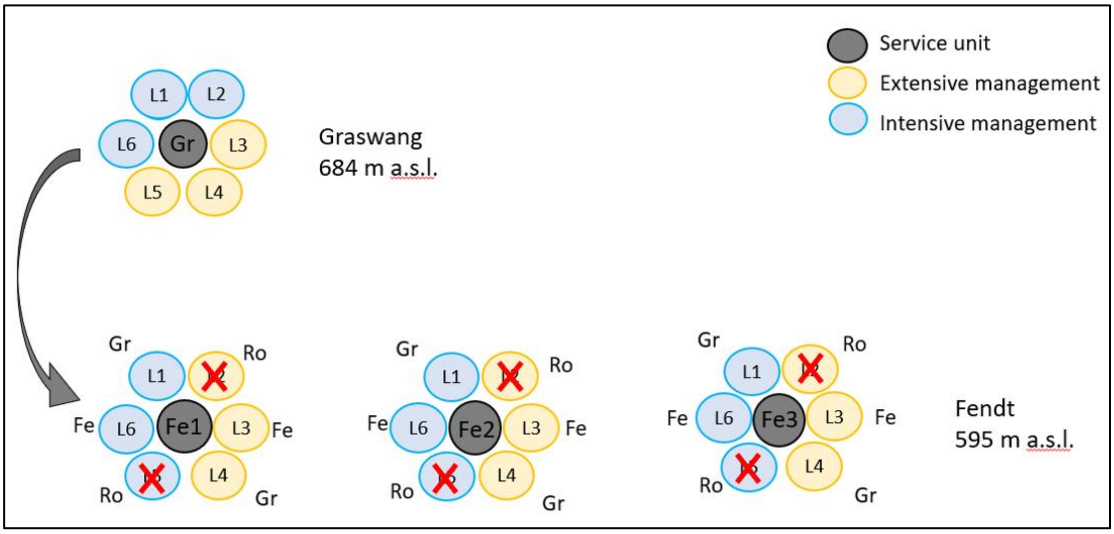

Figure 3. Overview of the lysimeter distribution in Fendt and Graswang. The abbreviations next to the lysimeters show their origin: Gr = Graswang, Fe = Fendt, Ro = Rottenbuch. The lysimeters from Rottenbuch are not considered in this thesis.

This study deals with data obtained from the control unit, which was kept in its original location in Graswang, and the three lysimeter units in Fendt. In Fendt, each lysimeter unit consists of two lysimeters originating from Graswang, two from Rottenbuch, and two as control lysimeters which originate form Fendt and still remain in this location. Data were obtained in 2019. The focus is on the comparison of Graswang and Fendt, thus the lysimeters in Fendt originating in Rottenbuch will not be looked at in detail.

At the bottom of the lysimeters, there is a unit of parallel suction pipes to control the lower boundary conditions of each lysimeter (Zacharias et al. 2011). With that, the soil water content inside the lysimeters is adjusted to match the soil water content of the surroundings: when the soil water content inside the lysimeter is higher than in the surrounding soil, water leaches via the suction pipes into a tank. When the soil water content inside the lysimeter is lower than in the surrounding soil, water is transferred back into the lysimeter from said tank (Zacharias et al. 2011).

Other relevant parameters for this thesis are the amount of daily precipitation (measured on site with pluviometers and calculated based on weight changes in the lysimeters) and its isotopic composition (random sampling; between four and seven samples per station and season). Furthermore, daily data about the amount of discharge from the lysimeters and daily actual evapotranspiration rates were used in this thesis.

2.2 Laboratory Analysis

Most of the precipitation and soil water samples were analysed in the laboratory of the KIT in Garmisch-Partenkirchen, about 400 samples were analysed in the laboratory of the Chair of Hydrology at the Albert-Ludwigs-University Freiburg. For the isotope analysis the filtered samples were analysed with a ring-down spectrometer (Picarro L2130-i, CRDS; Measurement accuracy: +/- 0,16‰ for $\delta^{18}O$, +/- 0,6‰ for $\delta^{2}H$).
Each sample was injected and analysed 6 times with the Picarro. With each Picarro run, validation and calibration standards were analysed. The mean of the last three measurements was calculated and used as result for the corresponding sample, the first three injections served only to prevent the results from being influenced by a memory effect and were not used in the further process. Where the standard deviation σ of the last three sample injections exceeded a certain threshold, data was examined in detail and, if necessary, unreliable injection results were erased, leaving only two values to be considered in the calculation of the mean. The thresholds can be seen in Equation 1 and Equation 2.

$$\sigma_{18O} > 0.08$$ **Equation 1**

$$\sigma_{2H} > 0.30$$ **Equation 2**

The Picarro results were processed in Excel. The rest of data processing and analysis was carried out using R Version 4.0.2 "Taking Off Again" by R Core Team (2020) with the help of R Studio Version 1.3.1073 “Giant Goldenrod” by RStudio (2009).

Isotope δ notation

As a result of the analysis run by the Picarro, $\delta^{18}O$ and $\delta^{2}H$ values of the water samples are provided. The following paragraph briefly presents the theoretical background of the δ (delta) notation.

Stable water isotopes are ^{1}H (protium) and ^{2}H (deuterium) as stable isotopes of hydrogen on the one hand and ^{16}O, ^{17}O, and ^{18}O as stable isotopes of oxygen on the other (Mook et al. 2001). ^{18}O and ^{2}H are rare oxygen and hydrogen isotopes, respectively (Leibundgut et al. 2009). The ratio of ^{18}O or ^{2}H to the abundant oxygen or hydrogen isotopes, ^{16}O or ^{1}H, respectively, is the so-called isotopic abundance ratio R (Leibundgut et al. 2009). Equation 3 shows how to calculate it according to Leibundgut et al. (2009):

$$R = \frac{Ni}{N}$$ **Equation 3**

With N_i rare isotopic species (e.g. ^{18}O)

N abundant isotopic species (e.g. ^{16}O)

To enable comparisons between isotope values, the isotopic abundance ratio of the water sample (R_{Sample}) is set in relation to the Vienna Standard Mean Ocean Water (V-SMOV2) by the International Atomic Energy Agency (IAEA) ($R_{Standard}$), which is the worldwide accepted standard for stable isotope analysis of water (Mook et al. 2001; Leibundgut et al. 2009; Stumpp et al. 2012). That is how the δ signature of the rare, heavy isotopes are calculated, as can be seen in Equation 4 (Stumpp et al. 2012; Leibundgut et al. 2009). In order to achieve a result giving the deviation of the sample from the standard in permille (‰), the result is multiplied by 1000 (Leibundgut et al. 2009; Stumpp et al. 2012).

$$\delta\ [‰] = \frac{Rsample - Rstandard}{Rstandard} * 1000$$ **Equation 4**

For instance, $\delta^{18}O$ indicates the content of the heavy oxygen isotope ^{18}O in a water sample as a deviation from the international standard V-SMOV2 (Mook et al. 2001). If the δ signature of a water sample is positive, the sample contains more heavy stable isotopes (^{18}O or ^{2}H) than the standard, while negative δ values indicate that the sample contains fewer heavy isotopes than the standard. In the first case one speaks of enrichment, in the second of depletion of heavy isotopes (Leibundgut et al. 2009; Stumpp et al. 2012).

2.3 Data Post-Processing

2.3.1 Outlier Analysis of Isotope Data

For the outlier analysis, an agglomerative hierarchical cluster approach in combination with the single linkage approach was used. That means the Euclidean Distance between the data points was calculated as a measure of similarity (i.e. distance) and in accordance with agglomerative hierarchical clustering, in each step the clusters closest to each other are merged (Almeida et al. 2007). Single linkage means that the distance between the two closest points of two clusters defines the distance between these clusters (Almeida et al. 2007). The dimensions, also called variables, considered for the clustering were *date*, $\delta^{18}O$, and $\delta^{2}H$. At first, the cluster analysis was carried out for the complete data set at once. That did not lead to reliable results, obvious outliers were not marked as such and vice versa. That is why the analysis was repeated, this time doing one cluster analysis per location ID consisting of station, lysimeter, and depth. The cluster analysis was only carried out on data sets with enough data points. The minimum sample size n was calculated according to Formann (1984) (Equation 5). Due to the small data sets per location ID the optimisation of the equation could not be used, and the minimum sample size n was therefore set to 8 observations (Equation 5a).

$$n > 2^k$$
$$(even\ better: n > 5 * 2^k)$$
Equation 5

n minimum sample size

k number of variables

$$n > 2^3 \rightarrow n > 8$$
Equation 5a

17 out of 91 sets corresponding to a particular station, lysimeter, and soil depth could not be analysed due to insufficient data and were only visually inspected for outliers. To be classified as such, a value had to be the only data point in a cluster. For almost 50 IDs, the calculation did not show any outliers. In the other cases, the calculated outliers were checked visually and subsequently removed from the data set. In two cases, after visual examination, one more data point had to be erased, even though it had not been declared an outlier by the cluster analysis. Both these data points showed severely lighter isotope signatures than the rest of the data in the corresponding location.

2.3.2 Data Processing of Soil Moisture Data

The soil moisture sensors in Fendt were not working flawlessly. Hence there is a lack of data, especially for Fe1 and Fe3. The sensors in Fe2 and in Graswang worked well over the course of the sampling time, although here, too, some lysimeters show missing data. Therefore, the soil moisture values from Fe2 were, whenever possible, transferred to Fe1 and Fe3, always transferring the values to the lysimeters of the other stations with the same soil properties, origin, and management. Moreover, values were only transferred to the same depth as their measurement depth. Thus, the values from Fe2_L1_10 were transferred to Fe1_L1_10 and Fe3_L1_10, and so on. To figure out whether any correlations existed between the soil moistures of the different Fendt-stations, the soil moisture data from 2018 were compared. In the first step, the different stations were plotted together for a first visual impression. This showed that for all identifiers, the corresponding identifiers at the other stations show a similar course. To ensure this similarity, a correlation test was carried out for some corresponding identifiers (picked randomly). The results showed correlations between the soil moisture data originating from the same measuring depth and lysimeter number (hence equal management and soil), but different Fendt-stations (e.g. Fe1_L1_10 correlates with Fe2_L1_10 etc.). The correlation was only weak in some cases. Nevertheless, all randomly checked test results were statistically significant on the significance level $\propto = 0.05$. No clear patterns, like one station always showing higher soil moisture values than another one, could be identified. Therefore, the Fe2-values were not further adapted to Fe1 and Fe3 but instead transferred as they were.

Two exceptions had to be made: For L6 in 30 cm depth, there are no soil moisture data available at Fe2 in 2019. In that case, the values from L3 were used for L6. Both lysimeters originate from Fendt, they merely differ in their management (L6 is managed intensively, L3 extensively). By comparing other intensively and extensively managed soils at a station from the same origin the conclusion was drawn that the management type does not influence the soil moisture strongly. Therefore, data observed at differently managed lysimeters can be exchanged to substitute missing data. Consequently, for Fe2_L6_30, the soil moisture data from Fe2_L3_30 was used. The same procedure was used at Fe2_L4_50 (origin: Graswang; extensive management) where the lack of data was handled by substitution with data obtained at Fe2_L1_50 (origin: Graswang; intensive management). In this case, data from 2018 was available for both lysimeters and they showed very similar courses. Consequently, the use of data originating from soil with the same origin and current location, but different management type, seems appropriate. To ensure that the values of the respective lysimeters correlate, a correlation test was carried out. In both cases, a strong correlation ($\rho > |0.5|$) was deducted and found to be statistically significant at the significance level $\propto = 0.05$. These results confirm the assumption that the described substitutions are suitable.

2.4 Data Analysis

2.4.1 RMSD

To analyse the magnitude of difference between the isotopic compositions at different measuring sites and under different environmental conditions, the Root Mean Square Deviation (RMSD) was calculated using the following equation:

Equation 6

$$RMSD = \sqrt{\sum_{i=1}^{n} \frac{(x_i - y_i)^2}{n}}$$

x_i / y_i daily median $\delta^{18}O$ values for the time series x/ y

n number of observations

For instance, the RMSD between isotope values at different measurement depths was calculated that way.

2.4.2 Kruskal-Wallis Test and Pairwise Wilcoxon Test

Since the RMSD does not make any assumptions about the significance of differences, the Kruskal-Wallis test was performed as a next step to detect any significant differences in data collected at different stations, depths, and/or lysimeters. The significance level $\propto$ for all statistic tests was set at 0.05, meaning that with a p-value of more than 0.05, the null hypothesis (H0) was accepted and differences in data were regarded as not significant. With a p-value of less than 0.05 (less than 0.01), the differences are considered (highly) significant. The Kruskal-Wallis test shows only that significant differences occur at least once comparing various groups, yet it does not show, which groups display these differences. That is why in case of $p < 0.05$, a pairwise Wilcoxon test was performed as a post hoc analysis to check between which groups the significant differences occur.

2.4.3 Correlations

Correlations were analysed with the Spearman rank-order correlation due to the data not being normally distributed. As for all statistical tests, the significance level was set to 0.05, meaning that a p-value of < 0.05 signals significant correlation between two variables.

2.4.4 Local Meteoric Water Line (LMWL), Evaporation Line (EL), and Line Conditioned-Excess (lc-excess)

The stable water isotopes in precipitation water correlate strongly and their relation is described by the Global Meteoric Water Line (GMWL) (Craig 1961; Rozanski et al. 1993). For the precipitation in a specific location, the Local Meteoric Water Line (LMWL) shows the relation of δ^2H to $\delta^{18}O$. The LMWLs for Fendt and Graswang were calculated with a linear model based on the isotope data of precipitation at the respective locations. The LMWL is defined by its slope and the y-axis-intercept in the dual isotope plot (i.e. the δ^2H-axis), shown in Equation 7 and Equation 8 for Fendt and Graswang, respectively.

$$\delta^2\mathrm{H} = 7.97 * \delta^{18}\mathrm{O} + 8.34$$ **Equation 7**

$$\delta^2\mathrm{H} = 8.44 * \delta^{18}\mathrm{O} + 12.28$$ **Equation 8**

When water evaporates, the ratio between ^{2}H and ^{18}O changes because of kinetic fractionation processes: $^1H_2{}^{18}O$ is heavier than $^1H^2H^{16}O$ and therefore, the first is more likely to remain in the liquid phase while the second is transferred to the water vapour that results from the evaporation. Thus, the remaining water will experience an enrichment in ^{18}O while simultaneously being depleted in ^{2}H and therefore, water that has undergone evaporation processes will plot below the LMWL in a dual-isotope plot (Sprenger et al. 2017a). With more evaporation, the effect of kinetic fractionation becomes more evident in the remaining water. As a consequence, the longer water has been exposed to evaporation, the bigger the deviation of their isotopic composition from that of the precipitation; hence they differ more from the LMWL.

The regression line through the water samples in the dual isotope plot, called Evaporation (Water) Line (EL), is therefore expected to have a lower slope than the LMWL (Sprenger et al. 2017a). For Fendt and Graswang, that is the case: The slope of the EL in Fendt is approximately 7.76 and the EL in Graswang has a slope of ca. 7.81.

Based on the LMWLs, the line conditioned excess (lc-excess) was calculated according to Landwehr and Coplen (2006), as shown in Equation 9, with *a* being the slope of the LMWL and *b* being the δ^2H -axis-intercept of the LMWL in the dual isotope plot. The lc-excess is an indicator of the deviation of the isotopic composition of the soil water from the isotopic composition of precipitation, i.e. it describes by how far a water sample's isotopic composition differs from the corresponding LMWL (Sprenger et al. 2017a). For inter-station comparisons it often makes more sense to analyse the lc-excess instead of δ^{18}O or δ^2H values of the samples because that way the influence of the different isotopic composition of precipitation at various stations is muted. The calculation of the lc led to one outlier where the lc-excess was 18.94. That value was erased because it clearly stood out from the rest of the data.

$$lc - excess = \delta^2\mathrm{H} - a * \delta^{18}\mathrm{O} - b$$ **Equation 9**

An lc-excess of 0 indicates that the sample's isotopic composition does not differ from that of the local precipitation, positive values indicate that the sample consists of lighter water than the precipitation water (i.e. the sample plots above the LMWL in the dual isotope plot), and negative values indicate heavier water in the sample than in precipitation water (Landwehr et al. 2014). Thus, if a sample has a negative lc-excess, it has probably been exposed to evaporation and thus fractionation processes, while a sample with a positive lc-excess might be the product of precipitation mixing with water from other sources, e.g. "relatively newly evaporated moisture" (Landwehr et al. 2014). The lc-excess as an indicator of the evaporation influence is usually more negative in the upper soil layers and decreases with increasing depth (Sprenger et al. 2016). In deep soil layers, evaporation usually does not alter the isotopic composition and the lc-excess is generally positive (Sprenger et al. 2016).

Lastly, it should be noted that the lc-excess is not to be confused with the LC-excess, which describes the deviation from the water sample's isotopic composition from the global meteoric water line (GMWL), and therefore resembles the deuterium-excess (d-excess) (Landwehr and Coplen 2006). An advantage of the lc-excess compared to the d-excess is that lc-excess is less influenced by seasonal variability (Sprenger et al. 2017b).

3 Results

In this section, the results of the isotopic analyses will be presented. Since δ^{2}H and δ^{18}O values correlate strongly, the results will mostly be shown on only one of the two. To distinguish which of the influencing factors has the biggest impact on the isotopic composition of the soil water, this section is divided into various subsections by influencing parameter.

3.1 Major Effects of Location

Firstly, the isotopic composition of the soil water at the two experiment locations Fendt and Graswang is compared (Figure 4 and Figure 5). In this first chapter, no distinction of the data based on climate (change) effects or management is made, but only the distinction of location is relevant. To enable a clear distinction between the values by soil moisture, the δ^{2}H and δ^{18}O values in the figures are also shown as boxplots, differentiated by soil moisture. It is clearly visible that in both locations, the soil water isotopes do not differ strongly from the corresponding Local Meteoric Water Line (LMWL). This means that the prevailing climate does have a big impact on the isotopic composition of soil water, apparently more than the soil and the climate of the origin of a lysimeter, otherwise a visible deviation from the LMWL of half of the data points at Fendt would be expected. The comparison also reveals that the variation of isotopic composition is bigger at Fendt than at Graswang, especially considering the δ^{2}H values: Fendt shows a range of 91.4‰ with the minimum being -122.8‰ and the maximum being -31.4‰ while Graswang displays values between -117.1 and -37.6‰, therefore showing a range of 79.5‰. As for the δ^{18}O values, the differences are not as strong: In Fendt, the δ^{18}O values differ from -16.22 to -4.86‰ (range = 11.36‰), while in Graswang, they vary between -15.98 and -5.61‰ (range = 10.37‰).

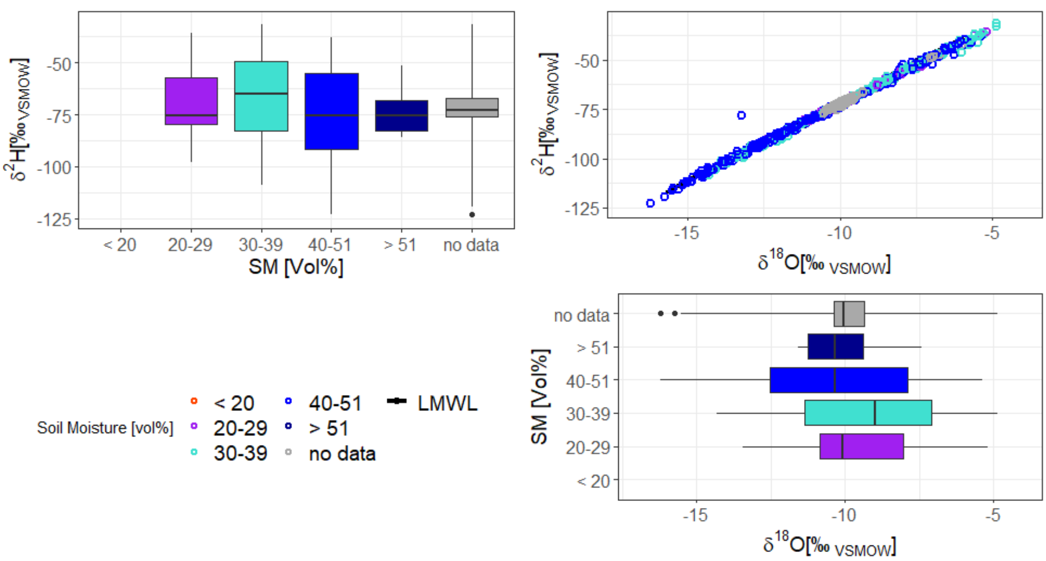

Figure 4. Isotopic composition of soil water at Fendt by soil moisture.

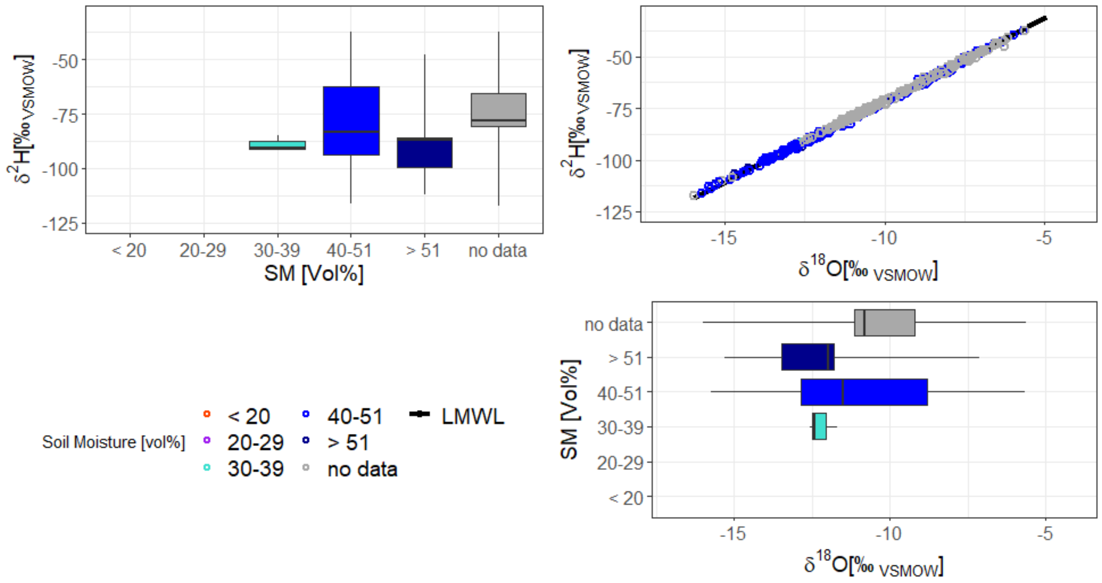

Figure 5. Isotopic composition of soil water at Graswang by soil moisture.

3.2 The Role of Climate Change

In order to analyse the effect of climate change on pre-alpine grassland soils, the monitored lysimeters can be grouped by their station, origin, and management. Hence, *Gr-int-control* and *Gr-ext-control* consist of the Graswang control lysimeters that are managed intensively and extensively, respectively. *Gr-int-cc* and *Gr-ext-cc* contain the Graswang replicates, i.e. those that were transferred from Graswang to Fendt and therefore display the impact of climate change on those soils. Lastly, *Fe-int* and *Fe-ext* contain the autochthonous lysimeters in Fendt (hence also referred to as *Fendt (int/ext) control*). Each group, hereafter also referred to as *status groups*, consists of three lysimeters. In the following, the groups are checked for similarity within each group first to ensure that the division of the data into these groups makes sense. After that, the groups will be compared to each other.

3.2.1 Differences Within the Status Groups

Figure 6 shows the composition of the groups and illustrates the differences in the distribution of $\delta^{18}O$ values at the different lysimeters within each group. The isotopic composition of Fe-ext, Gr-ext-cc, Gr-ext-control, and Gr-int-control does not differ significantly between the three lysimeters the groups consist of. Only Fe-int and Gr-in-cc are not as homogeneous and do have statistically significant differences in their $\delta^{18}O$ signature between the corresponding lysimeters. Apart from significance it is notable that differences within one group are usually small. Regarding the lc-excess, more groups show significant differences between their lysimeters (Fe-ext, Gr-ext-cc, Fe-int, Gr-int-cc), yet the differences within one group still are very small (Figure A 2).

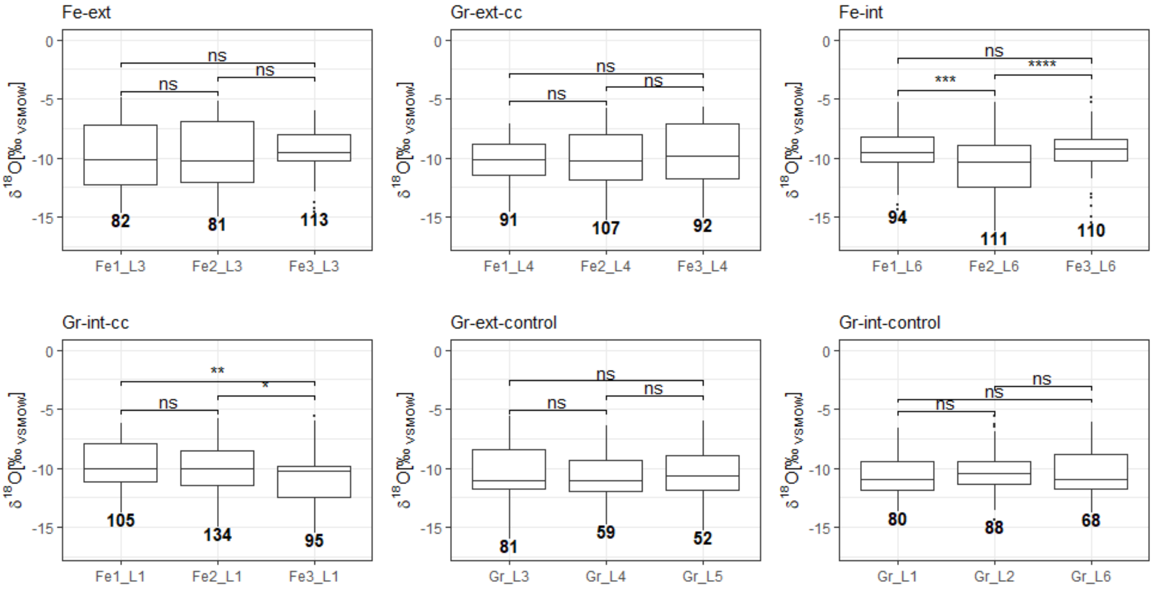

Figure 6. Differences in δ^{18}O within the status groups. ns: difference not significant; *: p ≤ 0.05; **: p ≤ 0.01; ***: p ≤ 0.001; ****: p ≤ 0.0001.

3.2.2 Differences Between the Status Groups

From chapter 3.2.1 we can deduct that differences within the groups are mostly not statistically significant and even if so, they are very small. Therefore, these groups serve the purpose of analysing the effect of climate change since they offer information on how the soil water changes in different circumstances. Fe-ext and Fe-int have on average the highest δ^{18}O values but also the highest standard deviations. Regarding the lc-excess, the control groups in Graswang have a positive average while the groups in Fendt all have negative means (and medians). For more details, please consult Table A 2.

The evaporation lines of the different status groups show that the soil water in Graswang is lighter than in Fendt. The evaporation lines of the soil water in the transferred lysimeters and in the reference group in Fendt are similar, yet the transferred ones still have on average lighter soil water than the lysimeters originating from Fendt (Figure 7).

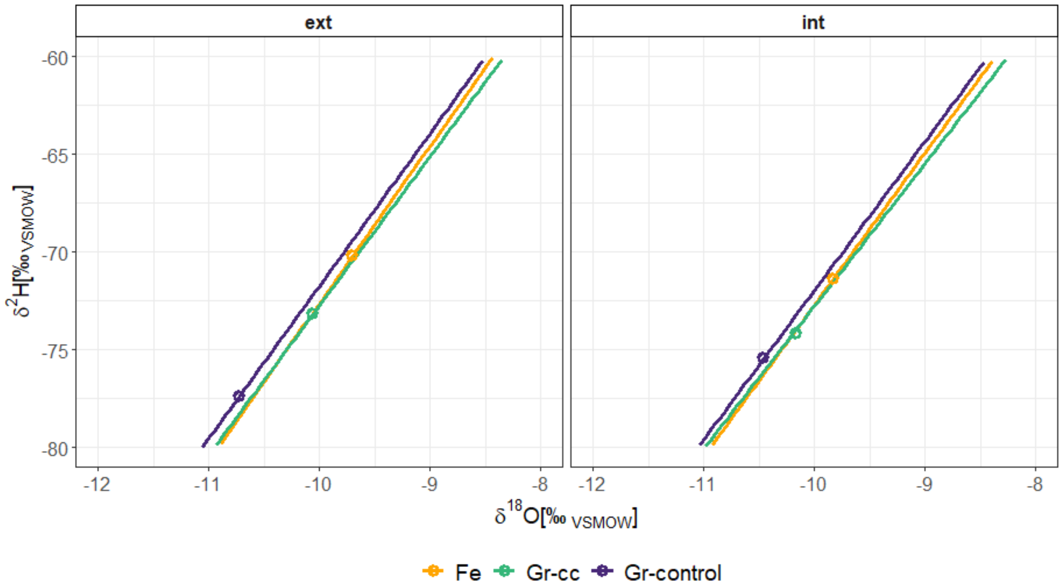

Figure 7. Comparison of the evaporation lines of the lysimeters from the different groups. The points indicate the mean isotopic composition of each group.

The distributions of lc-excess and $\delta^{18}O$ values in the different status groups show a similar pattern, even though it is much clearer for the comparison of lc-excess values. The differences between the groups at Fendt (Fe-ext, Gr-ext-cc, Fe-int, and Gr-int-cc) are negligible, as are the differences between Gr-ext-control and Gr-int-control, the two groups consisting of the lysimeters in Graswang. The differences between the groups in Graswang and those in Fendt, on the other hand, are not only greater, but also statistically significant. The differences between lc-excess values of lysimeters at the same location, however, are not statistically significant (Figure A 3).

For a more detailed picture, the distributions of lc-excess values in the different groups are compared to each other by measuring depth in Figure 8. Throughout the entire soil profile, the lysimeters in Graswang differ significantly in their lc-exess values from those in Fendt (both Fe and Gr-cc). The difference between Gr-cc and Fe is only statistically significant in the top soil layer (10 cm) and even there, the difference between these groups and Gr-control is still larger and more significant. Figure 9 illustrates that, regarding the $\delta^{18}O$ values of soil water, it also depends on the measuring depth whether there are significant differences between the groups. In the top soil layer, no significant differences between Fe, Gr-cc, and Gr-control can be detected. At 140 cm of soil depth, however, all groups differ significantly from each other. This proves that soil depth does have a considerable influence of the isotopic composition of the soil water.

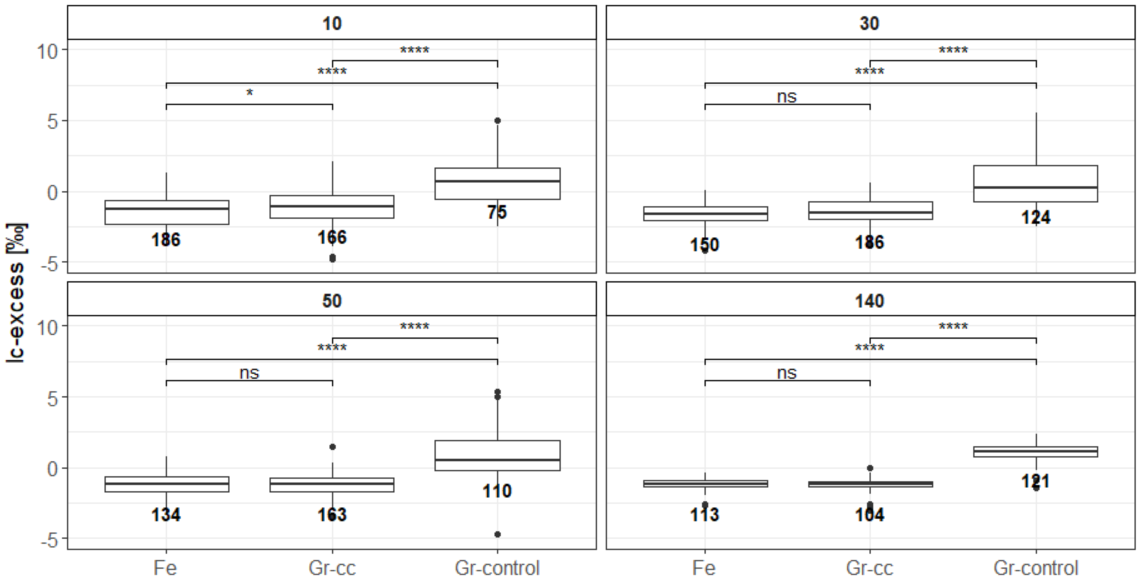

Figure 8. Distribution of lc-excess values in soil water by status and depth. ns: difference not significant; *: p ≤ 0.05; **: p ≤ 0.01; ***: p ≤ 0.001; ****: p ≤ 0.0001.

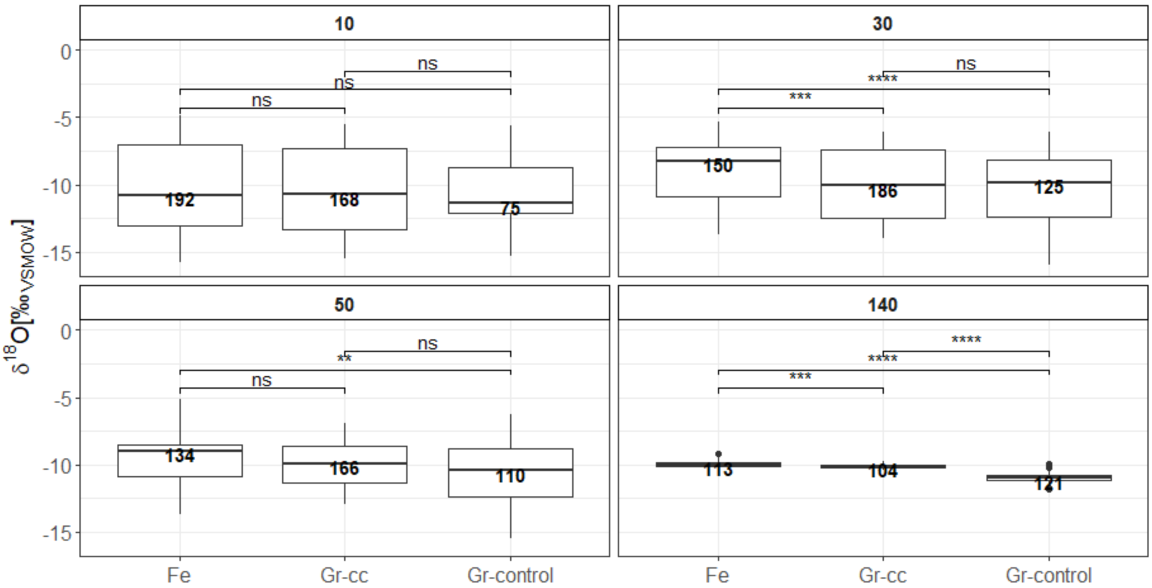

Figure 9. Distribution of $\delta^{18}O$ signature in soil water by status and depth. ns: difference not significant; *: p ≤ 0.05; **: p ≤ 0.01; ***: p ≤ 0.001; ****: p ≤ 0.0001.

Apart from the distribution of the isotope values, its course over the year is interesting to compare. In Figure 10, the course of $\delta^{18}O$ in the different status groups is depicted, with extensively and intensively managed lysimeters being looked at as one, as only minor differences arise due to different management (see chapter 3.3). According to Sprenger et al. (2019), the stable water isotopes observed at a soil depth of 30 cm are representative for said soil. That is why only the values observed at 30 cm are shown in this graph; for all measuring depths, see Figure A 4. The overall course of all groups is similar. The isotopic signature of the soil water is at its maximum (i.e. relatively heavy water) in fall and at its minimum (i.e. light water) in spring. It is clearly visible that Fendt has overall higher $\delta^{18}O$ values than Gr-cc and Gr-control, except for at the beginning and end of the year. Gr-control shows the lowest values of $\delta^{18}O$, except for a short period of time around February and one measuring point in September. The transferred lysimeters do not show the same isotopic composition in soil water as either of the control groups. At the beginning and end of the year, Gr-cc even has the heaviest soil water of all groups. In February and March, the soil water in Gr-cc is the lightest of all groups, while Gr-control has the heaviest in these months. In January and from April to December, Gr-control has the lightest isotopic composition. Overall, the soil water in the transferred lysimeters behaves more like that in the other lysimeters in Fendt than that in Graswang.

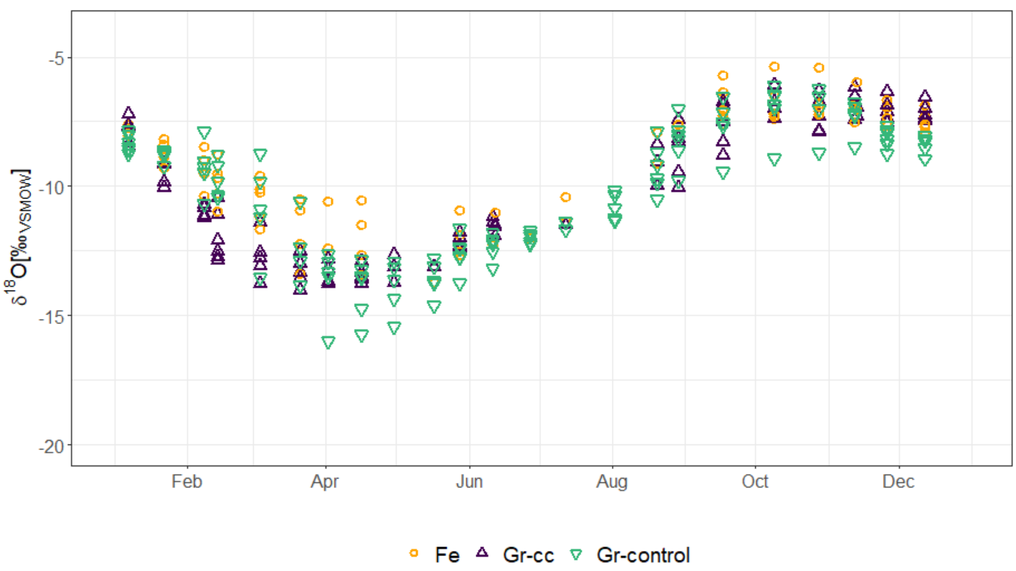

Figure 10. Course of $\delta^{18}O$ values of soil water from a soil depth of 30 cm over the year 2019.

3.3 Negligible Effect of Management

The agricultural management of the lysimeters has only a minor effect on the isotopic composition of the soil water. Overall, differences caused by distinct management types are small and not statistically significant. Only at a soil depth of 50 cm (Gr-cc) and 140 cm (all groups), differences are statistically significant according to the Kruskal-Wallis test, yet they are negligibly small (Figure 11). The examination of the lc-excess leads to the same result, only that significant differences were found at 30 cm (Fe and Gr-cc) and at 140 cm (all groups) (Figure A 5). In the appendix, the courses of the $\delta^{18}O$ signature of the soil water in the different groups and at different soil depths are compared by management (Figure A 6, Figure A 7, Figure A 8). These graphs convey the same message: overall, the differences between extensively and intensively managed lysimeters are minimal.

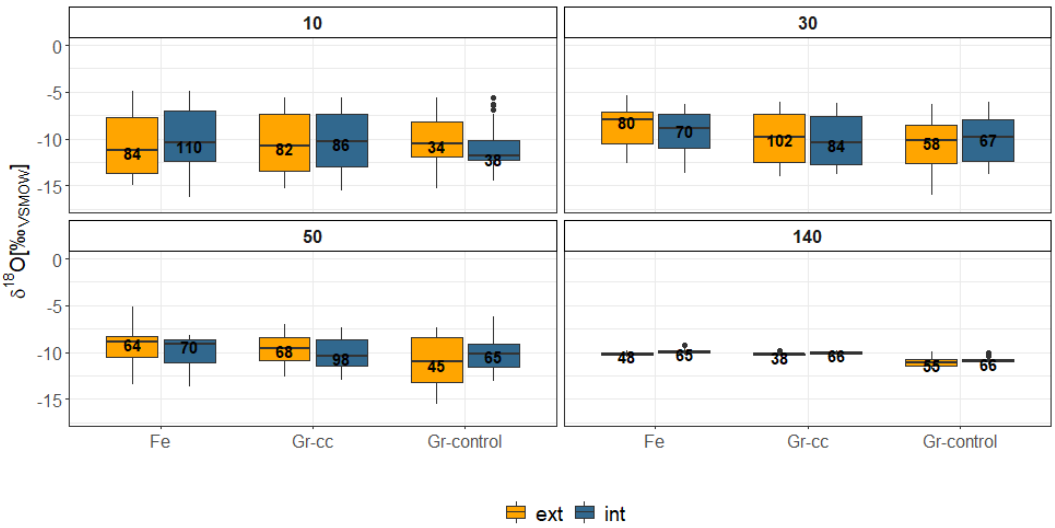

Figure 11. Difference in $\delta^{18}O$ signature of soil water in differently managed lysimeters. ns: difference not significant; *: p ≤ 0.05; **: p ≤ 0.01; ***: p ≤ 0.001; ****: p ≤ 0.0001. The numbers in bold indicate the number of observations per boxplot.

3.4 Seasonal Differences in Isotopic Composition of Soil Water

The seasonal differences in the precipitation's isotopic composition are very similar in Graswang and Fendt. The lightest precipitation falls in winter, the heaviest falls in summer. The isotopic composition of rainwater in spring and fall is quite similar, in Graswang they are almost equal. In Fendt, the rainfall tends to be heavier in fall than in spring. Details on the distribution of $\delta^{18}O$ by seasons can be seen in Figure A 9.

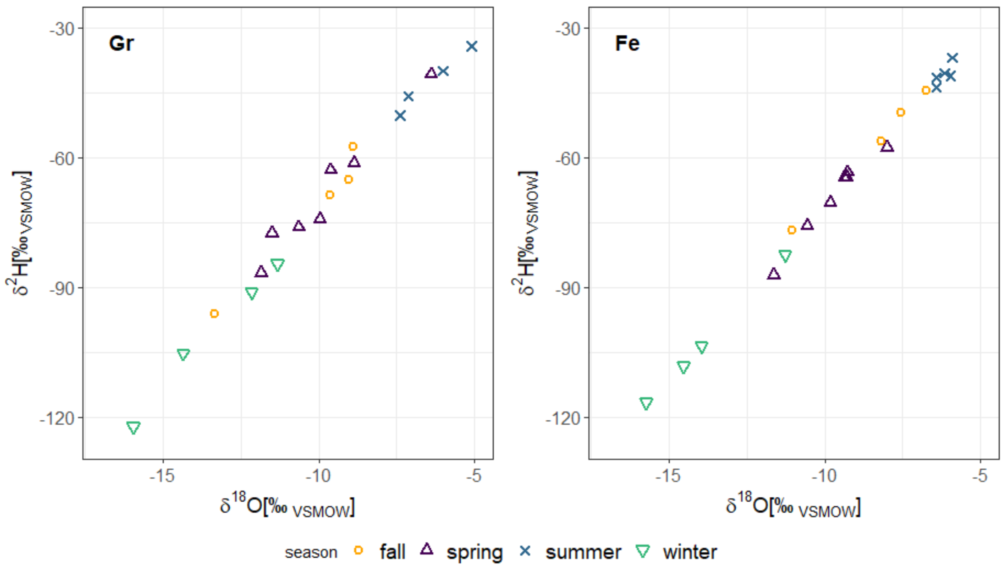

Figure 12. Comparison of isotopic composition of precipitation at both locations, by season.

With regard to the seasonal differences in the isotopic composition of the soil water, it can be noted that all seasons differ significantly from each other in Gr-control. In the climate change simulating group Gr-cc, almost all seasons differ significantly from each other (with the exception of winter and summer), and in the Fendt control group, fall differs significantly from the other seasons, while the rest of the differences is not significant. Not taking into consideration the statistical significance of differences, Gr-control shows clearly bigger differences in the isotopic composition of soil water based on seasons than the two groups located in Fendt. Of those two, Gr-cc shows slightly bigger differences in its seasonal lc-excess distributions than Fe (Figure 13).

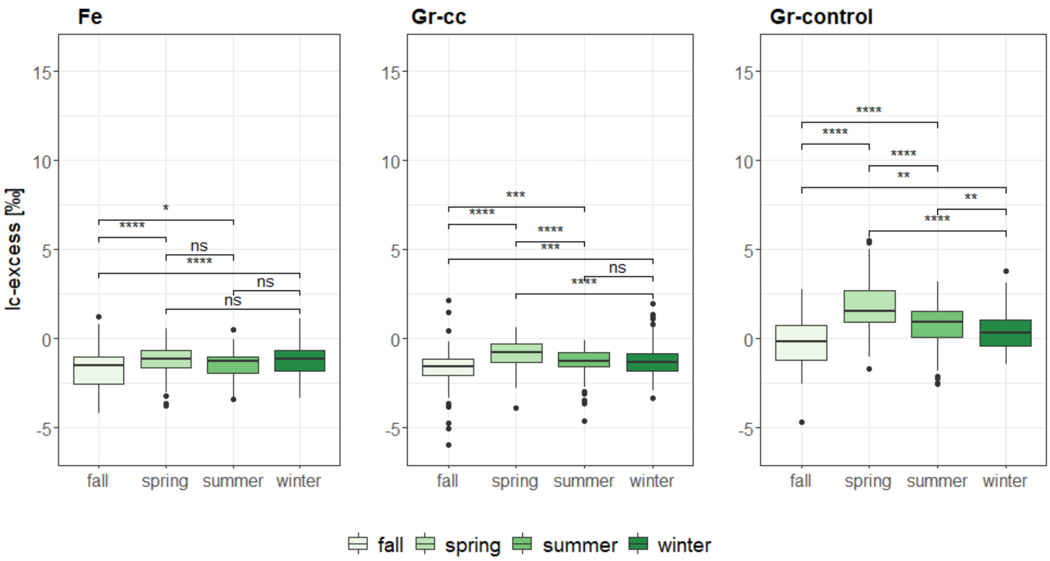

Figure 13. Lc-excess by season and by status group, with significance bars indicating whether differences between seasons are significant in each group. ns: difference not significant; *: p ≤ 0.05; **: p ≤ 0.01; ***: p ≤ 0.001; ****: p ≤ 0.0001.

3.5 Relation of Volumetric and Isotopic Soil Water Content

Fendt has the driest soils of the three groups in the entire soil profile, Gr-cc and Gr-control do not differ strongly from each other in 30 and in 50 cm depth (Figure 14). In the upper soil layer (10 cm), the course of the soil moisture in all three groups is very similar and varies a lot over time. A clear delineation of the analysed lysimeters is evident. The relocated lysimeters (Gr-cc) show the highest variability in soil moisture at this soil level, in Gr-control, the soil moisture is the most stable. The average soil moisture in the relocated lysimeters and in the reference ones is very similar. The volumetric soil content in Graswang is on average ca. 10% higher than in Fe and Gr-cc. In a soil depth of 30 cm, Gr-control already shows only small variability (σ = 1.22%vol), while Fe and Gr-cc still vary intensly. In the relocated lysimeters, the variability in volumetric soil moisutre has decreased more intensively than in the control lysimeters in Fendt. On average, Gr-cc and Gr-control show very similar values at this depth. Only during summer months do these two groups differ slightly more and lower soil moisture levels are evident in Gr-cc. The volumetric soil water content in Fe is ca. 8% lower than in the other two groups. Lastly, at 50 cm, all groups show little temporal variability in soil moisture, with Gr-control having by far the most stable soil water content. Again, the mean in Gr-cc and in Gr-control are quite similar, Fendt, however, differs on average by ca. 16%vol from Gr-cc which, on average, has the highest soil water content at this depth. More details can be seen in Table A 6.

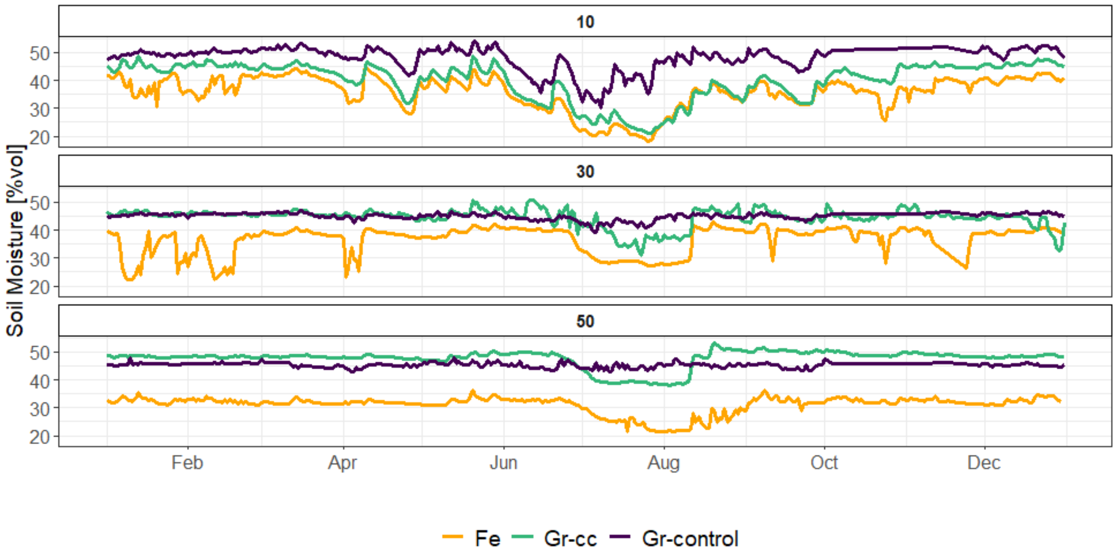

Figure 14. Soil Moisture in 10, 30, and 50 cm soil depth. Mean values per status group are displayed.

The soil moisture shows an intermediate correlation with the soil depth, which is not the same for all lysimeters: While in Gr-cc, the soil moisture increases with increasing depth (i.e. soils become wetter downwards), it decreases with increasing soil depth in the control groups Fe and Gr-control (i.e. soils become drier downwards) (Figure A 11). No correlation was found between the soil moisture and the $\delta^{18}O$ signature of soil water in Gr-control and Gr-cc (Figure 15, Figure A 12).

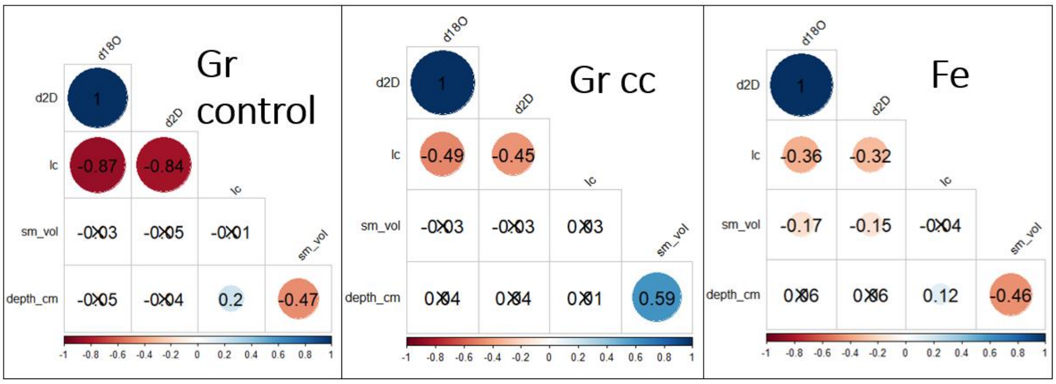

Figure 15. Correlation matrices indicating the correlations between δ^2H (= δ^2D), $\delta^{18}O$, lc-excess, soil moisture, and soil depth. The numbers in the squares show the corresponding ρ (Spearman rank correlation coefficient). Non-significant results are marked with a cross. The colourful circles indicate the strength of the correlation as a help to gain a quick overview.

3.6 Impact of Soil Depth on Isotopic Composition of Soil Water

For the RMSD matrix in Figure 16 the isotope data were grouped by measuring depth and status group. Then, the RMSD was calculated between all of the resulting groupings. Thus, for instance, the top left square in the matrix shows the RMSD between the data measured in Graswang at a soil depth of 140 cm and the δ^{18}O values observed in the control lysimeters in Fendt at 10 cm. The bigger squares with the dark red margins help to have a clear overview of the plot's main message: the top left one, e.g., contains all RMSDs between data gained at 140 and 10 cm of soil depth. The second square contains all RMSDs between data from 140 and 30 cm, the next one shows all RMSDs between data from 140 and 50 cm soil depth, and the top right square marks the RMSDs between data from 140 cm in different status groups, and so on. It is obvious that the bigger the difference in measuring depth, the bigger the difference in δ^{18}O values of the soil water. RMSDs between data gained at the same depth range from 0 to 2, whilst the RMSD between data from 140 cm and 10 cm soil varies between 2 and 3.

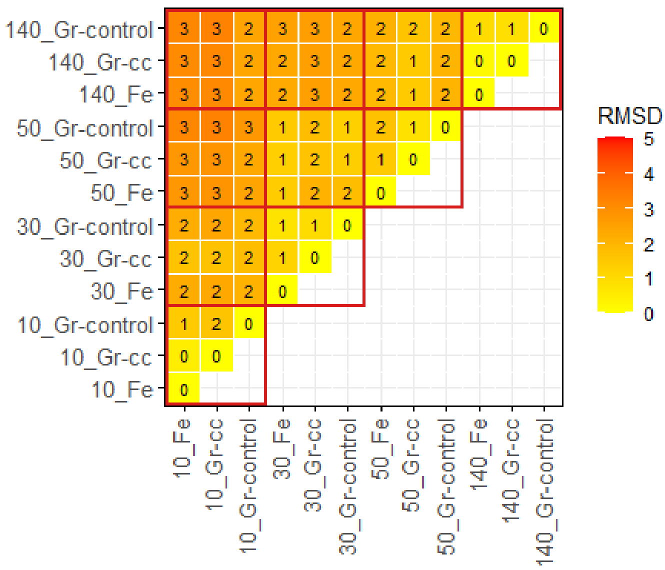

Figure 16. RMSD Matrix of δ^{18}O signature of soil water measured in different lysimeter units and depths.

With increasing soil depth, the soil water's variability in isotopic composition decreases strongly. However, the average δ^{18}O signature of the soil water is similar at all depths (Table A 3; Figure 18), as is the median. Thus, the main difference is the shape of the distribution. Nevertheless, when looking at the status groups separately, big differences arise: In the lysimeters transferred from Graswang to Fendt (Gr-cc), no significant differences are caused by a difference in measuring depth. In Graswang (Gr-control), only between 140 and 30 cm there is a significant difference in the soil water's isotopic composition. In the control group in Fendt (Fe), however, all differences between the measuring depths are significant (Figure 18). The picture painted by the comparison of the lc-excess values in the different groups and depths is very similar (Figure 17).

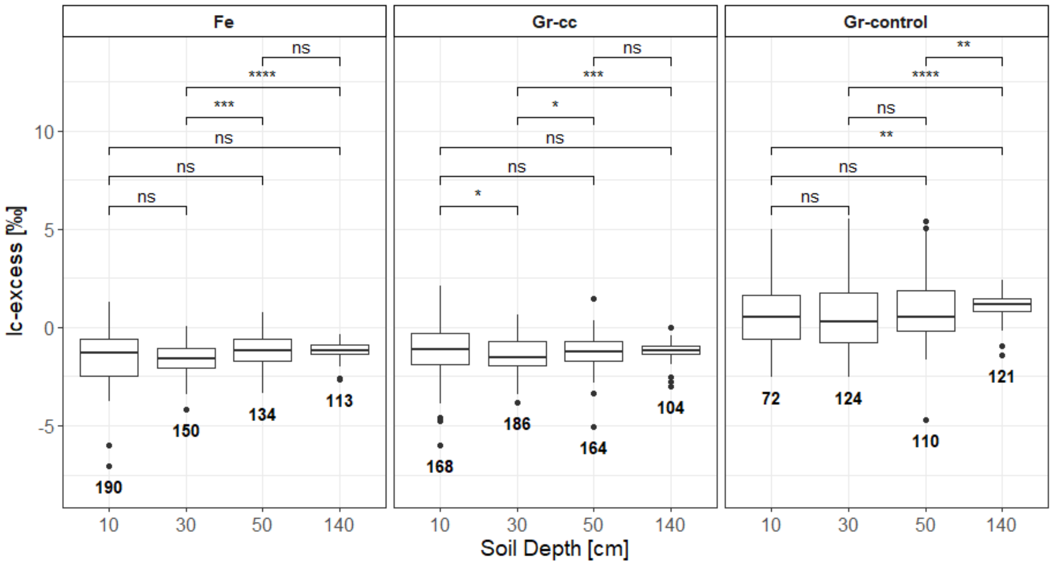

Figure 17. Distribution of lc-excess values in the soil water at different soil depth. ns: difference not significant; *: p ≤ 0.05; **: p ≤ 0.01; ***: p ≤ 0.001; ****: p ≤ 0.0001.

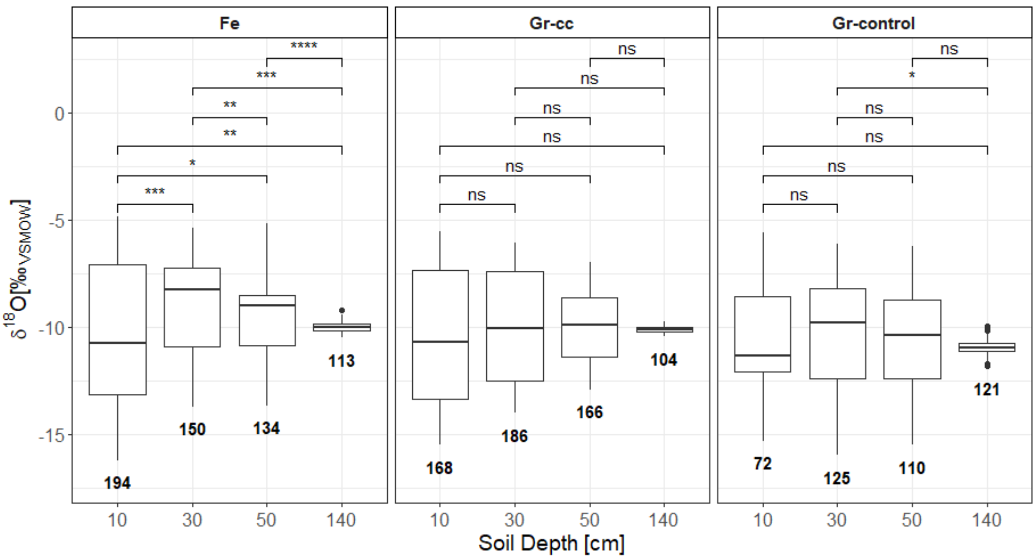

Figure 18. Distribution of $\delta^{18}O$ signature in soil water at different depths. ns: difference not significant; *: p ≤ 0.05; **: p ≤ 0.01; ***: p ≤ 0.001; ****: p ≤ 0.0001.

3.7 Relationship of Precipitation, Water Balance, and Soil Water

The occurrence of a rainfall event does not correlate with the isotopic signature of the soil water in Graswang. In Fendt, however, a weak correlation exists, thus an increase in in the amount of precipitation tends to go along with slightly lighter soil water.

3.7.1 Isotopic Composition of Precipitation

Table 3 and Table 4 show statistical overviews of $\delta^{18}O$ values in precipitation and soil water in Fendt and Graswang, respectively. It is striking that the soil water has a more negative (i.e. lighter) isotopic composition than the precipitation in spring and summer, but in fall and winter, it is the other way around. The standard deviation of the $\delta^{18}O$ signal in precipitation is overall clearly greater than that in the soil water, apart from summer (in both locations) and spring (only in Fendt). The data also show that the extreme values measured in soil water and precipitation do not take place in the same season: the rainfall with the heaviest isotopic signature falls in summer in both locations, while the $\delta^{18}O$ signature in the soil water reaches its maximum in Fall. The lightest precipitation falls in winter in Graswang and in fall in Fendt, while the lightest soil water was measured in spring in both sites. Furthermore, it seems noteworthy that in summer and winter, the isotope values of the soil water are quite similar. The data for $\delta^{2}H$ can be seen in the appendix in Table A 4 and Table A 5.

Table 3. Mean, minimum, maximum, and standard deviation σ of $\delta^{18}O$ values of precipitation (P) and soil water (SW) in Fendt in 2019 [in ‰].

		Mean	σ	Min	Max
Total	**P**	-9.95	3.98	-19.4	-4.22
	SW	-9.95	2.37	-16.22	-4.86
Spring	**P**	-9.71	1.15	-11.64	-8.00
	SW	-11.83	1.74	-16.22	-8.39
Summer	**P**	-5.85	0.83	-6.43	-4.22
	SW	-9.74	1.86	-12.92	-5.33
Fall	**P**	-10.58	5.19	-19.4	-6.73
	SW	-7.62	1.43	-10.45	-4.86
Winter	**P**	-14.56	2.24	-17.29	-11.27
	SW	-10.00	2.04	-15.14	-5.41

Table 4. Mean, minimum, maximum, and standard deviation σ of $\delta^{18}O$ values of precipitation (P) and soil water (SW) in Graswang in 2019 [in ‰].

		Mean	σ	Min	Max
Total	**P**	-9.99	3.24	-15.96	-4.77
	SW	-10.59	2.04	-15.98	-5.61
Spring	**P**	-9.84	1.84	-11.85	-6.39
	SW	-12.12	1.55	-15.98	-8.3
Summer	**P**	-6.08	1.17	-7.39	-4.77
	SW	-10.95	1.64	-14.84	-6.33
Fall	**P**	-11.33	3.07	-15.76	-8.9
	SW	-8.74	1.73	-11.45	-5.61
Winter	**P**	-13.45	2.1	-15.96	-11.33
	SW	-9.79	1.42	-14.26	-7.11

The EL and the LMWL are very similar, especially in Fendt where they are almost not distinguishable (Figure A 10). That means that the isotopic composition of soil water does not differ strongly from that of precipitation at the corresponding location. However, taking the temporal course into consideration, there are clear differences between precipitation and soil water: the annual course of the isotopic signal in precipitation is evident in the upper soil layers of the soil, as well, but with a time shift of two to three months (Figure 19, Figure 20).

Overall, there is no correlation between the isotopic composition of precipitation and soil water. In Graswang, however, rainfall and the soil water at 50 cm soil depth correlate negatively ($\rho = -0.5$, $p = 2.1 * 10^{-8}$), rainfall and soil water at 140 cm have a weak negative correlation ($\rho = -0.21$, $p = 0.0018$). In Fendt, the precipitation's isotopic signature correlates with that of soil water at 10 cm ($\rho = 0.31$, $p = 3.3 * 10^{-9}$), at 50 cm ($\rho = -0.28$, $p = 9 * 10^{-7}$), and at 140 cm ($\rho = -0.21$, $p = 0.0018$). Still, considering all data from Fendt, there is no correlation with the local rainfall's isotopic composition.

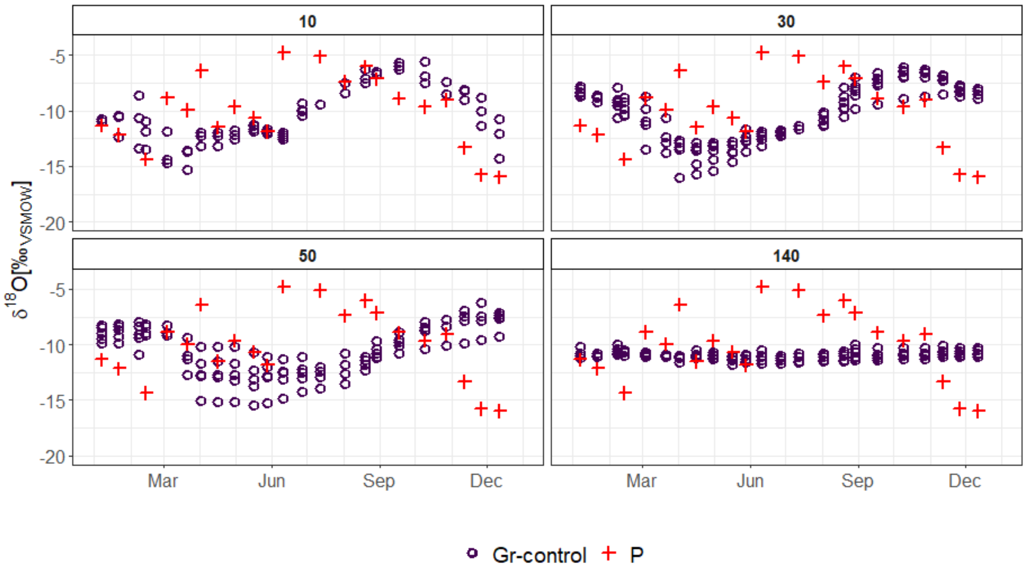

Figure 19. δ^{18}O signature in precipitation (P) and soil water in Graswang over the year 2019.

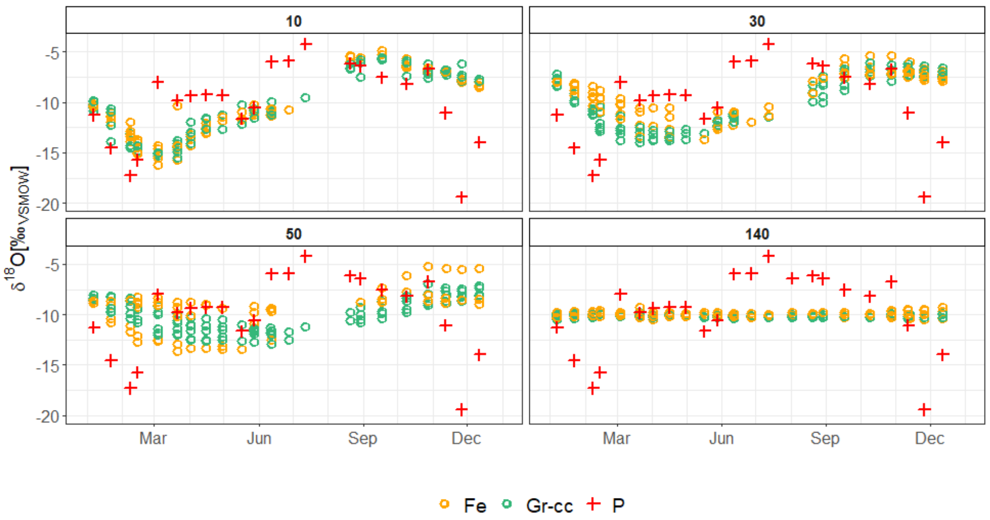

Figure 20. δ18O in precipitation (P) and soil water in Fendt.

Lastly, the connection between water balance and soil water will be examined. The lysimeters in Gr-control, Gr-cc, and Fe differ strongly from each other in their annual water balance of 2019. While the lysimeters in Fendt and Graswang-control show a positive balance (i.e. more precipitation than evaporation and drainage), Gr-cc shows a slightly negative one. The exact numbers can be found in Table 5.

Table 5. Water Balance in Fendt, Graswang-cc, and Graswang-control for the year 2019. P = Precipitation, E = Evaporation, D = Drainage. P, E, and D were calculated from the weight changes of the lysimeters, then the average per group was used in this table.

	P [mm]	E [mm]	D [mm]	Balance [mm]
Fe	998	701	240	57
Gr-cc	1006	716	295	-6
Gr-control	1518	579	712	228

3.7.2 Water Balance and Soil Moisture

Figure 21 illustrates the mean monthly soil moisture in relation to the monthly water balance, including the values for Spearman's ρ and the corresponding p-values. In the transferred soil monoliths, an intermediate negative correlation is indicated between soil moisture and water balance, yet this relation is not statistically significant. A weak positive connection was also indicated for the lysimeters in Fendt, yet not statistically significant, either. The lysimeters in Graswang do not indicate any relation between these two factors.

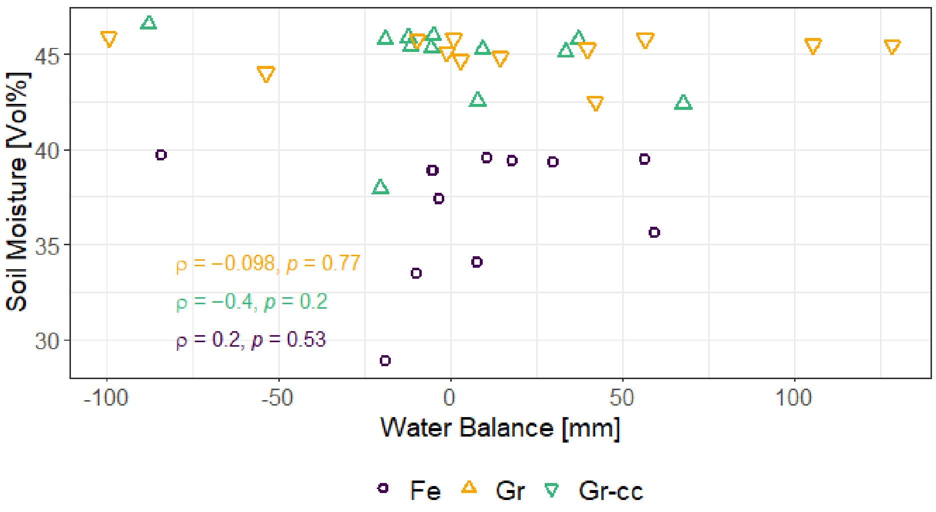

Figure 21. Relation between Soil Moisture and Water Balance (ρ: Spearman rank correlation coefficient).

3.7.3 Water Balance and Isotopic Composition of Precipitation

Figure 22 illustrates the relation of the soil moisture in different soil depths and the isotopic composition of precipitation water (left) as well as the relationship between the monthly water balance and the isotopic composition of precipitation water (right). The corresponding correlation coefficients and p-values describing the relations can also be seen in the graph. Regarding the relation with soil moisture it is evident that the strongest correlation exists between the $\delta^{18}O$ values of rainfall and the moisture volume in the top soil layer. This negative correlation exists regardless of the status group. However, in the lysimeters transferred from Graswang to Fendt, this connection is strongest (ρ = -0.9). The lysimeters in Graswang are the only ones where said connection is still measurable at 30 cm of soil depth, in the other status groups, the correlation is limited to the top soil layer. As for the relationship of the isotopic composition of precipitation and the monthly water balance, no significant correlation could be detected in either of the status groups. The only group indicating a slight (non-significant) relation between those factors is Gr-control, where an increase in water balance tends to go along with lighter rainwater (i.e. more depleted in heavy isotopes).

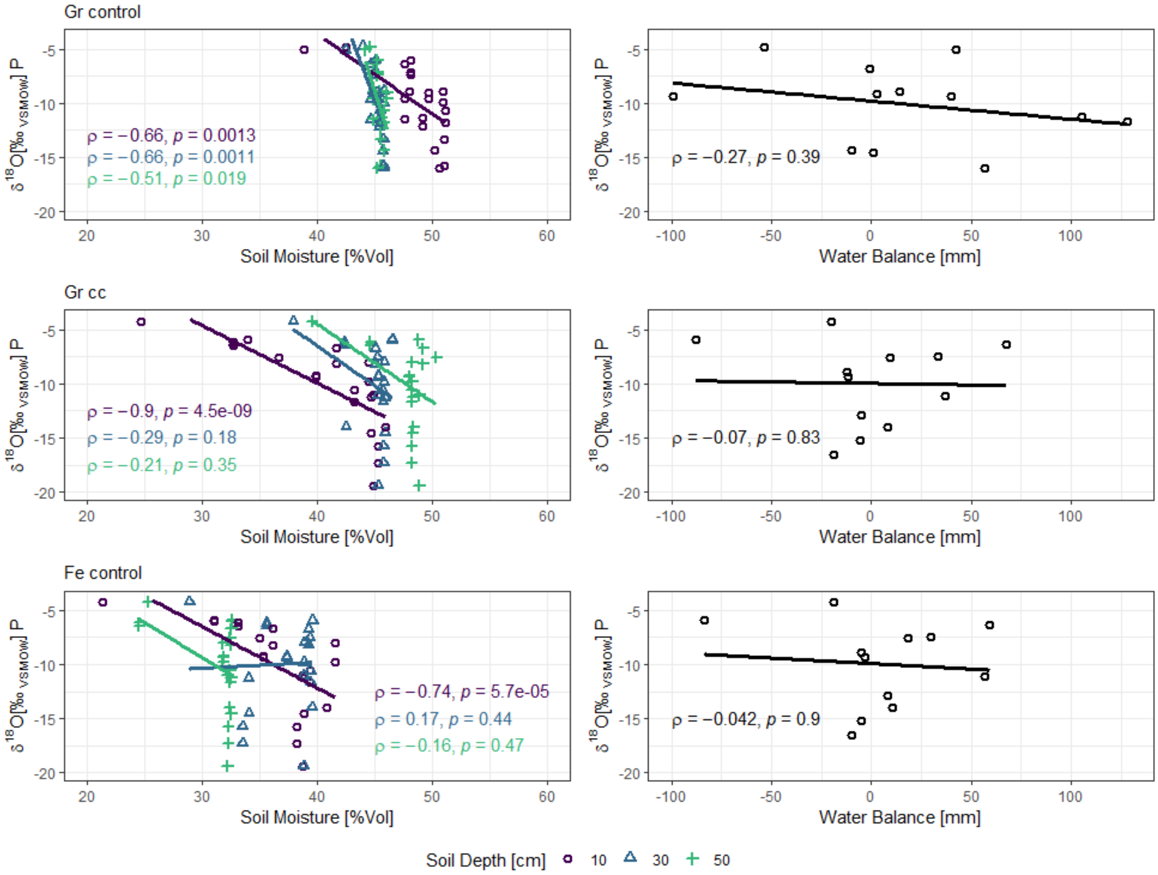

Figure 22. Left: $\delta^{18}O$ in precipitation water in relation to soil moisture at different depths; Right: $\delta^{18}O$ in precipitation water in relation to the monthly water balance (ρ: Spearman rank correlation coefficient).

4 Discussion

4.1 Influences of Climate Change on the Isotopic Composition of Soil Water

Significant differences exist between the lysimeters in Graswang and those transferred from Graswang to Fendt. The soil water in the transferred lysimeters is more enriched in heavy stable water isotopes than that in the control lysimeters in Graswang, indicating that climate change will lead to heavier soil water in pre-alpine grassland soils. Since the translocation of the lysimeters led to the soil being exposed to warmer and drier climate, these findings meet the expectations, and Hypothesis I is accepted: *Climate change affects the isotopic composition of the soil water in the lysimeters transferred from Graswang to Fendt*. One reason for the enrichment of the soil water is the increase in evaporation along with kinetic fractionation processes, caused by the rise in temperatures. As explained in the introduction, fractionation occurs mostly when water transitions from one phase to another, like from liquid to vapour when water evaporates (e.g. Gat 1996; Sharp 2017). The second reason is the isotopic signature of the new input, i.e. the precipitation at the new site. As pointed out by McDonnell (2014), the isotopic signal of the precipitation determines that of the mobile soil water. The isotopic composition of meteoric waters, in turn, is highly dependent on temperature, as explained in the introduction (Leibundgut et al. 2009). Therefore, the isotopic composition of precipitation in the pre-alpine region will change in the course of climate change, and with that, so will the isotopic composition of the soil water. Thirdly, the climate change induced alteration of the snow cover needs to be mentioned as a reason of the change in isotopic signature of the soil water. In Fendt, the period of snowfall is not as long, and the snow cover does not get as thick as it does in Graswang. Therefore, the soil is not as well insulated in Fendt as it is in Graswang, which leads to increased soil freezing in the transferred lysimeters (Hardy et al. 2001). The change in snow dynamics has a knock-on effect on infiltration and runoff generation during snow melt: the melting snow cannot infiltrate through a thick frozen layer and, thus, runs off superficially (Iwata et al. 2010). This explains why Gr-control has the heaviest soil water in February and March, while it usually has the lightest soil water during the rest of the year. In winter, Gr-cc has the heaviest water instead, due to the new climate conditions and particularly the missing snow cover in Fendt.

4.2 Differences within the Soil Profile

The results clearly show a dampening of the isotope signal of precipitation with increasing soil depth (Figure 19, Figure 20). This means that the seasonal differences are clearly visible in the upper soil layers and become less pronounced with increasing depth. At 140 cm, the isotopic composition of the soil water is rather homogeneous throughout the year. The reason, why the isotopic signal of the rainfall gets damped while passing through the soil profile, is mainly the occurrence of dispersion processes, combined with ecohydrological processes like plant water uptake or litter interception (Sprenger et al. 2016). However, since the studied lysimeters are covered in grassland, it is expected that the dampening is almost exclusively caused by dispersion in the soil. Dispersion is mostly determined by soil texture (Sprenger et al. 2016). Consequently, it is not surprising that the attenuation of the isotopic signal throughout the soil profile is not altered by the translocation of the lysimeters (no difference between Gr and Gr-cc).

Previous studies found that differences between soil water were most pronounced in the upper soil layers and disappeared with increasing soil depth. In a review of various studies on this topic, Sprenger et al. (2016) analysed lc-excess values from several sites and found that in temperate regions, effects of evaporation are detectable at most up to a soil depth of 20 to 30 cm. In a study by Sprenger et al. (2017a), evaporation effects disappeared already within the upper 15 cm of the soil profile. Therefore, mostly positive lc-excess values were observed in deep soil layers because they are not affected by evaporation influences (Sprenger et al. 2016). Contrary to that, both Fe and Gr-cc show negative lc-excess values at 140 cm depth which indicates that evaporation influences the soil water to greater depths than expected. However, Sprenger et al. (2016) compared studies that had samples of mobile and less mobile soil water because sampling was carried out using cryogenic extraction, for example. For this thesis, on the other hand, suction lysimeters were used to sample the soil water, thereby analysing the mobile soil water only. Thus, the discrepancy in findings might indicate that kinetic fractionation has a farther-reaching effect on mobile soil water than on tightly bound soil water. Nevertheless, when comparing findings from different studies it should be kept in mind that the sampling method influences the results of the isotopic analysis significantly, even if they sample water from the same reservoir (Orlowski et al. 2016, 2019). There have also been studies that used cryogenic extraction methods and still reached the conclusion that evaporation affects soils in deeper layers, as well. Mostly, these studies were carried out in arid or semi-arid regions, though, thus they are not easily transferrable to the data presented in this study (Yong et al. 2020). Since the complete soil profile is influenced by evaporation, no statement regarding the intensity of said influence can be made. Generally, kinetic fractionation only has minor influences on the isotopic composition of soil water (Sutanto et al. 2012; Sprenger et al. 2016).

In both control groups (Fe and Gr-control), the evaporative effect vanishes slightly with increasing depth, indicated by a weak correlation of depth and lc-excess. However, the transferred lysimeters did not show such a correlation. Therefore, the evaporative influences do not decrease with increasing depth. This indicates that climate change will in fact alter the evaporation dynamics and with that the isotopic composition of soil water. Furthermore, significant differences between the transferred lysimeters and the reference lysimeters in Graswang in their stable water isotope values show that climate change will not only affect the topsoil, but the entire soil profile. This disproves Hypothesis II, *the isotopic composition of the upper soil layers will be most affected by climate change effects*.

4.3 Soil Moisture Dynamics in a Changed Climate

The comparison of the volumetric soil moisture content of the lysimeters shows that the lysimeters remaining in their original locations differ significantly from each other. In Fe-control, all soil layers dry out much more than those in Gr-control, particularly evident at a depth of 50 cm. This is consistent with expectations because of the higher temperatures and resulting higher evaporation rates in Fendt. The comparison of Gr-cc with the control groups indicates that the soil moisture in deeper layers will not be strongly affected by climate change because the soil moisture in the translocated lysimeters shows a higher agreement with those remaining in Graswang, especially from 30 cm downwards. In summer, the transferred soils generally dry out significantly more than the non-transferred ones in Graswang, but they do not become as dry as those in the reference lysimeters in Fendt. Thus, climate change will affect pre-alpine grassland soils mostly in summer. It will not – at least not quickly – lead to a decline in soil moisture over the entire soil profile during the entire year. A continuous decline of the volumetric soil water content over the entire year is only expected in the upper 10 cm. The reason for that are higher temperatures and evaporation rates in summer on the one hand, and the lack of an insulating snow cover in winter on the other (Groffman et al. 2001; Hardy et al. 2001; Iwata et al. 2010; Schuerings et al. 2014). The latter will not affect soil moisture in winter, though, but primarily in spring during snow melt. Due to increased soil freezing, the snow melt cannot infiltrate and thus soils will be drier in spring than they are today (Iwata et al. 2010).

In summer, the differences between the translocated lysimeters and the control group in Graswang are most pronounced. This is consistent with observations from previous studies. For instance, Tromp-van Meerveld and McDonnell (2006) analysed the soil moisture at a hillslope scale and they, too, found significantly more spatial variation during the summer months than during the winter months. Furthermore, Zhou et al. (2008) confirmed the crucial impact of seasons on soil hydraulic properties like soil water content.

While Huang et al. (2016) reached the conclusion that soils tend to become wetter downwards, our results indicate otherwise. A significant trend for soils to become drier with increasing depth was detected in the non-relocated lysimeters (Fe-control and Gr-control). This result is in line with the results obtained by Tromp-van Meerveld and McDonnell (2006).

However, the transferred lysimeters (Gr-cc), in agreement with Huang et al. (2016), become wetter with increasing depth (Figure A 11). The reason for this discrepancy might be that the climate has an immediate effect on the upper soil only. The lower soil layers appear to be still conditioned by the climate to which the soil was exposed during its formation. This hypothesis is supported by the fact that a connection between precipitation events and soil moisture is recognisable only in the top soil layer (10 cm); already at 30 cm below the ground, precipitation events no longer have an immediate effect on soil moisture (Figure 14). This is in line with results obtained by Tromp-van Meerveld and McDonnell (2006). Their results showed that in summer, rain events only rewetted the top soil layer and did not reach the deeper soil, thus leading to discrepancies in soil moisture within the soil profile. In conclusion, hypothesis III can partially be accepted: *Soil moisture dynamics will be affected by the lysimeter translocation and change in climatic conditions.* However, the results of the present study indicate no correlation between volumetric soil moisture and isotopic composition thereof, thus no knock-on effect on the isotopic composition could be detected.

4.4 Relationship between Soil Water and Precipitation

There is a highly significant, yet weak correlation between the amount of precipitation and the $\delta^{18}O$ signature of the soil water in the transferred lysimeters ($\rho = 0.25$, $p = 2.3 * 10^{-10}$) and in the reference ones in Fendt ($\rho = 0.27$, $p = 2.6 * 10^{-11}$). That means that the occurrence of intense precipitation events tends to go along with more enriched soil water. The reason for this is that heavy rainfall mostly happens in summer when evaporation rates are high. As a result, the soils are dried out, and consequently soil water is isotopically enriched. In Graswang, on the other hand, no such correlation could be detected ($\rho = 0.06$; $p = 0.23$). This corresponds with expectations because the evaporation rates are not as high as in Fendt, and the precipitation variability is smaller than in Fendt.

The volumetric soil moisture in the top soil layer (10 cm) correlates negatively with the isotopic composition of precipitation (Figure 22). This means that rainfall is more enriched in heavy isotopes during and at the end of the period of low soil moisture. This accounts for Fe, Gr-cc, and Gr-control. As described above, the soils in Graswang and Fendt are driest in July and August, i.e. rainfall is most enriched in heavy isotopes in (late) summer. This corresponds to the typical seasonal course of the isotopic signature of meteoric waters (Gat 1996). As discovered by Sprenger et al. (2019), a precipitation event during dry conditions leads to the replacement of almost the entire mobile soil water by event water, whereas in a wet soil, a significantly smaller part of the mobile soil water gets replaced by event water. Consequently, when the isotopically enriched precipitation water infiltrates the dry soils at the end of the summer, the mobile soil water consists almost exclusively of that precipitation water. That is why the soil water is enriched in heavy isotopes after the summer and why the isotopic signal of the precipitation is only marginally attenuated at this time of the year. It is striking that Sprenger et al. (2019) observed the strongest correlation between the isotopic composition in precipitation and volumetric soil water content in a depth of 30-60 cm, while in Fendt (Fe and Gr-cc), the relation is limited to the top soil layer and in Graswang, it is almost equally strong in 10 and 30 cm of depth. At a depth of 50 cm, however, neither Graswang nor Fendt indicate any relation between soil moisture and isotopic composition of rainfall. This difference might be caused by the different measuring techniques: Sprenger et al. (2019) used cryogenic vacuum extraction, and, therefore, they analysed mobile and tightly bound soil water, whereas this study is focused on mobile water only due to the sampling with suction lysimeters. In contrast to the study by Sprenger et al. (2019), the present study did not detect any significant correlation between the monthly water balance and the isotopic composition of precipitation. The reason why no such correlation could be detected could be that the water balance was calculated based on data from only one year, while usually, water balances are calculated with long-term data. Repeating this analysis with a larger data set is therefore recommended. This also accounts for the examination of the relation of volumetric soil moisture and water balance.

5 Conclusion

Lysimeters of pre-alpine soils covered with grassland were relocated to a less elevated location. Therefore, the transferred soils were exposed to increased temperatures and reduced precipitation, which corresponded to the predicted consequences of climate change in this region. By comparing the soil water in the translocated lysimeters to the reference lysimeters in both locations, the effect of climate change on soil water in pre-alpine grassland soils was investigated. Climate change will – according to the results of this study – lead to soil water more enriched in heavy isotopes in the future. The increase of evaporation rates in summer, the lack of a snow cover in winter, and an overall more isotopically enriched input are the primary reasons for the alteration of the isotopic composition of the soil water. The findings further suggest a clear impact of climate change not only on the top soil layer, but on the entire soil profile. Previous studies either found evaporation to only affect the top soil layer (Sprenger et al. 2016) or were carried out in arid or semi-arid climates (Yong et al. 2020) – in both cases, bulk water samples were analysed rather than just the mobile fraction of the soil water, as in this study. The results of these previous studies are therefore only partially transferrable to the results obtained in this thesis and further research is required to confirm them. In terms of soil moisture dynamics, however, climate change will mainly affect the top soil layer: under future climate conditions, the upper soil layer will be drier throughout the year than it is currently, while deeper soil layers only dry out more in summer. The translocated lysimeters have only been exposed to the changed climate for 9 years. Therefore no conclusions about the long-term effects on soil moisture can be made so far and further investigation is required in this aspect. Lastly, the connection between isotopic composition of meteoric waters and the volumetric soil moisture was analysed in this thesis. It became clear that heavy rainfall coincides with low soil moisture, leading to a concurence of heavy rainfalls and a higher fraction of event water infiltrating the soil and becoming mobile soil water. This connection does not appear to be altered by climate change. In 2019, a major difference in the soil water balance caused by the altered climate was observed, highlighting once again the heavy impact climate change will have on pre-alpine grassland soils. To better understand the processes and to ensure reliability of these results, further research with larger data sets is required. One possibility is to broaden our analysis from a single year of data to the five or ten years. Still, this study presents an important summary of the impacts of a changed climate on the isotopic composition of pre-alpine grassland soils.

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Appendix

Table A 1. Soil characteristics at Graswang and Fendt.

Depth	Clay	Silt	Sand	Organic C	Total N	pH	Bulk density
[cm]	[%]	[%]	[%]	[%]	[%]	[-]	[g/cm^3]
DE-Gwg: Fluvic Calceric Cambisol							
0-10	51.7	39.3	9.0	6.4	0.7	6.4	0.8
10-30	51.0	39.3	9.3	1.9	0.2	6.8	1.2
30-50	50.7	42.4	6.1	1.0	0.1	6.9	1.3
50-140	43.3	37.4	19.3	0.7	0.1	7.2	1.2
DE-Fe: Fluvic Calceric Cambisol							
0-10	30.1	42.9	27.0	3.9	0.4	5.7	1.1
10-30	31.0	42.0	27.0	1.6	0.2	5.9	1.4
30-50	37.5	36.2	26.3	0.9	0.1	6.0	1.4
50-140	35.5	38.1	26.4	0.4	0.0	6.4	1.4

Source: Kiese et al. 2018.

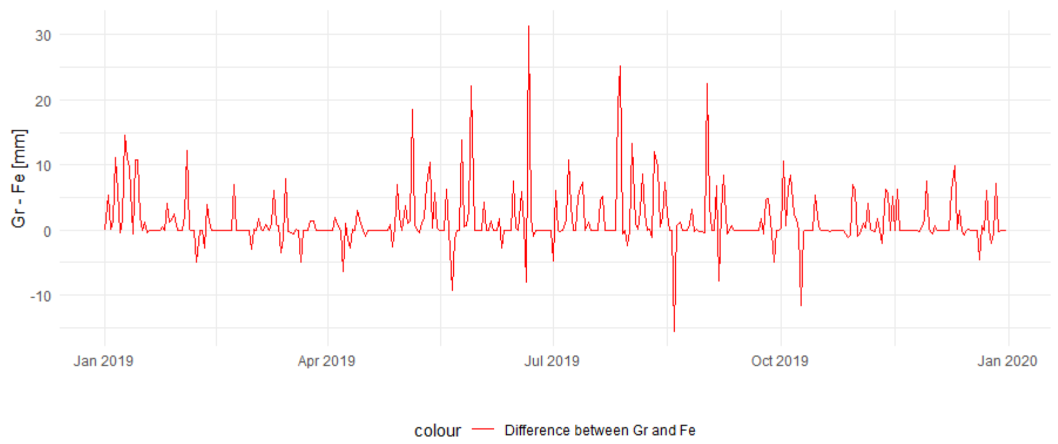

Figure A 1. Difference in precipitation at Fendt and Graswang. Values > 0 show a surplus of precipitation in Graswang compared to Fendt, values < 0 mean that there was more precipitation at Fendt than at Graswang.

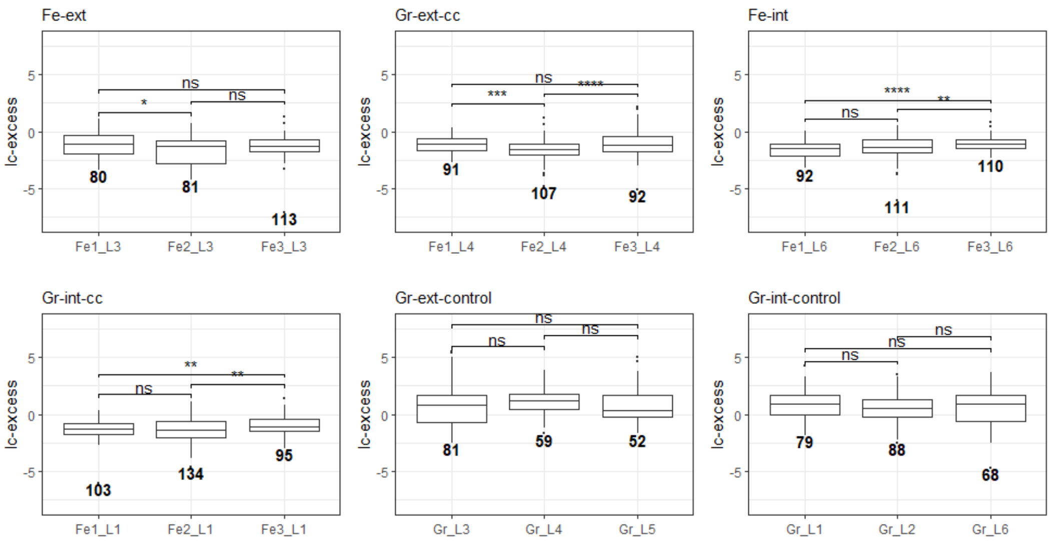

Figure A 2. Differences in lc-excess [‰] within the status groups. ns: difference not significant; *: p ≤ 0.05; **: p ≤ 0.01; ***: p ≤ 0.001; ****: p ≤ 0.0001.

Table A 2 Overview of $\delta^{18}O$ and lc-excess statistical values per group. Blue marks the lowest, red marks the highest values in each column. Even though medians are displayed in boxplots, as well, they were included in this table because that way they can be examined more clearly.

	$\delta^{18}O$ [‰]			lc-excess [‰]		
	Mean	**Sd**	**Median**	**Mean**	**Sd**	**Median**
Fe-ext	-9.7	2.46	-10.03	-1.4	1.14	-1.25
Gr-ext-cc	-10. 73	2.27	-10.2	-1.23	1.03	-1.29
Gr-ext-control	-10.74	2.26	-10.96	0.93	1.59	0.82
Fe-int	-9.84	2.36	-9.79	-1.28	1.85	-1.24
Gr-int-cc	-10.17	2.22	-10.06	-1.25	1.03	-1.23
Gr-int-control	-10.47	1.82	-10.89	0.66	1.36	0.74

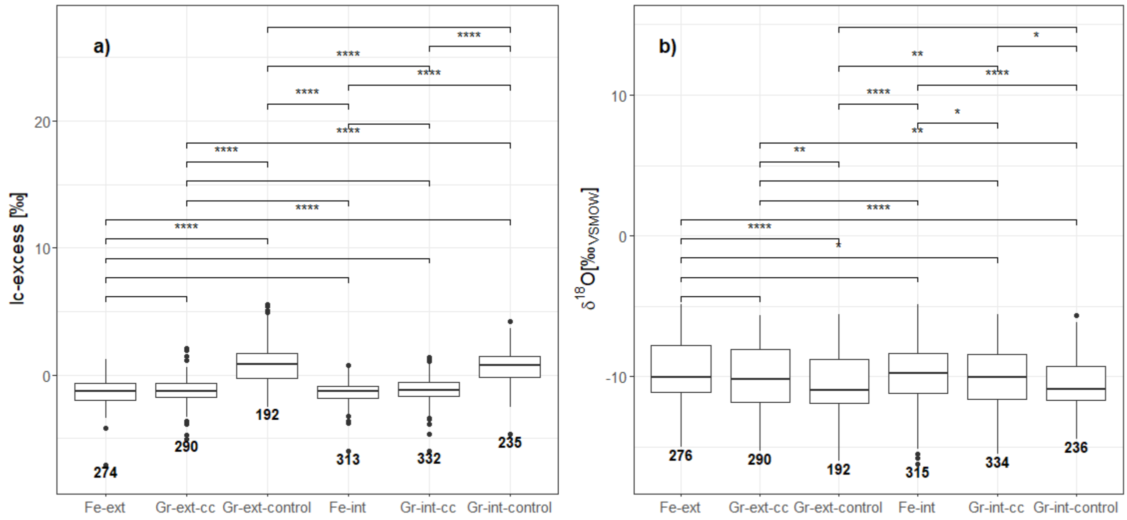

Figure A 3. a) lc-excess by status; b) $\delta^{18}O$ by status. Includes all values (from all soil depths). The numbers indicate the number of observations. The bars on top show whether differences are statistically significant: *: p ≤ 0.05; **: p ≤ 0.01; ***: p ≤ 0.001; ****: p ≤ 0.0001.

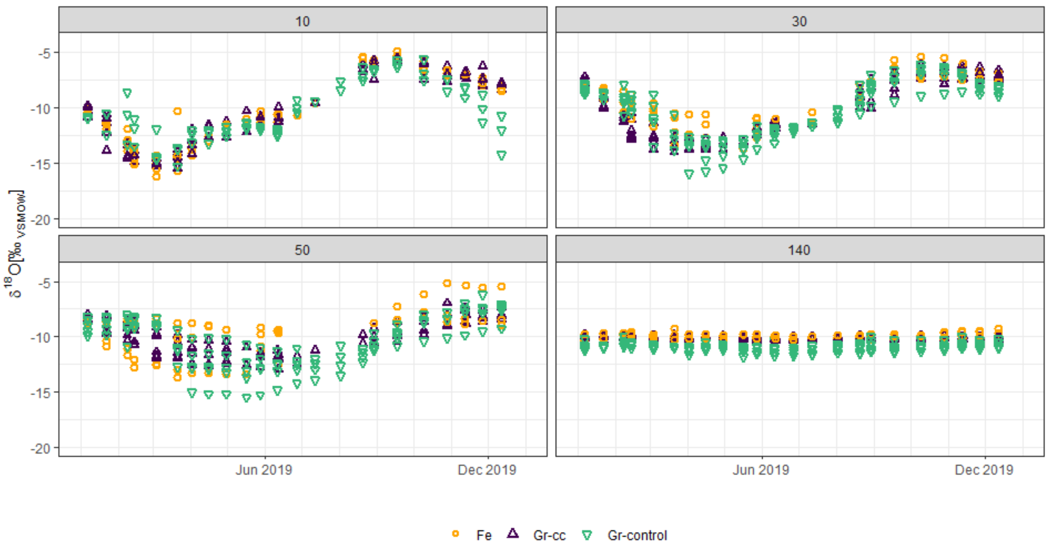

Figure A 4. Course of $\delta^{18}O$ in SW by status group and by measuring depth.

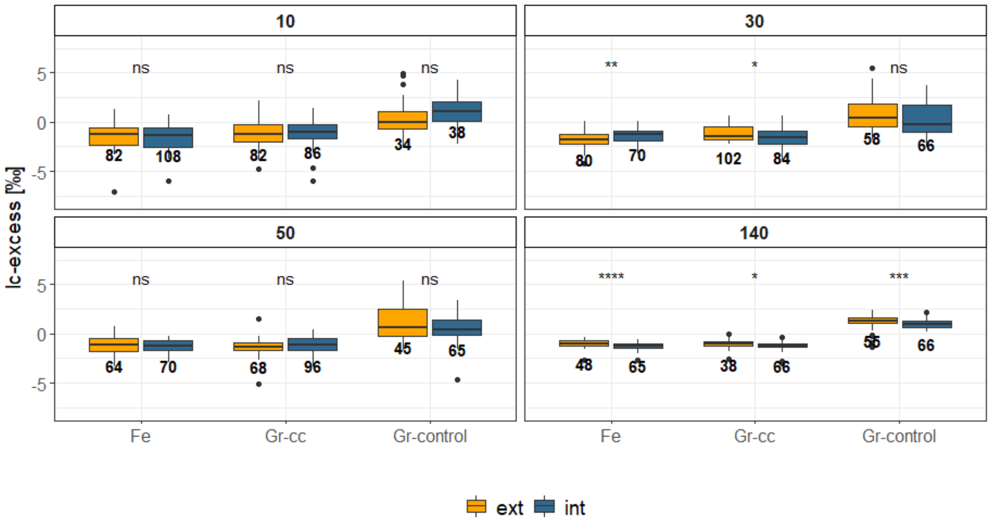

Figure A 5. Difference in lc-excess [‰] of soil water in differently managed lysimeters. ns: difference not significant; *: $p \leq 0.05$; **: $p \leq 0.01$; ***: $p \leq 0.001$; ****: $p \leq 0.0001$.

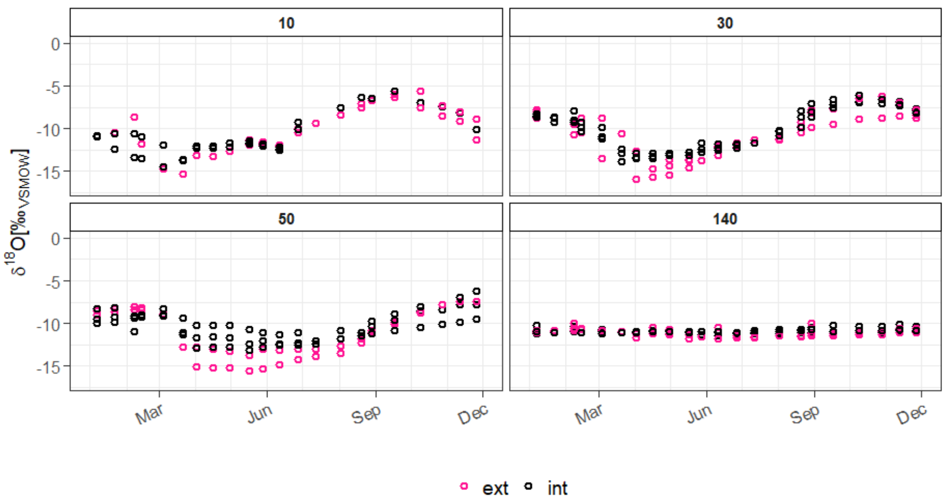

Figure A 6. Gr-control $\delta^{18}O$ signature of soil water, intensive vs. extensive management, by soil depth.

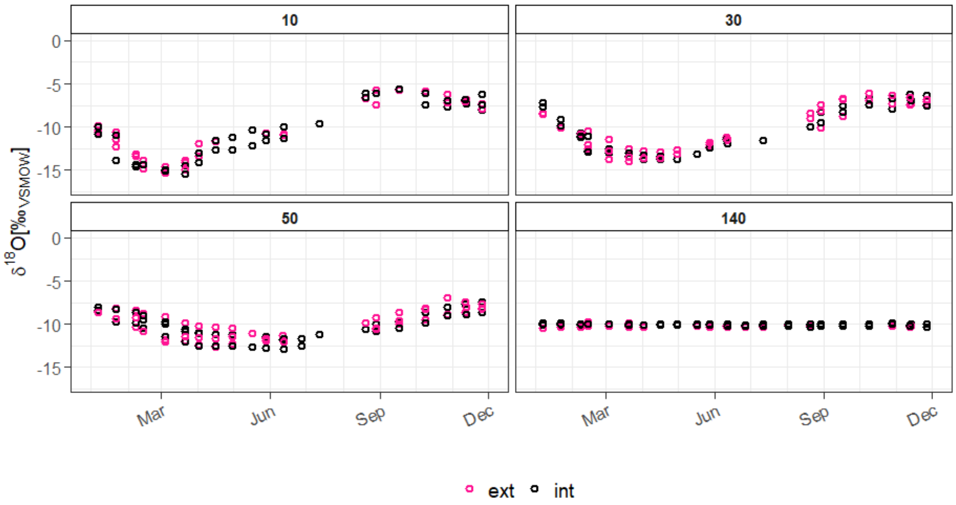

Figure A 7. Gr-cc δ18O signatures of soil water, intensive vs. extensive management, by soil depth.

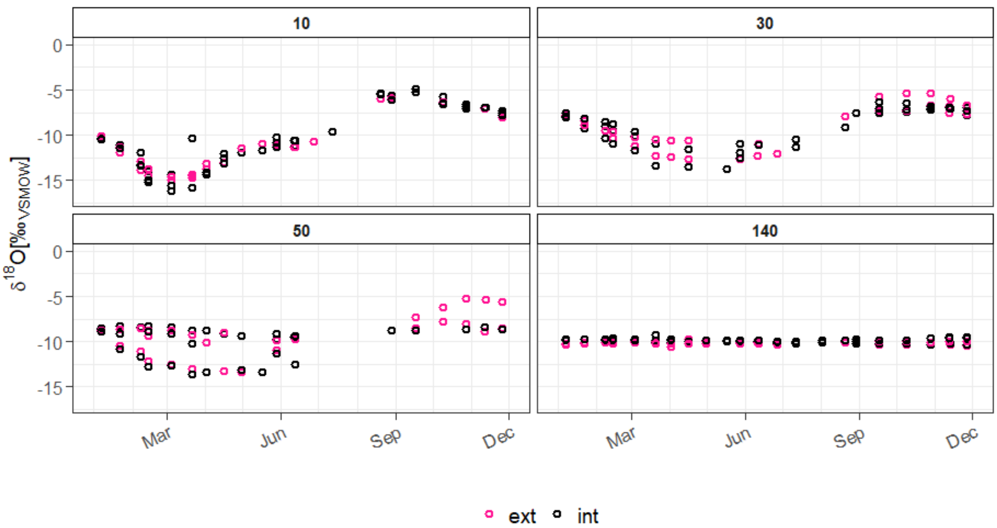

Figure A 8. Fendt δ18O values of soil water, intensive vs. extensive management, by soil depth.

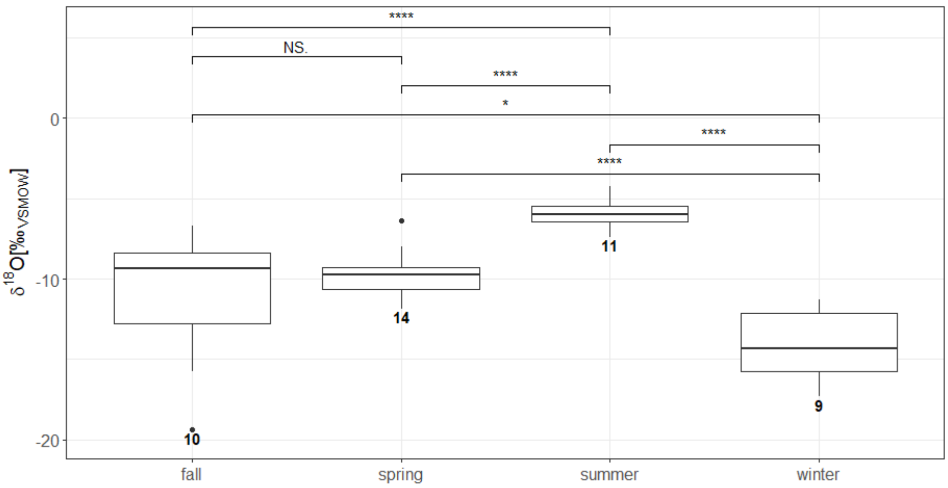

Figure A 9. δ^{18}O values of precipitation by season (Graswang and Fendt). ns: difference not significant; *: p ≤ 0.05; **: p ≤ 0.01; ***: p ≤ 0.001; ****: p ≤ 0.0001. The numbers below the boxplots indicate the amount of observations in the corresponding boxplot.#

Table A 3. Overview of the δ^{18}O signatures observed in soil water at different soil depths.

Depth [cm]	**Mean**	**Sd**	**Min**	**Max**	**Range**
10	-10.39	3.08	-16.22	-4.86	11.36
30	-9.76	2.48	-15.98	-5.36	10.62
50	-10.02	1.95	-15.5	-5.18	10.32
140	-10.37	0.52	-11.84	-9.23	2.61

Table A 4. Mean, minimum, maximum, and standard deviation σ of δ^{2}H values of precipitation (P) and soil water (SW) in Fendt in 2019 [in ‰].

		Mean	σ	Min	Max
Total	**P**	-70.96	31.81	-143.2	-28.5
	SW	-72.27	18.38	-122.8	-31.4
Spring	**P**	-69.1	9.76	-87.1	-57.8
	SW	-86.87	13.78	-122.8	-60.4
Summer	**P**	-38.75	5.5	-43.8	-28.5
	SW	-70.83	14.25	-95.00	-36.2
Fall	**P**	-74.14	40.5	-143.2	-44.6
	SW	-54.14	11.04	-76.5	-31.4
Winter	**P**	-109.04	18.89	-134.3	-82.5
	SW	-72.57	15.66	-113.1	-37.5

Table A 5. Mean, minimum, maximum, and standard deviation σ of δ^{2}H values of precipitation (P) and soil water (SW) in Graswang in 2019 [in ‰].

		Mean	σ	Min	Max
Total	**P**	-72.04	27.82	-136.2	-34.3
	SW	-76.28	15.96	-117.1	-37.6
Spring	**P**	-68.47	15	-86.6	-40.8
	SW	-88.25	11.89	-117.1	-58.8
Summer	**P**	-41.24	6.76	-50.3	-34.3
	SW	-79.35	12.83	-109.8	-43.00
Fall	**P**	-84.82	32.2	-136.2	-57.6
	SW	-61.76	13.56	-83.1	-37.6
Winter	**P**	-100.8	16.68	-122.2	-84.6
	SW	-70.00	11.21	-104.3	-47.5

Table A 6. Mean, standard deviation σ, minimum, and maximum of soil moisture data at different soil levels in the three status groups. All values in [%vol].

	Mean	σ	Min	Max
10 cm				
Fe	35.73	6.08	18.02	44.22
Gr-cc	39.89	6.87	21.15	48.82
Gr-contr	47.81	4.53	30.32	53.98
30 cm				
Fe	36.79	4.92	22.13	43.11
Gr-cc	44.53	3.34	30.89	50.84
Gr-contr	44.9	1.22	39.27	47.06
50 cm				
Fe	31.1	3.13	21.38	36.24
Gr-cc	47.68	3.19	38.12	53.12
Gr-contr	45.22	0.89	42.99	47.97

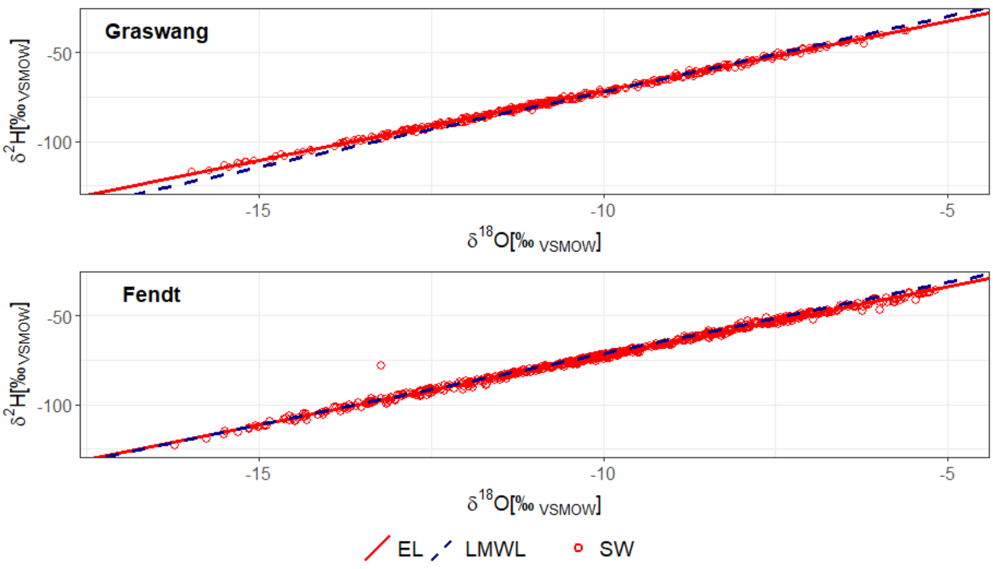

Figure A 10. Dual Isotope Plots showing the Evaporation Line (EL), the Local Meteoric Water Line (LMWL), and the isotopic composition of the soil water in Graswang (above) and in Fendt (below).

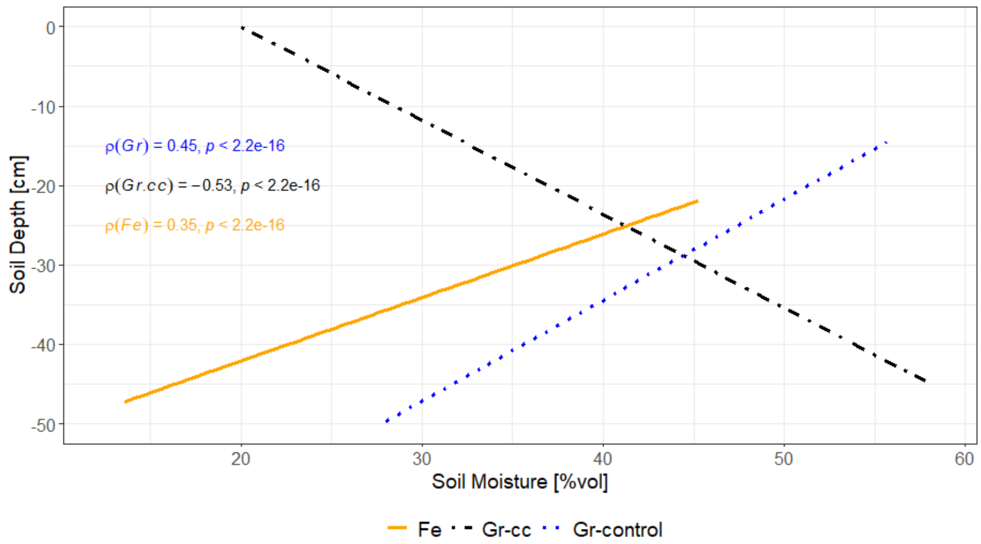

Figure A 11. Soil depth by soil moisture (ρ: Spearman rank correlation coefficient).

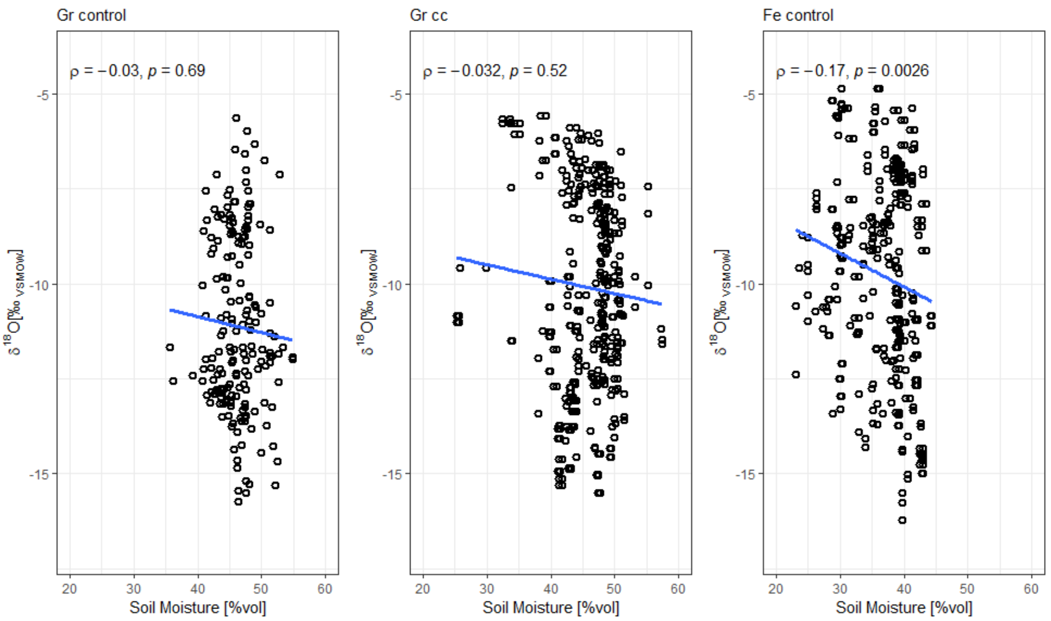

Figure A 12. $\delta^{18}O$ signatures in relation to soil moisture (ρ :Spearman rank correlation coefficient).

Ehrenwörtliche Erklärung

Hiermit erkläre ich, dass die Arbeit selbständig und nur unter Verwendung der angegebenen Hilfsmittel angefertigt wurde..

Tanja Vollmer

Freiburg, 30.04.2021