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Master Thesis

Effects of a soil drought stress experiment on the beech sap flow dynamics in the Rosalia Forest Demonstration Center

submitted by

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Affidavit

I hereby declare that I have authored this master thesis independently, and that I have not used any assistance other than that which is permitted. The work contained herein is my own except where explicitly stated otherwise. All ideas taken in wording or in basic content from unpublished sources or from published literature are duly identified and cited, and the precise references included.

I further declare that this master thesis has not been submitted, in whole or in part, in the same or a similar form, to any other educational institution as part of the requirements for an academic degree.

I hereby confirm that I am familiar with the standards of Scientific Integrity and with the guidelines of Good Scientific Practice, and that this work fully complies with these standards and guidelines.

Vienna, 24.01.2022 Miriam Dunzendorfer *(manu propria)*

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Abstract

In light of climate change an increase in frequency, duration and severity of drought is assumed for the 21st century. European beech (Fagus sylvatica L.) is, despite being rather vulnerable to droughts, insufficiently researched when it comes to drought stress related behaviour of adult trees. As throughfall-exclusion experiments for adult trees are very expensive. The aim of this master thesis is to investigate the setup of an existing forest soil drought-and-rewetting-experiment ("the experiment"), which is very similar to a throughfall-exclusion-experiment. Is the experiment able to induce drought stress in the trees and does it produce valuable information about trees under drought stress? The experiment was established 2013 on forest soil of an adult beech stand at the site Rosalia Forest Demonstration. Sap flow measurements were conducted in 2019 in trees within the influence of the experiment ("influenced trees") and trees outside the influence ("control trees"). A comparison analysis between the sap flows (Qt) of the two groups was done as well as a correlation analysis of Qt, soil moisture, and temperature. Nocturnal sap flows (Qn) were also compared after precipitation or irrigation events, and a correlation analysis between Qn and precipitation amount was done. Contrary to expectations, the Qt of the influenced trees was significantly higher than of the control trees and no correlation to the soil moisture content of the experiment was found. Neither were the Qn of the groups different nor was a correlation with precipitation amount found. These results indicate that the influenced trees did not suffer drought stress compared to the control trees. Instead, the experiment was likely to irrigate the influenced trees additionally. Valuable information about drought stress behaviour could potentially be obtained either after alterations in the experiment setup or when investigating a natural drought with the influenced trees being an irrigated control group.

Kurzfassung

Durch den Klimawandel werden schon in diesem Jahrhundert Hitzestress und Dürren in Länge, Häufigkeit und Stärke zunehmen. Die durch Dürren gefährdete europäische Buche (*Fagus sylvatica* L.) ist unzureichend erforscht, was Trockenheitsstressverhalten von adulten Buchen betrifft. Denn Trockenheitsstressversuche an erwachsenen Bäumen sind aufwändig und kostspielig. Daher untersucht diese Masterarbeit, ob ein bereits bestehendes Trockenheitsexperiment an Waldboden, das im Aufbau einem Trockenheitsstressversuch für adulte Bäume ähnelt, ebenfalls Wassermangel in den nahestehenden Bäumen auslöst und ob damit neue Erkenntnisse über adulte Buchen während Dürren generiert werden können. Am Standort Rosalia Lehrforst wurde ein Dürre- und Starregenereignisse-simulierender Versuch an Waldboden in einem adulten Buchenwald errichtet. Später wurden Saftstromsensoren in den Buchen installiert, manche innerhalb (beeinflusste Bäume) und manche außerhalb (Kontroll-Bäume) des Einflussbereiches des Versuches. Die Saftströme (Q_t) der beiden Gruppen wurden verglichen und auf mögliche Korrelationen mit dem Bodenwassergehalt und der Temperatur untersucht. Ebenso wurden die nächtlichen Saftstromwerte (Q_n) nach Niederschlägen oder Bewässerungen verglichen und auf Korrelationen mit den Wassermengen erforscht. Der Q_t der beeinflussten Bäume war signifikant höher als der Kontrollbäume, zudem konnte keine Korrelation mit dem Bodenwassergehaltes des Experimentes festgestellt werden. Keine Unterschiede gab es bei den Q_n, eben so wenig Korrelationen mit den Wassermengen. Diese Resultate zeigen, dass die beeinflussten Bäume keinen Wassermangel erlitten, sondern im Gegenteil durch den Versuch zusätzlich bewässert wurden. Durch Veränderungen im Versuchsaufbau oder das Beobachten der Bäume während einer natürlichen Dürre, mit den beeinflussten Bäume als bewässerter Kontrollgruppe, könnten möglicherweise dennoch neue Erkenntnisse über das Trockenheitsstressverhalten von adulten Buchen gewonnen werden.

1. Introduction

1.1. Climate change – Droughts and heavy rain events

Global warming as a result of anthropogenic greenhouse gas emissions (IPCC, 2013) was revealed throughout climate observations. Global average temperature has increased by 0.8 °C from the past century (Hansen et al., 2006). Global warming originates from a disturbance of the natural greenhouse effect and an increased radiative forcing. This radiative force increased mainly because of additional amounts of carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and other greenhouse gases, caused by anthropogenic activities (IPCC, 2013). This could increase the global mean temperature about 1- 4°C by end of the 21st century (IPCC, 2013). Local differences in warming can be observed (IPCC, 2013): The northern hemisphere, for example, has already experienced an increase in temperature of 1.5 °C since 1970, whereas temperature in Austria increased by 2°C in the same period (Blöschl et al., 2018). Since the start of Austrian measuring, the years 2014, 2018 and 2019 have been the hottest (Chimani et al., 2020). This altered global temperature has tremendous effects on our climate. The global water system is also part of the climate system. Severe modifications in the global water cycle are a consequence of the altered global temperature. Several alterations are expected in weather patterns globally. In general, an augmentation in the contrast between wet and dry regions and seasons is predicted. This can lead to more extreme weather events like droughts, heat waves or heavy rainfalls (IPCC, 2013). The occurrence of droughts is influenced by three factors, namely warm temperatures, lack of precipitation and enhanced evapotranspiration (Spinoni et al., 2015). Water limitations are expected to be a serious threat in Europe where an increase in frequency, severity and duration of droughts is expected (Grillakis, 2019; Lindner et al., 2010). In the Alpine region, precipitation and evaporation have already been altered (Blöschl et al., 2018). The annual evaporation increased approximately 80mm a^{-1} as well as the annual rainfall. The seasonal distribution of precipitation did change as well, leading to a decrease in winter (-7%) and an increase in summer precipitation (+14%) in Austria (Blöschl et al., 2018). Gobiet et al. (2014), too, expect an increase of temperature and precipitation extremes with more frequent droughts in Austria by the end of the century. These shifts and changes have impacts on ecosystems. At present, droughts are a serious threat for the Austrian agriculture (Leitner et al., 2020).

Forest ecosystems are especially susceptible to climate change, as long living and immobile organisms such as trees are limited in their adaptive capacities (Lindner et al., 2010). An altered climate will change soil water availability as well as evaporative water usage (Way et al., 2013) and require trees to adapt to these new conditions. Droughts as consequences of warmer and drier climate will further increase tree mortality globally, even in areas so far not prone to water limitation such as Austrian forests (Allen et al., 2010; Seidl et al., 2017).

1.2. Beech behaviour during drought stress

Before replaced with the faster-growing Scots pine and spruce by humans it was *Fagus sylvatica* L. (beech) that dominated the Central European forests (Förster et al., 2021). Beech still shapes the appearance of the European forests with its wide spread distribution and importance for the timber industry (Chakraborty et al., 2017). Its economic importance is even rising as beech is seen as a drought and climate change resistant alternative compared to the vulnerable spruce monocultures (Konôpka et al., 2013). However, beech is prone to be sensitive to drought according to many studies (Leuschner, 2020; Rubio-Cuadrado et al., 2018; Walthert et al., 2021). An individual beech tree uses about 30l of water a day for transpiration (Wimmer, 2006), depending on respective transpiration rates. Not exclusively for this tree species, beech can store large amounts of water in there tissue (Leuschner, 2020). Under normal conditions, this water storage is used and refilled daily (Wimmer, 2006). During a drought, this inner reservoirs help trees to overcome water shortage (Leuschner, 2020) and can make up to 67% of the water used for transpiration (Betsch et al., 2011). When access to water is limited, this refilling becomes hard to maintain and trunk shortage can be measured (Wimmer, 2006). Water limitations can lead to several behavioural responses (Leuschner, 2020) such as decreased sap flow density (Aranda et al., 2005), reduced transpiration (Nalevanková et al., 2018) and limited photosynthesis (Arend et al., 2016). If drought conditions persist in time, the responses may become more and more severe, including early defoliation, severe crown transparency, severe leaf browning (Michelot et al., 2012), reduced growth (Rohner et al., 2021) and finally, crown dying due to embolism (Walthert et al., 2021). Due to their debilitated conditions, drought-suffering trees are also more vulnerable to attacks by pathogens or insects (Ryan, 2011). Soil water availability is therefore a crucial factor for beeches' health and can in combination with other environmental factors, abiotic or biotic, lead to the death of the trees (Chakraborty et al., 2017). One single drought event may lead to death of trees due to xylem dysfunctions, while chronic drought kills trees through starvation due to limited photosynthetic activity (Eilmann and Rigling, 2012). European beech dying events as a response to drought are reported by Allen et al. (2010).

There are many environmental aspects influencing the vulnerability of beech and its response to drought, such as forest management (Mausolf et al., 2018) ,growth in mixed stands, soil water storage capacity (Chakraborty et al., 2017) or precipitation distribution and temperature of the current year (Michelot et al., 2012). European beech forests, for example, are more vulnerable to droughts occurring in June and July, and precipitation shortages stress them more than high temperatures (Gennaretti et al., 2020). However, our picture on the behaviour of beech trees to more frequent droughts is still incomplete, and more research is probably required. Several studies tried to examine the consequences of drought for the ecology or climate-change relevant carbon fluxes (Förster et al., 2021; Konôpka et al., 2013; Rohner et al., 2021) (Gennaretti et al., 2020; Rubio-Cuadrado et al., 2018); others focused on economy-related topics such as beech growth and market supply (Bosela et al., 2021; Rais et al., 2021). However, several aspects of the beech physiological response to drought and the resulting consequences are still rather poorly understood.

1.3. Sap flow reduction as indicator of drought

„Sap flow“ or „ascent of sap“ means the movement of fluids (sap) in the xylem and phloem tissue of plants (Sinha, 2004; Taiz et al., 2018). Phloem sap flow has no explicit direction, but it moves from source to sink, mostly from leaves to roots. Carbohydrates have the highest concentration amongst the solutes in the water of the phloem sap flow, but also amino acids, hormones and inorganic ions are present (Taiz et al., 2018). Xylem sap flow is often used synonymously with plant water transport; this is not entirely correct, as xylem sap contains not only water, but also dissolved minerals and organic substances like amino acids or sugars (Sinha, 2004). The xylem sap flow is usually, but not necessarily, upwards, as its direction is determined by the lowest water potential within the plant. The xylem sap will therefore move to locations in the plant where for example the solute concentration is increasing or where water is being removed trough transpiration (Sinha, 2004). Thus, xylem sap flow is a proxy for the transpiration and an indicator for the plant water status (Giménez et al., 2013; Sitková et al., 2014). Xylem sap flow (henceforth termed sap flow) is significantly and positively influenced by solar radiation, temperature, wind speed and water vapour pressure deficit (VPD) (Li et al., 2019). Sap flow of deciduous trees in temperate regions is also dependent on the season and follows a certain seasonal pattern during the vegetation period when not limited due to drought. With the foliation in spring the sap flow rises, having the highest sap flow values in late spring and early summer, while in autumn the sap flow is continuously reduced until the fall of leaves as can be seen by Sitková et al. (2014). Sap flow is also dependent on water availability.

Sap flow reduction is one of the first signs of water scarcity in trees. Sap flow reduction as a response to drought stress in beech is rather well studied (Aranda et al., 2005; Kovalčíková et al., 2012). Leuzinger et al. (2005) found a relative decline of 40 % of the sap flow rate with ongoing drought in their studies while Dietrich and Kahmen (2019) found a sap flow reduction of 80% during a severe drought. Beech sap flow rate is also very sensitive to drought intermediate rain events. Sap flow rate recovered up to 50% when measured on the seasonal maximum after rain events. Precipitation events with < 2mm are enough to lead to a sap flow recovery of 10% (Dietrich and Kahmen, 2019). With these qualities sap flow reduction is a good indicator to identify whether trees suffer water limitations.

1.4. Nocturnal sap flow

Nocturnal sap flow must not be neglected in sap flow investigations. Until recent years nocturnal sap flow was thought to be non-existing or negligible (Forster, 2014; Wu et al., 2020) due to the high association between to transpiration and sap flow (Giménez et al., 2013). Day-time patterns of sap flow were the main interest of sap flow measuring studies, as nocturnal sap flow was not understood very well. Nocturnal sap flow was assumed to be zero and very frequently corrected in sap flow studies (Forster, 2014). However, in most wind-spread species nocturnal sap flow is present and makes on average 10% of the total sap flow (Forster, 2014). The importance of nocturnal sap flow becomes even clearer when considering plants that originate or grow in dry areas have higher water loss during the night than ones in other regions (Chen et al., 2020). Main driver of nocturnal flow is stem refilling, notably in drought facing trees (Forster, 2014). Similar results were found by Wu et al. (2020), where nocturnal transpiration fostered nocturnal sap flow but the main reason for its occurrence was stem refilling. This stem refilling is done to rehydrate the inner tissue and eliminate embolism and cavitation (Chen et al., 2020). Wu et al. (2020) found positive correlations between nocturnal sap flow and wind speed, VPD, and diurnal sap flow, while the last had the greatest impact. Furthermore, they found that nocturnal sap flow was influenced positively by precipitation and that soil moisture, stem storage water volume and water status of the previous day limit nocturnal sap (Wu et al., 2020).

1.5. Sap flow measurement - Heat-balance-method

As sap flow reduction is a clear sign of water shortage stress in trees (Aranda et al., 2005; Kovalčíková et al., 2012; Leuzinger et al., 2005), measurements of sap flow are commonly used as a proxy to estimate the drought exposure of trees (e.g Cranston et al., 2020). Heat using sap flow measurements on living plants are a common tool (Grime and Sinclair, 1999). They date back to 1932 (Steppe et al., 2010) and developed to commercially sold instruments in 1990 (Grime and Sinclair, 1999). Different specific techniques exist like heat pulse, heat dissipation, heat field deformation or heat balance. There are different forms of how the device is heated and how the temperature change in the sapwood is measured (Flo et al., 2019). The heat balance method, one of the main measuring sap flow methods, is based on the amount of energy which is needed to keep a certain temperature difference between two electrodes (Kučera, 2015). Stainless steel electrodes are hammered into the xylem (Kučera, 2015) where most sap flow in trees takes place (Granier et al., 2000). A current flowing between the electrodes induces heat in the xylem. The sap flow carries away the heat. The sap flow can be calculated from the energy demand of the heated electrodes. To avoid damage on the tree the high conductive phloem is protected trough insulation (Kučera, 2015).

1.6. Throughfall-exclusion experiments

There are three main ways to investigate the effects of drought stress in trees. First, the effects of water scarcity in trees can be measured during a naturally occurring drought as several studies like Walthert et al. (2021) did during the drought in 2018 or Jacobs et al. (2021) did during the drought in 2003, both occurring in Europe. Those measurements have the disadvantage of being dependent on weather conditions, not being able to control the level of drought, and not being able to be planned in advance or repeatable. Second, indoor experiments on trees in greenhouses with the major advantage that the duration and severity of the drought can be regulated (e.g. Creek et al., 2018). Those experiments are constrained to juvenile or potted trees due to space limitations. Samplings and young individuals differ in their drought response behaviour and the achieved results may not be true for mature trees under natural conditions (Choat et al., 2018). Third, throughfall-exclusion-experiments where roofs prevent the throughfall to reach the soil (eg. Rötzer et al., 2017; Tomasella et al., 2018). This kind of experiment combines the advantages of studying mature trees from the first and the exact and repeatable setup from the second method. Their main disadvantage is the high expenses for installation and maintenance (Cranston et al., 2020).

The principle of a throughfall-exclusion-experiment is well described by Cranston et al. (2020) and Tomasella et al. (2018): the studied plots are covered with a roof between crown and the soil surface and an optional trench with foil, impermeable for roots and water, is installed from surface to a reasonable depth in order to prevent runoff water entering the study plots. Throughfall-exclusion-experiments can theoretically be done with all kinds of trees independent of their age and size. Moreover also the size of such experiments can vary. For example could there be a total exclusion of the throughfall when the whole surface is covered with roofs, or the throughfall is as reduced for example by 30% when only percentages of the surface were covered. A collaboration of throughfall exclusion experiments is the international "Drought-Net Research Coordination Network", where the comparative studies also the standardisation of such experiments is encouraged (DroughtNet, n.d.). However, throughfall exclusion experiments are expensive to set up and maintain (Cranston et al., 2020) especially for mature and large trees (Breast Height Diameter >50cm) and are often performed on juvenile trees (e.g. Massonnet et al., 2021). Mature and large trees are therefore underrepresented in throughfall studies (Cranston et al., 2020) even though they are predicted to be more sensitive to drought than smaller trees (Bennett et al., 2015).

1.7. Rosalia and LTER

The Rosalia Forest Demonstration Centre was settled in 1972 as a cooperation between BOKU and Austrian Federal Forests (Österreichische Bundesforste). BOKU performs teaching and research activities, with various focuses. Since 2013, a long-term experiment simulating drought and extreme precipitation events (DRAIN) is operated at the Rosalia site by the Institute of Soil Research, investigating forest soil responses under extreme weather events (Filipović et al., 2018). The core objective is to better understand the effects of changing precipitation patterns on different soil properties and processes such as soil hydraulic properties (Schwen et al., 2015), nutrient fluxes (Leitner, 2017), microbial communities (Liu et al., 2019) or greenhouse gas fluxes (Díaz-Pinés et al., 2018; Leitner, 2017). For those purposes, a relatively large area in-between mature trees was covered with roofs and a sealing layer was installed (Schwen et al., 2015). In 2019 the DRAIN experiment setup was complemented with sap flow measurement gauges on the near growing beech trees. This arrangement is very similar to a tree throughfall-exclusion-experiment, albeit the beech trees are not growing in the plots but beneath. Investigating if this setup is capable to induce drought stress in trees would be of great scientific interest, especially when considering that the experiment is part of the LTER (Long term ecological research) network and a multitude of researchers could directly benefit from the information obtained. The LTER network is a collaboration of research sites with the united goal of investigating long term effects on ecosystems (Haase et al., 2016). Founded in 1980 in the US with six sites the prospering project expanded soon all over the world (Michener et al., 2011). Nowadays it covers more than 600 research sites from all different kinds of ecosystems in 39 countries (ILTER, 2021). The network works bottom-up (Haase et al., 2016), therefore a multitude of national LTER networks exist which are consorted first on regional level (US-, European- and East Asian and Pacific LTER) and then joint on international Level (ILTER) (ILTER, 2021). The Austrian Network consists of 38 research sites and platforms, one of the sites is the Rosalia Forest Demonstration Centre (LTER Austria, 2021).

2. Research aims and hypotheses

2.1. Research aims

The influence of droughts and water scarcity on beech is a topic of urgent concern in the frame of climate change. Our understanding of the responses of beech ecosystems upon changes in water availability is still incomplete. With resources usually being limited, and manipulation approaches being costly, it is of great interest to take advantage of the already existing experiment simulating drought and extreme precipitation events on forest soils in the Demonstration Forest Rosalia (DRAIN) and investigate whether the experiment induces drought stress in the surrounding beech trees. This is possible due to the high similarities between this experiment in Rosalia and a through-fall-exclusion experiment for trees, like large roofs between crown and surface and a detent, impermeable for roots and water (Cranston et al., 2020; Tomasella et al., 2018). Subsequently, it is of interest to investigate which further valuable information can be gained from this setting about mature beech behaviour under drought stress. Because mature trees are predicted to be more susceptible to drought than juvenile ones (Bennett et al., 2015); the research should specially focus on them. However, mature trees are generally underrepresented in through-fall-exclusion experiments because of the high set up costs (Cranston et al., 2020). The DRAIN set up is an ideal opportunity to constraining/filling the existing knowledge gaps without incurring into high expenses. In this context, my research aim is:

The investigation of the capability to introduce drought stress in trees of the DRAIN experiment and discover if valuable information on beech drought stress behaviour could be gained.

Drought stress behaviour of beech has many aspects, and degrees (Walthert et al., 2021). I used the beech sap flow behaviour as an indicator of the beech water status (Giménez et al., 2013; Sitková et al., 2014). Hence I deduced my specific research aims:

1. *Investigate the effect of the DRAIN infrastructure on the sap flow of beech trees.*
2. *Understand the relationship between sap flow and soil moisture.*
3. *Investigate the nocturnal sap flow behaviour after rain events and artificial irrigation events.*

2.2. Hypotheses

For the investigation of my specific research aims I formulated two hypotheses for each. I assumed the DRAIN experiment to be able to introduce drought stress also for the beech trees. Therefore I set my hypotheses according to the results I would expect, if the trees suffered water limitation.

2.2.1. Hypotheses regarding aim 1

Investigate the effect of the DRAIN infrastructure on the sap flow of beech trees.

2.2.1.1. Hypothesis 1

Trees near to the DRAIN experiment have significant lower sap flow rates compared to the trees in further distance.

I assume, that trees growing near to the DRAIN experiment (further termed influenced trees) are negatively influenced in their water consummation through the roof infrastructure and are throughout exposed to a degree of drought stress. Sap flow reduction is a good indicator for water limitations suffered by trees and such behaviour could therefore be expected, if the trees are exposed to drought stress (Dietrich and Kahmen, 2019; Kovalčíková et al., 2012; Leuzinger et al., 2005). This response is already well studied (Aranda et al., 2005; Kovalčíková et al., 2012) and clear declines during droughts have been documented (Dietrich and Kahmen, 2019; Leuzinger et al., 2005). The trees in further distance to the DRAIN experiment (further termed control trees) are assumed to be unaffected by the roof infrastructure. The sap flow of the control trees is not reduced, as the trees do not suffer water limitations.

2.2.1.2. Hypothesis 2

The sap flow of the influenced trees decrease in the course of the experiment measured in a monthly comparison.

The water limitation stress for the influenced trees increases and has limiting impacts on the capability of the influenced trees during the vegetation period. The sap flow of the influenced trees decreases stronger during the vegetation period when compared monthly to the sap flow of the control trees. I expect both to still follow the seasonal pattern with sap flow showing an increase in spring, the highest values in summer and a decrease in autumn (Sitková et al., 2014) as explained in the introduction. However, I suppose that the difference of the Q_t between two treatments will increase during the vegetation period as the sap flow of the influenced trees decreases.

2.2.2. Hypotheses regarding aim 2:

Understand the relationship between sap flow and soil moisture.

2.2.2.1. Hypothesis 3

The sap flow of the trees show a correlation with the soil moisture content for all measured soil layers.

In case drought stress was successfully induced in the influenced trees, the available soil water of the experiment would determine the water available for the influenced trees. This would reveal if the behaviour of the influenced trees coincides with the dryness of the experiment. The strongest positive correlation between experiment soil moisture content and the influenced trees is assumed to be found in deep layers because beech can use water of deeper layers if the top soil layers are too dry (Magh et al., 2020). The control trees show a correlation with the control soil moisture content outside of the experiment influenced area.

2.2.2.2. Hypothesis 4

In the course of the experiment the influenced trees become increasingly correlated to soil moisture content, while the control trees show a higher correlation with temperature.

Sap flow is dependent on water availability and on temperature (Li et al., 2019).If the influenced trees undergo increasing water stress during the ongoing experiment the available water is the limiting factor for the sap flow. As explained in the introduction beech forests are known to be more sensitive to water limitations than to high temperatures (Gennaretti et al., 2020). I test this in a monthly comparison of the correlation between sap flow and soil moisture content with the correlation between sap flow and temperature: the correlation between the sap flow of the influenced trees and the soil water content of the experiment is hypothesised to become stronger in the course of the experiment and to be higher than the correlation between sap flow of the influenced trees and temperature. The sap flow of the control trees is not limited by water and show higher correlation with temperature than to soil moisture content.

2.2.3. Hypotheses regarding aim 3

Investigate the nocturnal sap flow behaviour after rain events and artificial irrigation events.

2.2.3.1. Hypothesis 5

After precipitations events the nocturnal sap flow of the influenced trees is significantly lower and they show a negative correlation with the rain amount of the previous day, while the nocturnal sap flow of the control trees show a positive correlation.

The influenced trees should be limited in their rainwater access through the experiment infrastructure. Therefore I do expect their nocturnal sap flow to be reduced in nights after rain events compared to the nocturnal sap flow of control trees. The control trees show also a positive correlation between nocturnal sap flow and rain water amount of the previous day, as they have more water available to fill up their inner reservoirs according to the rain amount. For the influenced trees I do expect a negative correlation between the nocturnal sap flow and the rain amount of the previous day. Because the sap flow is dependent on the vapour pressure deficit VPD (Li et al., 2019). Nocturnal sap flow is dependent on VPD as well (Wu et al., 2020) and the sap flow rate of the previous day. When VPD drops so does the diurnal sap flow and in consequence the nocturnal sap flow too. During rain events the VPD also drops but trees use water to fill up inner reservoirs the nights afterwards (Wimmer, 2006; Wu et al., 2020), especially when they were under drought stress before they have high nocturnal values despite low VPD. In case the VPD drops due to rain and trees cannot fill up their reservoirs, their nocturnal values drop as well.

2.2.3.2. Hypothesis 6

The influenced trees have higher nocturnal values after artificial irrigation events and show a positive correlation with the irrigation amount.

These hypotheses suggest that the influenced trees get significant more water from the artificial irrigation of the DRAIN experiment whereas the control trees are not able to use water from the irrigation. Comparing the treatments, results in significant higher nocturnal values in the influenced trees in the night immediately after an irrigation event. That is, because sap flow rate is very sensitive to rain events interrupting droughts (Magh et al., 2020), and because the trees refill their inner reservoirs at night (Wimmer, 2006; Wu et al., 2020). I also expect a positive correlation between the nocturnal sap flow values of the influenced trees and the irrigation amount. As the trees have access to more water to refill their inner water reservoirs after great irrigations and less when only a small irrigation took place. The nocturnal sap flow of the control trees is expected to be indifferent to the artificial irrigation amount. As the VPD is not affected by the irrigation and they have no access to the water I do expect their nocturnal sap flow neither to drop nor to rise nor show any correlation.

3. Material and Method

3.1. Study area

The measurements were taken at the LTER-site in the Rosalia Forest Demonstration Centre. The location is LAT 47°42'N, LON 16°17' E. The Demonstration Forest Rosalia encompasses a 950ha area in the Rosalian mountains, an eastern mountain spur of the alps at the border between Lower Austria and the Burgenland in Austria (Figure 1) (Fürst, 2020; Gasch and Díaz-Pinés, 2019). The Rosalia Forest Demonstration Centre was settled in 1972, but Boku University is engaged in this area since 1875. The Demonstration Forest Rosalia features all major tree species (Beech, Fir (*Abies alba Mill*), Larch (*Larix decidua*), Norway spruce (*Picea Abies*), Oak (*Quercus robur*), Scots pine (Pinus *sylvestris*), etc.) and all forest types in Austria (Gasch and Díaz-Pinés, 2019). Very steep slopes and the domination of spruce and beech forests characterize the site. The elevation ranges from 320 to 725 m a.s.l. Bedrock types are prevalently Crystalline rocks, coarse grain gneiss, sericitic schist, phyllite and dolomite (Fürst, 2020).

The DRAIN experiment site is located at an elevation of 600m a.s.l. (47° 42′ 26″ N /16° 17′ 59″ E) and the site is oriented to the west (Leitner et al., 2016) and the slope is » 16° (Schwen et al., 2015). The annual average precipitation is 796mm and the annual mean temperature is 6.5°C (Schwen et al., 2015). The site is a pure and mature beech stand (*Fagus sylvatica* L.) with a stand age of 120 years (Leitner et al., 2017) on a pseudo-gleyic Cambisol soil with a metamorphic crystal-line bedrock (Leitner et al., 2016).

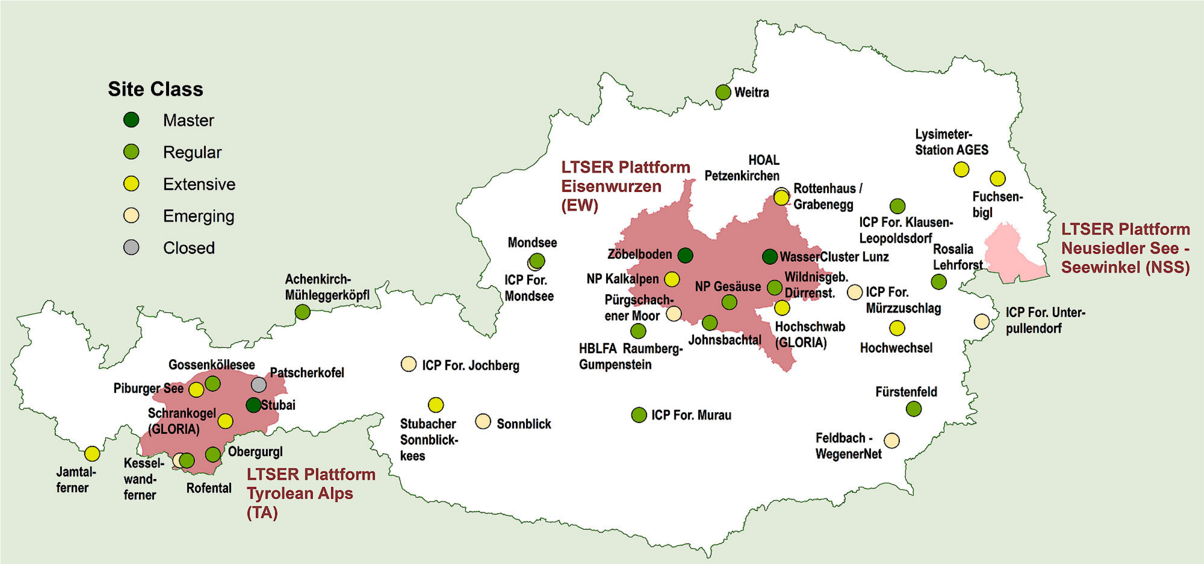


Figure 1: Map of the Austrian LTER sites (LTER Austria, n.d.). Rosalia Forest Demonstration Centre is marked with a green dot, west to the LTSER Plattform Neusiedler See-Seewinkel (NSS)

3.2. Experimental design

3.2.1. DRAIN Experiment: Drying-rewetting of soil

The original experiment was set up in 2013 with the purpose of investigating effects of changing precipitation patterns on forest soil characteristics, ecosystems and processes. For this purpose, a rainfall manipulation was set up with three soil treatments with four replicates: four of the plots were kept under moderate, four others under severe drought stress during the growing season, and four served as control plots with no precipitation alterations. The moderate plots were kept during four weeks without precipitation; in the severe plots, the period without precipitation was eight weeks. After each drought period, a single precipitation event was simulated. Then they were again exposed to drought stress while the control treatment was kept under natural precipitation (Figure 2).

Transparent, acrylic 4 m x4 m roofs have been installed 1.2 m above the ground (Leitner et al., 2017). Those roofs prevented natural rainfall from entering eight of the twelve experimental plots (2 m x 2 m). An irrigation system placed beneath the roof watered the moderate drought plots (1; 4; 7; and 11 in Figure 4) every 28 days with 75mm precipitation (262.5 litre), and the severe drought plots (2; 5; 8; 12 in Figure 4) every 56 days with 150mm (525 litre) of water (Figure 2). The control plots (3; 6; 9; 10 in Figure 4) had no coverage and were not irrigated. At the uphill side of the plots 0.40 m deep trenches were dug, sealed with plastic foil and filled with gravel (Figure 3). These trenches stopped the lateral flow (surface runoff or through soil) from entering the drought plots (Schwen et al., 2015).

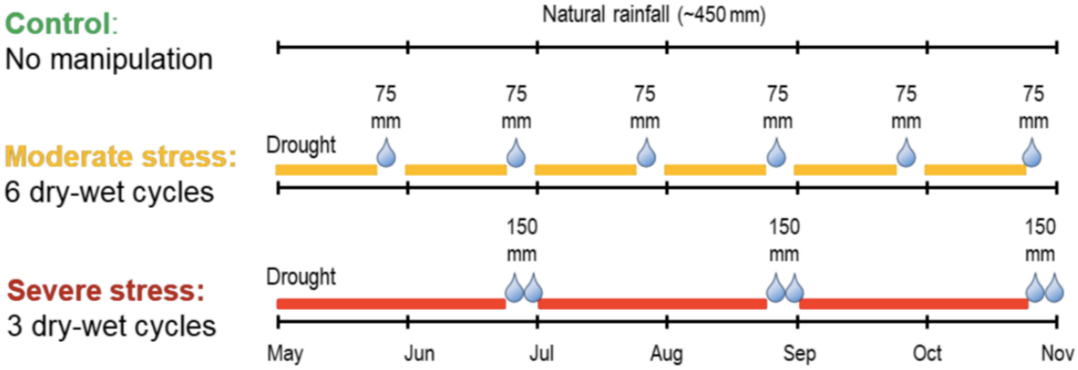


Figure 2: Rainfall manipulation scheme at the LTER site Rosalia (Figure credit: Institute of Soil Research, BOKU)

Figure 3: Picture of the DRAIN experiment in the LTER site Rosalia Forest Demonstration Center in 2019 (Figure credit: Institute of Soil Research, BOKU). Uphill sided of the transparent acrylic roofs the green foil of the trenches is visible

3.2.2. Sap flow measurements

The beech trees used for the sap flow measurements were similar in size and had an average breast height circumference of 143cm (range: 121cm - 168cm) and an average diameter at breast height of 45.1cm (range 38.5cm - 53.4cm). Bark and phloem thickness have been measured for later calculations (Table 1). The location of the trees respect to the experimental plots differed. None was directly inside the plots but some were close and some in more distance. Trees 1.3, 1.4 and 2.9 (Figure 4) were near to the drought exposed plots and therefore were considered to be affected by the water manipulation (influenced trees). Tree 1.5 (Figure 4) grows in distance to the experiment plots but downhill sided and could perceive drought stress due to the limitation of the lateral flow and is therefore also treated as an influenced tree. On the other hand, the trees 1.1, 1.2, 2.6, 2.7, 2.8 and 2.10 (Figure 4) grow uphill sided or in distance to the manipulated plots and were therefore considered control trees, hence unaffected by the rainfall manipulation experiment. This classification was done following the spatial position of the tree stem and the topography of the slope; however, there is an uncertainty on this approach because there is no information about the actual rooting system of these beech trees.

Table 1: Characteristics of the beech trees equipped with sap flow probes at the LTER-site Rosalia

Tree	Diameter at Breast height [cm]	Breast height circumference [cm]	Bark and Phloem thickness [mm]
1.1	47.80	158.3	4
1.2	38.50	121.0	5
1.3	53.35	168.0	5
1.4	51.20	161.40	6
1.5	41.70	131.30	4
2.6	44.05	138.40	4.5
2.7	43.15	135.70	5
2.8	40.00	125.70	4.5
2.9	44.10	138.70	4
2.10	46.90	147.40	4.5

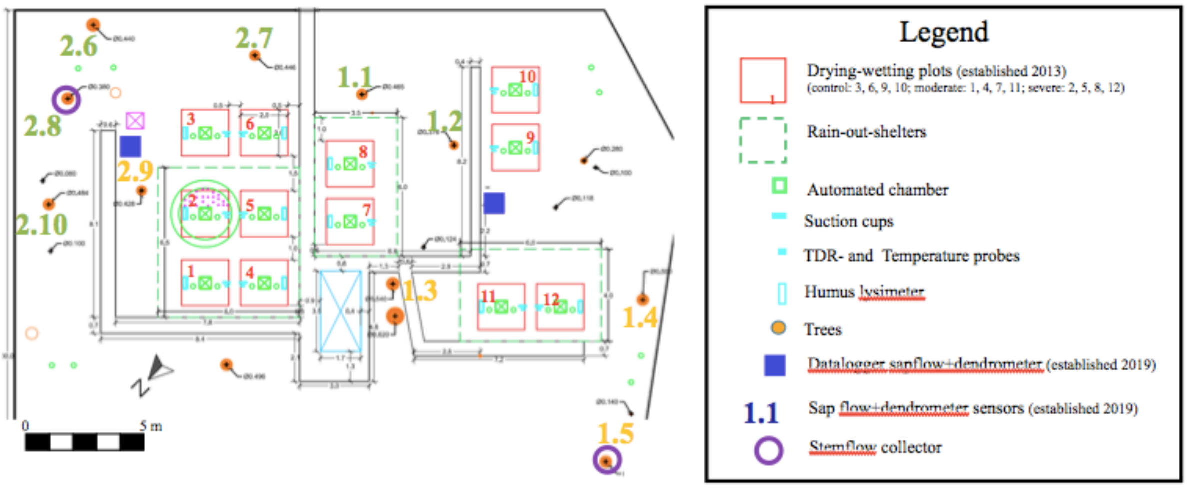


Figure 4: Experiment setup at LTER site Rosalia in 2019 (Figure credit: Institute of Soil Research, BOKU). The influenced trees were the trees next to or downhill sided from the drought exposed plots, therefore trees number: 1.3; 1.4; 1.5 and 2.9 (Yellow marked). The control trees were in distance of the drought exposed plots, the trees with the numbers: 1.1; 1.2; 2.6; 2.7; 2.8; 2.10 (Green marked).

Sap flow measurement started in 2019 and a heat balance method was used. Thereby the amount of energy to maintain a certain temperature difference between a heated and a non heated electrode in the trunk is recorded (Kučera, 2015). The Sap Flow System EMS81 (Environmental Measuring Systems s.r.o, Brno, Czech Republic) was installed on the ten trees under investigation. The system consists of a controlling and data-logging unit (MicroSet 8X), the sap flow sensor SF 81, a set of stainless electrodes, weather shields and connecting cables (Figure 5). The sensors with a length of 80mm were hammered in at a height of 1.2-1.3 m. The measuring device recorded the power of heat input [W] and automatically converted to sap flow rate [kg $s^{-1}cm^{-1}$] by the software (Kučera, 2015). Data were collected as 30-minute averages and stored in a datalogger MicroSet 8X. The measuring devices were connected via cable to the power supply of the site. An additional insulating weather shield prevented disturbing factors like direct sun irradiation, heavy rain, or wind (Figure 6) (Kučera, 2015).

Figure 5: Sap flow measuring system on a beech tree on the DRAIN experiment in the LTER site Rosalia Forest Demonstraion Center (Figure credit: Kager, BOKU). To be seen are cables connecting the stainless electrodes (on top) with the sap flow sensor SF 81 (bottom) and the half removed weather shield.

Figure 6: Insulating weather shield over a sap flow measuring system on a beech tree on the DRAIN experiment in the LTER site Rosalia Forest Demonstraion Center (Figure credit: Kager, BOKU)

3.2.3. Ancillary measurements

The volumetric water content [vol %] of the soil was measured with time-domain reflectometry (theta.ML2x probes, UMS GmbH, now METER ENVIRONMENT) at three points of the site. One set of probes was located above the experimental plots and used as control soil moisture content; another set of probes was located in between the experimental plots (i.e. under the rain out shelters) and was used as experiment soil moisture content; the last set of probes was located below the experimental plots. All of this measured the volumetric water content of the soil in 30 minute intervals in four different depths: 10cm, 20cm, 30cm, and 40 cm. These depths were already given by the original experiment setting. As beech trees have around 66% of their fine roots in the uppermost 30 cm of the soil profile (Leuschner, 2020) and most of their entire root biomass in the top 40cm (Granier et al., 2000), this depth was considered be sufficient to monitor soil moisture over the root zone. The soil moisture measurements started in October 2019.

The meteorological station *Heuberg* nearby (in ~500m distance) supplied the weather data which is available at (Gasch and Díaz-Pinés, 2021). A Sartorius QS8 (Sartorius s.r.o Göttingen, Germany) at 150 cm height over the surface measured the 30-minute sum value of precipitation by weight [l/m^2] (further given in mm). Relative air humidity [%] and air temperature [°C] was measured with an UMS RFT-2 device (UMS GmbH, now METER ENVIRONMENT s.r.o München, Germany /Pullman, USA) at 200 cm over the surface level as 30-minute average from measurements taken every minute. Delta-T ES2 device (Delta-T s.r.o Burwell, United Kingdom) was used to measure global radiation [Watt/m^2] in a height of 2400 cm over the surface level, again as 30-minute average from one-minute resoluted measurements (Gasch and Díaz-Pinés, 2021).

3.3. Data processing

3.3.1. Data periods

In this work, sap flow rates for the periods 01.08 - 04.10.2019 and 27.04 - 12.06.2020 were analysed. The measurement period started on 18.07.2019 for the trees with numbers 1.1 to 1.5 and on 02.08.2019 for the trees numbered 2.5- 2.10. Owing to the different start of the measurements and a power breakdown at the beginning of October 2019 the investigation period was from the 01.08.2019 until 04.10.2019. Due to frequent failures of the measurement devices in 2020, the data from this year was of bad quality or missing for large periods. High-quality data for all trees (and therefore usable for further analysis) were only available in the period from 27.04.2020 (when the rain-out-shelters were installed) until 12.06.2020.

3.3.2. Data preparation

The raw data needed some preparations before it could be used for the further investigation. The software of the measuring device automatically converted the measured energy input [W] in to sap flow rate [kg s^{-1}cm^{-1}] so from this side no further conversion had to be done. But the delivered sap flow rate data had to be prepared, because it contained still improper or implausible data occurring through the measuring process. This data preparation consisted of three main processes. First, the baseline subtraction: to exclude improper data occurring from the used measurement type. Second the zeroing of non-reliable data: to clear the data from implausible data, occurring from to recording errors. Third the gap filling: to estimate values where small data periods were missing.

3.3.2.1. Baseline subtraction

The Baseline subtraction of the measured sap flow data, was necessary as the measured values contain: The actual sap flow, which is relevant for me, but also a and the „fictitious“ sap flow, which constitutes the unintended heat loss from the heated xylem (Hoelscher et al., 2018). Therefore, a so-called baseline subtraction needs to be applied: the baseline, standing for the heat loss by the heat conductivity of the xylem, had to be subtracted from the measurement sap flow data (Kučera, 2015). I manually conducted a baseline subtraction on the sap flow data. For the baseline subtraction, I used the EMS Universal Software mini32 (Environmental Measuring Systems). In this program I removed the baseline of each day and each tree according to the weather conditions from zero up to the lowest measured sap flow value at 3 am in the morning.

3.3.2.2. Zeroing of non-reliable data

Data of low quality that needed to be zeroed happened to be in diurnal and in nocturnal sap flow. Diurnal sap flow showed in general plausible data, which I left untouched. However right before or right after a power break down the documented sap flow values were often ten times higher than the rest of all measurements. At such occasions I set those values to zero and either performed gap filling, if the gap was short (half hours to several days) and only one tree affected, or excluded the whole day entirely from the measurement period, if it was either long (weeks and months) or several trees were involved.

In general I did not zero all nocturnal data, as others did, but I excluded unreasonable high peaks at nocturnal values from the data following very strict rules. Those unreasonable peaks occurred very often before or after a power break down too. In order not to falsify my data I did this zeroing of nocturnal peaks after very strict rules. I only set peak nocturnal values to zero. If the nocturnal sap flow was high but continuously diminishing, e.g from a high day value, I left it. If there was a rise during the night, I would set it to zero when there was no explanation, like rain or high vapour pressure deficit (VPD). I did not zero such peaks, when the (VPD) was above the threshold of 0.1kPa (Wu et al., 2020) or when the temperature was above 19.5° the whole night. When there was rain or an irrigation event (Table 2) 24 hours before, I also left the peak values.

Vapour pressure deficit was calculated in advance with the meteorological data from the Heuberg climate station, according to the empirical equation (Campbell and Norman, 1998):

$$VPD = \left(1 - \frac{RH}{100}\right) \cdot a \cdot e^{b \cdot \frac{T}{T+c}} \qquad [1]$$

Where *T* is the air temperature [°C], *RH* is the relative humidity [%] and *a* [kPa], *b* and *c* [°C] are constants to optimize the fit of the equation (Campbell and Norman, 1998)

$$VPD = \left(1 - \frac{RH}{100}\right) \cdot 0.611 \cdot e^{17.502 * \frac{T}{T+240.97}} \qquad [2]$$

Table 2: Relevant irrigation dates of the drain experiment plots at the LTER site Rosalia

Date	**Plots**	**Water amount in mm**
21.08.19	1,4,7,11	75
21.08.19	2,5,8,12	150
18.09.19	1,4,7,11	75
25.05.20	1,4,7,11	75
22.06.19	1,4,7,11	75
22.06.19	2,5,8,12	150

3.3.2.3. Gap-filling

As mentioned before, there were some gaps in the measurements ranging from 30 minutes to several months, which I needed to fill or exclude from the measurement. I interpolated missing measurements as long as they did not exceed more than two hours by linear interpolation. Gaps of missing values between 2 and 12 hours I interpolated by inserting the mean value in the middle of the gap, then calculating the mean between the measurement before/ after the gap and the previous mean going in this way up/ downwards until the gap was filled. For larger gaps bigger than 12 hours up to several days, I chose two trees with the most similar values to estimate the missing data. Trees with the most similar values were found by using the root mean square difference with known values. I calculated the mean from trees with the most similar values during the missing period to replace the missing measurements. When more than one tree had missing values during a period of several days, they were mostly a couple of four to five trees. In the small sample size of ten trees it would mean that one half of the trees is used to estimate the values of the other half. As this would falsify my data I excluded gaps of several days of more than one tree from the observation period.

3.3.3. Calculation of cumulative values

For the statistical analysis the sap flow rate [kg s^{-1} cm^{-1}] data per 30 min must be converted in sap flow per day [kg]. Then the primed data, as explained above, was expanded to the total sap flow per tree (Q_{tree}), with the formula provided in the user manual (Kučera, 2015):

$$Q_{tree} = Q \cdot (A - 2\pi \cdot B) \quad [\mathrm{kgh}^{-1}] \qquad [3]$$

Where *Q* is the measured sap flow per 1cm stem circumference [kg h^{-1} cm^{-1}]. *A* is the tree circumference [cm] and *B* the bark and phloem thickness [cm] (Kučera, 2015). Sap flow changes according to meteorological conditions (Li et al., 2019). Therefore, the current rain, temperature and global radiation patterns were plotted with the sap flow rates of some example days. Thereby the influence of the current weather pattern on the sap flow rates were demonstrated. However, for my research questions I am not interested in rapid responses to rapid changes in the weather conditions. As sap flow does not react immediately to changes in the weather conditions, it can lag minutes or hours behind, having the temporal resolution too fine may lead to a bias when looking for relationships (Braun et al., 2010). To prevent the results from such kinds of measurement errors, I will only use cumulative total, nocturnal or diurnal values for my statistical analyses, which are considered to be more robust for my purposes. Thus, I will integrate the sap flow per tree (Q_{tree}) using simple numerical integration in half-hour steps:

$$Q(t_{\frac{i}{2}}) = \left[f\left(t_{\frac{(i-1)}{2}}\right) + f\left(t_{\frac{(i)}{2}}\right) \right] \Delta t/2 \quad [t_0 = 00{:}00,\ t_{1/2} = 00{:}30,\ \ldots t_{24} = 24{:}00;\ \Delta t = 30\ \mathrm{min}] \qquad [4]$$

Where *t* is the time in hours. The summation of the cumulative sap flow per day (00:00- 24:00), also referred as the total cumulative sap flow per day (Q_t) was further used for the most comparison analyses:

$$Q_t = \sum_{i=1}^{48} Q\left(t_{\frac{i}{2}}\right) \quad [\mathrm{kg}] \qquad [5]$$

To see the behaviour of the Q_t during the measurement periods, the mean Q_t for each year was plotted. As precipitation has an influence on the nocturnal sap flow values (Wu et al., 2020), it was necessary to calculate the cumulative nocturnal sap flow (Q_n) as well. Night was defined as the absence of global radiation. So, the Q_n was calculated with the $Q(t_{i/2})$ measurements where the global radiation was zero, excluded were values in which the global radiation was zero during day time (8:00 - 18:00). As the calculation period went over midnight, the date was always given by the previous day. To compare nocturnal and day sap flow, I calculated the cumulative diurnal sap flow (Q_d), the day was defined as time of global radiation.

$$Q_d = Q_t - Q_n \qquad \text{[kg]} \qquad [6]$$

I compared the Q_n and the Q_d graphically and I calculated the mean difference. To compare my sap flow measurements to air temperature, global radiation, and soil moisture I calculated the daily (00:00- 24:00) means, so I got the mean daily temperature, mean daily global radiation, and mean daily soil moisture content (MDSMC). Concerning the soil moisture, this was done for all of the four different soil layers. The three soil moisture measurements were compared graphically for all depths. For precipitation I calculated the cumulative daily rainfall (R_{cd}). The mean daily temperature, mean daily global radiation and the cumulative daily rainfall (R_{cd}) were graphically compared to the mean Q_t.

3.4. Statistical analyses

The statistical analyses were performed in SPSS (IBM s.r.o Armonk, USA) and the output fields are attached in the appendix. The figures were designed in MS Excel (Microsoft Cooperation s.r.o Remond USA) . The significance level for all analyses was p= 0.05 unless stated otherwise.

3.4.1. Comparison between experiment and control trees

For inspection of my first hypothesis, I compared the Q_t of the influenced trees to the Q_t of the control trees. Results from all trees were plotted in their groups to visually detect outliers. Then, the means of both groups were calculated, one time with and the other time without outliers. Then the means were plotted for visual comparison, also as cumulative graphs. To compare the means statistically, a Welch-test was done (Eid et al., 2013; Fagerland and Sandvik, 2009). This analysis only worked where data from all trees were available, namely the period from the 02.08.2019 to 4.10.2019 and 27.04.2020 to 11.06.2020 and 22.06.2020 to 28.06.2020.

3.4.2. Correlation between sap flow and soil moisture content or temperature

To assess the correlation between the soil moisture or the temperature and the sap flow rate, a correlation coefficient after Bravais-Pearson was determined (Bamberg and Baur, 2001). For this analysis, the mean MDSMC and mean daily temperature (MDT) were used. The MDT and MDSMC values were presented against the mean Q_t of each group, again with and without outliers. The control group was opposed to the soil moisture content above the plots. The influenced group was opposed to all three soil moisture measurements, above, in between and below the plots. A correlation cloud was plotted and a Bravais-Pearson coefficient calculated (Bamberg and Baur, 2001). When the requirements for conducting a Bravais-Pearson correlation was were not met not possible, due to outliers, the Spearman correlation coefficient was calculated (Bamberg and Baur, 2001). Owing to the late start of the soil moisture measurement there was no correlation analysis possible for the 2019 data. Therefore, only data from the period 27.04.2020- 12.06.2020 and 22.06.2020 to 28.06.2020 were investigated. Due to this data limitation, a monthly comparison of the correlations was not possible as there was only one complete month.

3.4.3. Analysis of nocturnal values after irrigation and heavy rainfall events

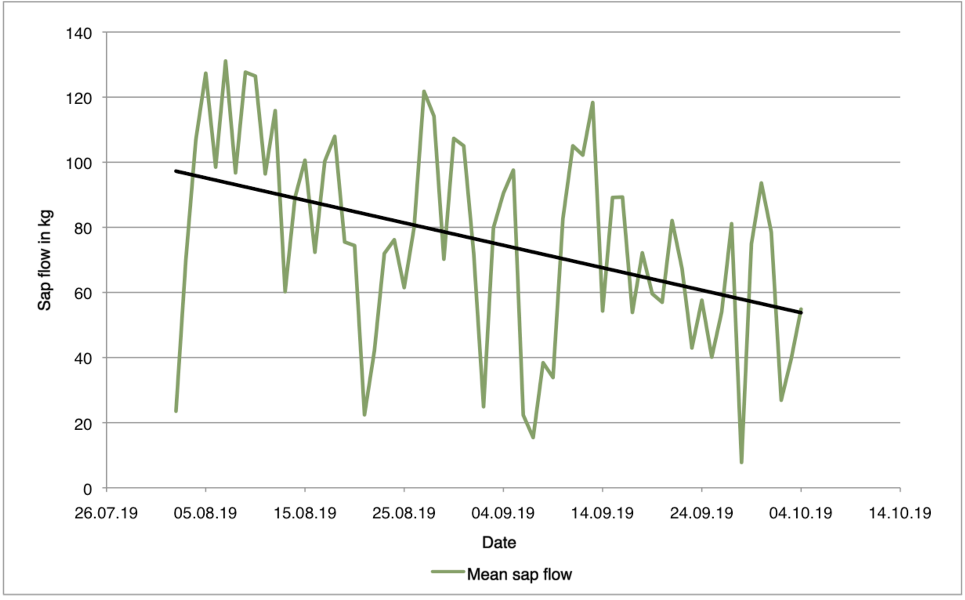
At first, a correlation analysis between the Q_n of the treatments and the R_{cd} was performed, then a comparison analysis between the groups of the Q_n after rain or irrigation events.

The R_{cd} was compared to the Q_n of the different treatments in a Spearman correlation analysis (Bamberg and Baur, 2001), where I compared the R_{cd} of the first measuring day ($R_{cd}(0)$) to the Q_n of the night immediately afterwards ($Q_n(0)$). After irrigation events, one week was excluded from the calculation. Due to unexpected data limitations, a correlation analysis could not be done between nocturnal values and irrigation dates: after excluding all irrigation data when there was rain in the previous week, only one irrigation date was left with data of all trees available.

The next step was the comparison of the Q_n between the groups, after irrigation and precipitation events. Therefore, the mean Q_n of each group was calculated for the event and compared to the other group graphically as well as through a Mann-Whitney-U-test, as the Gauss distribution and variance homogeneity for these small samples were not given (Benesch and Schuch, 2009). Due to the above mentioned lack of irrigation events data, all irrigation events where at least eight trees showed data were taken, irrespective whether or not there was a rain event in the week before. Nevertheless, only three irrigation events could be analysed, which is an insufficient sample size and prone to be non-significant.

4. Results

4.1. Mean sap flow behaviour



In 2019 measurements started in late summer early autumn and ended before fall of leaves, due to a power brake down. In autumn 2019, the mean Q_t decreased, as expected in a deciduous tree before the fall of leaves. The trend line (Figure 7:Mean total cumulative sap flow per day (Q_t) of all measurement trees on the LTER site Forest Rosalia in 2019. The black line showed the overall trend during the measurement period) was clearly downwards facing implying a negative trend in the mean Q_t. In 2020 the measurement period begun with the installation of the rain out shelters and ended in mid June, due to frequent failures of the measurement devices. The mean Q_t measurements in spring 2020 increased gradually (Figure 8). In those 47 days of measuring the Q_t increased as expected with beginning foliation. The clear seasonal pattern, from the increase of Q_t in spring, followed by the highest sap flow in late spring, followed by a decrease in autumn could not be seen in 2020. Due to the aforementioned lack of data during the summer and autumn months of 2020, the measuring period was therefore too short as it did not cover the whole vegetation period.

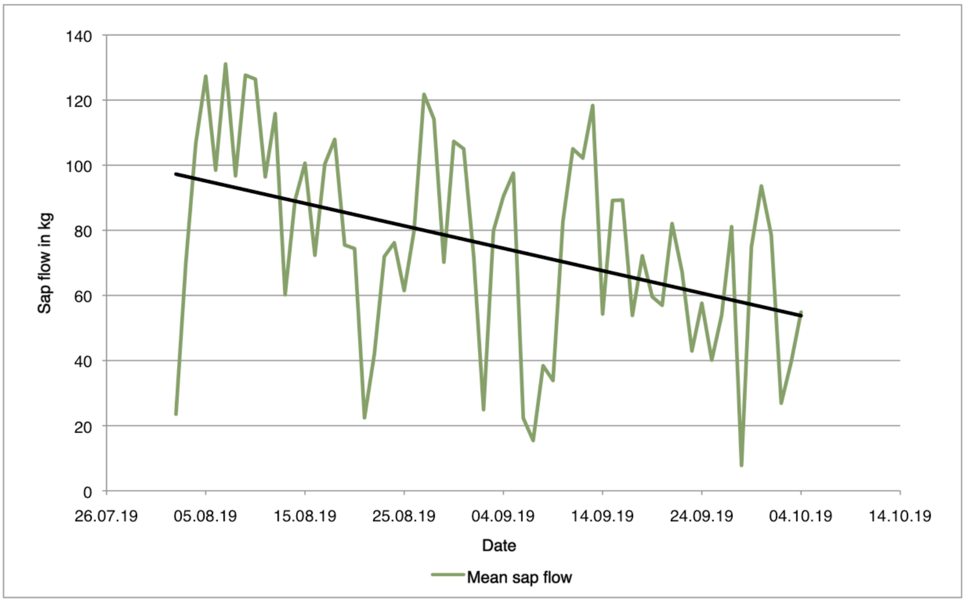


Figure 7:Mean total cumulative sap flow per day (Q_t) of all measurement trees on the LTER site Forest Rosalia in 2019. The black line showed the overall trend during the measurement period

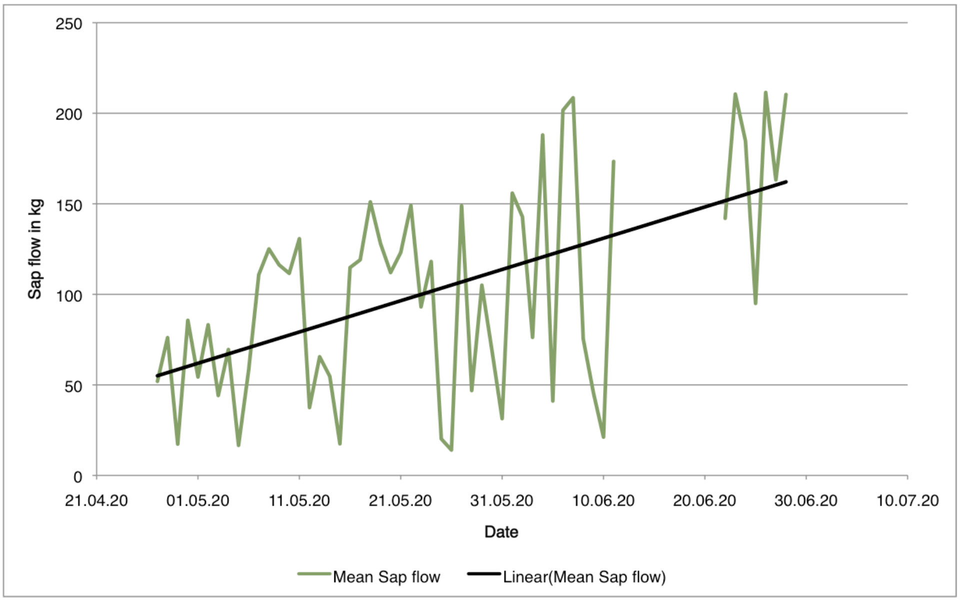


Figure 8: Mean total cumulative sap flow per day (Q_t) of all measurement trees on the LTER site Forest Rosalia in 2020. The black line showed the overall trend during the measurement period.

4.2. Meteorological data and sap flow

The meteorological conditions influenced the sap flow. The daily sap flow rate reacted correspondingly to changes in global radiation or temperature, whereas sudden rain events triggered peaks in the nocturnal sap flow rates. That behaviour was also displayed when comparing mean Q_t to the mean global radiation, mean temperature or rain. The mean Q_t patterns were similar to the ones of temperature and global radiation, and nearly opposite to the ones from precipitation.

4.2.1. Daily sap flow rates compared to the daily weather situation

Sap flow rates reacted very similar to changes in global radiation (Figure 9,Figure 10). By day, all sap flow rates showed the same shape as the global radiation in all graphs. This similar pattern becomes particularly clear on the 29th of August 2019 (Figure 9), when the global radiation suddenly dropped, likely due to clouds, and after a short delay, all sap flow rates dropped too.

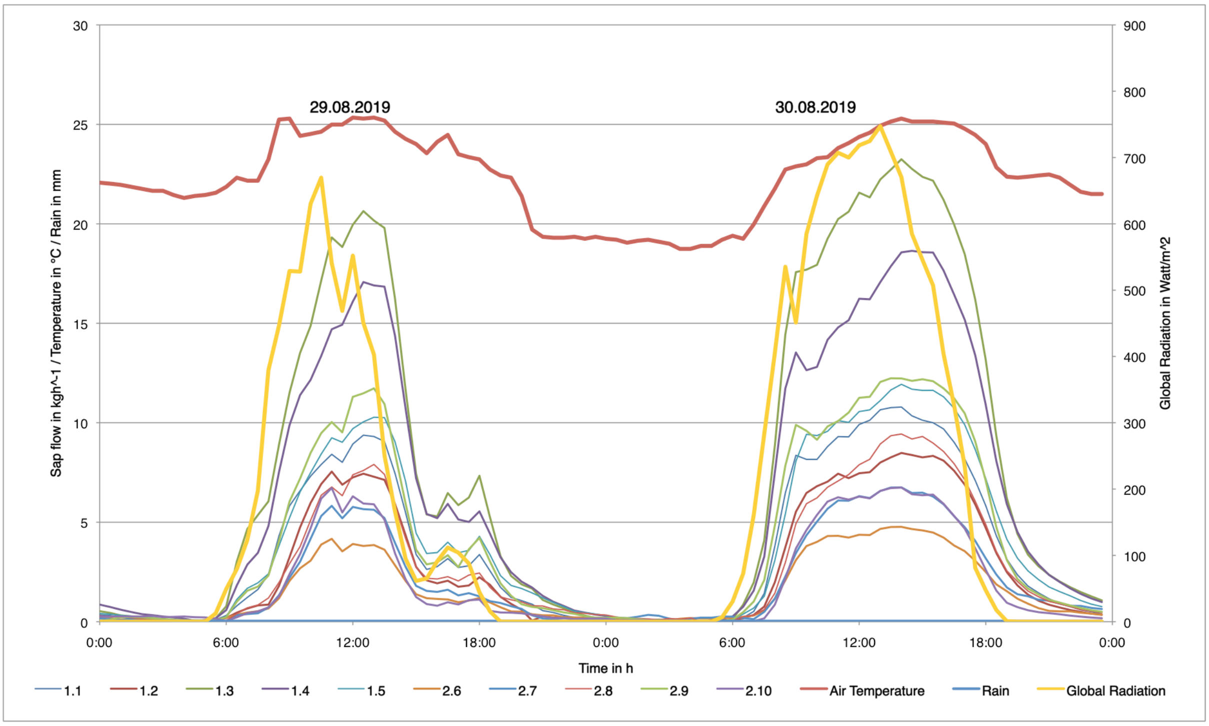


Figure 9:Exemplary sap flow rates of all measurement trees from 29.08.2019 and 30.8.2019. The numbers 1.1 to 2.10 represent the sap flow rates of the measurement trees on the LTER site Forest Rosalia

Drops of air temperature could also have negative impacts on the daily sap flow rate. In between the days of the 13th and 14th of September, the temperature dropped (Figure 10) despite the global radiation remaining quite high. However, the sap flow rates dropped along with the temperature on the 14th of September about one third to a half of the rates from the 13th of September.

In the night between 13th and 14th of September the sap flow rate showed an interesting slow decreasing pattern (Figure 10): The trees continued to have sap flow rates until the morning hours of 14th of September, when the global radiation started again, in contrast to the very distinct lack of sap flow on the other example night with no rain (Figure 9). Such remarkable sap flow behaviour has occurred often in a row of days.

To illustrate the influence of alterations in rain amount on the nocturnal sap flow rates, another couple of exemplary days, the 2nd and 3rd of September 2019, are graphically displayed (Figure 11). There were several small rain events during the 2nd of September. The global radiation was quite constant on those days, only the temperature dropped about 5°C over night. After the small rain events on the 2nd of September, irregular peaks of sap flow occurred in some trees in the night. Also, in the early morning of the 3rd of September the sap flow of some trees was not corresponding to the available light indicated by the global radiation.

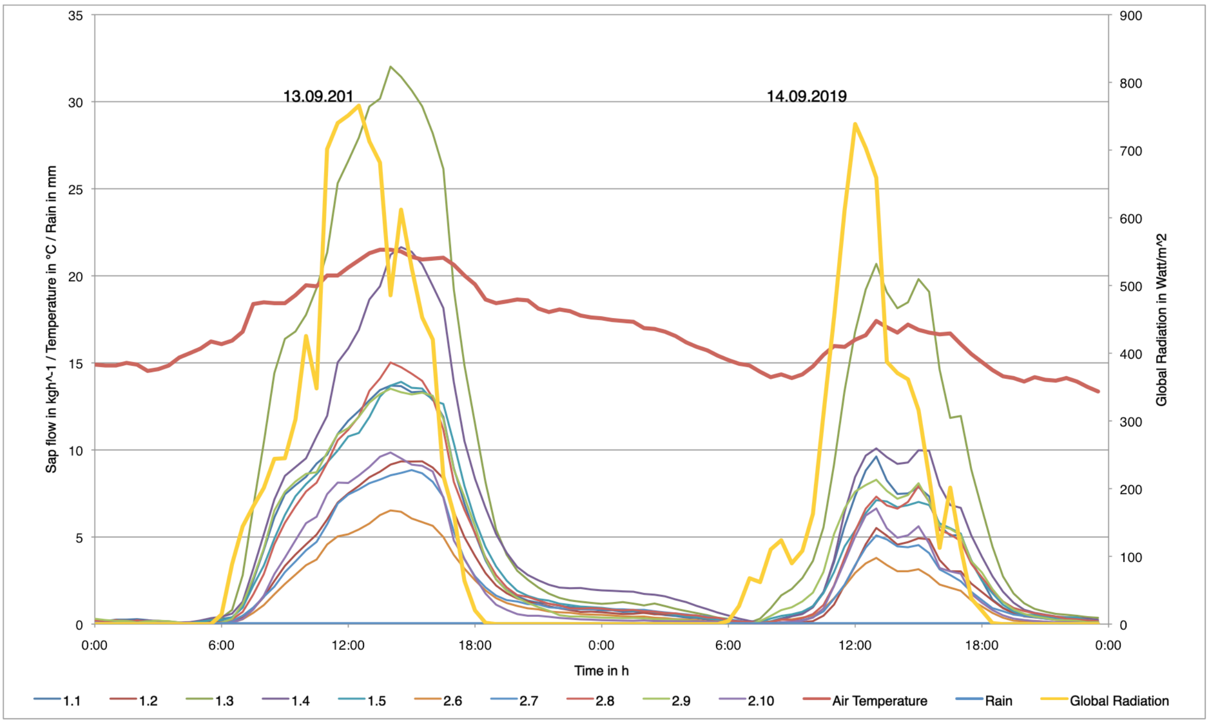


Figure 10: Exemplary sap flow pattern of all measurement trees from 13.09.2019 and 14.09.2019. The numbers 1.1 to 2.10 represent the sap flow rates of the measurement trees on the LTER site Forest Rosalia

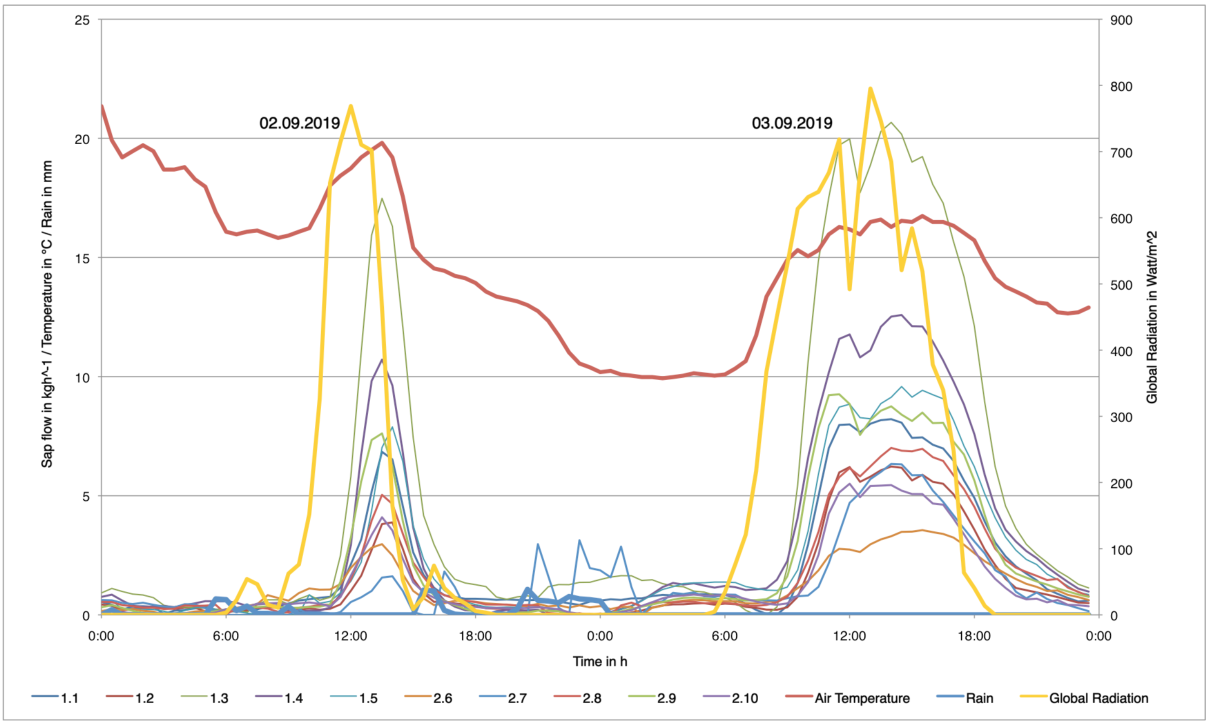


Figure 11: Exemplary sap flow pattern of all measurement trees from 02.09.2019 and 03.09.2019. The numbers 1.1 to 2.10 represent the sap flow rates of the measurement trees on the LTER site Forest Rosalia. Note that some modest precipitation occurred

4.2.2. Sap flow and meteorological data during the measuring periods

Mean Q_t and the global radiation and air temperature usually followed a similar pattern. The sap flow rate corresponded with the pattern of the global radiation for both years (Figure 12, Figure 13), especially in 2019 (Figure 12). The corresponding behaviour of global radiation and sap flow was also confirmed through a correlation diagram, where in both years the values showed a strong positive correlation (Figure 14). In April and begin of May 2020 the synchronic behaviour between global radiation and mean Q_t was not so distinct as in 2019 but increased during the measurement (Figure 13). This can also be seen in the lower R^2 values of the correlation line. In 2019 could around 70 % of the mean sap flow be explained through the global radiation in 2020 nearly 60% (Figure 14). When the mean Q_t and the air temperature were displayed for the years 2019 and 2020, the same behaviour to temperature alterations could be noticed as with global radiation (Figure 15, Figure 16). However, the simultaneous behaviour of Q_t and temperature was not as distinct as of Q_t and global radiation as can be seen in some temperature unrelated drops in Q_t in June 2020 (Figure 16). Also the correlation diagram confirmed a strong positive relation ship between temperature and sap flow (Figure 17). Even so the R^2 values were a bit lower than the ones of global radiation. With the temperature in the measuring period of 2019 around 41% of the sap flow values could be explained and 2020 around 50% (Figure 17).

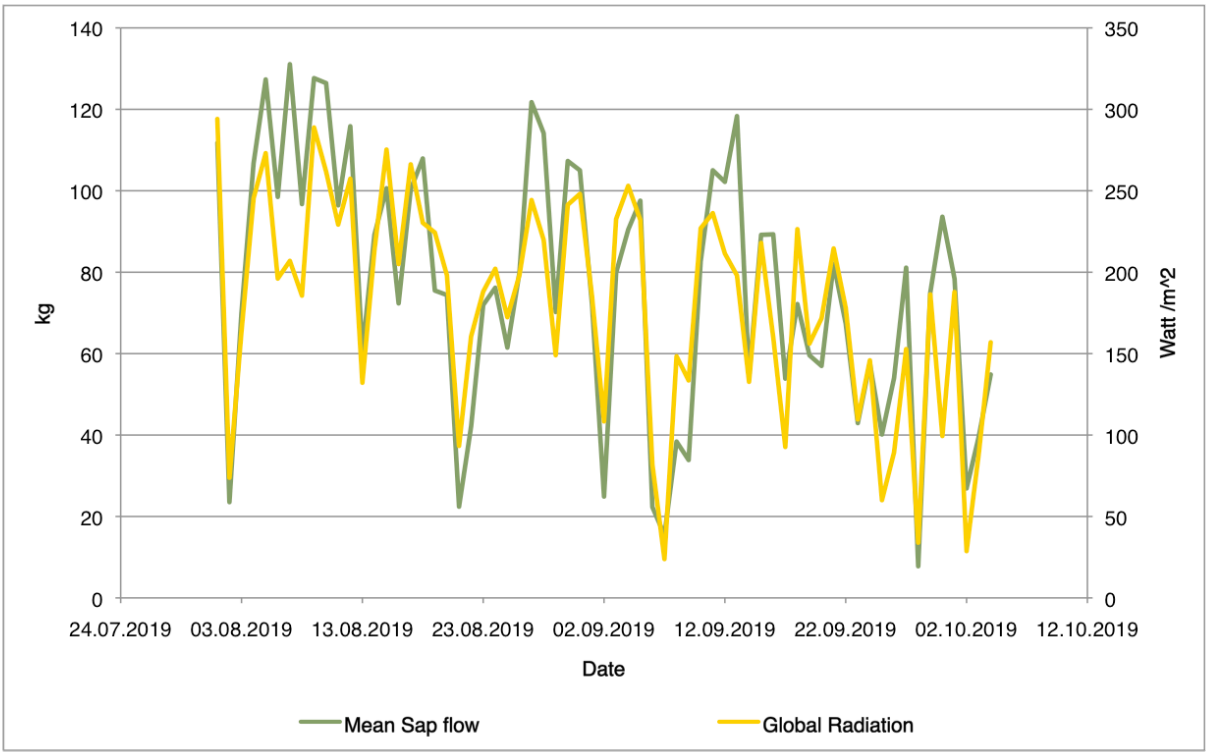


Figure 12: Mean total cumulative sap flow per day (Q_t) of all measurement trees on the LTER site Forest Rosalia and mean daily global radiation in 2019.

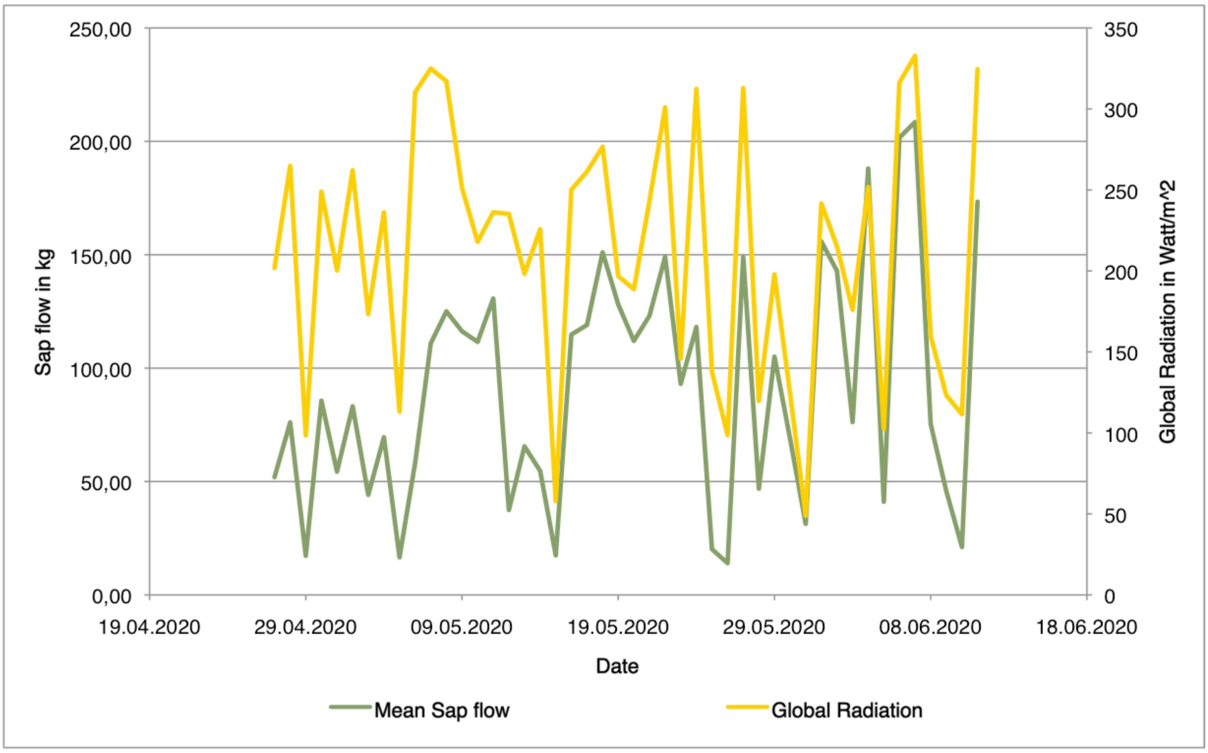


Figure 13: Mean total cumulative sap flow per day (Q_t) of all measurement trees on the LTER site Forest Rosalia and mean daily global radiation in 2020

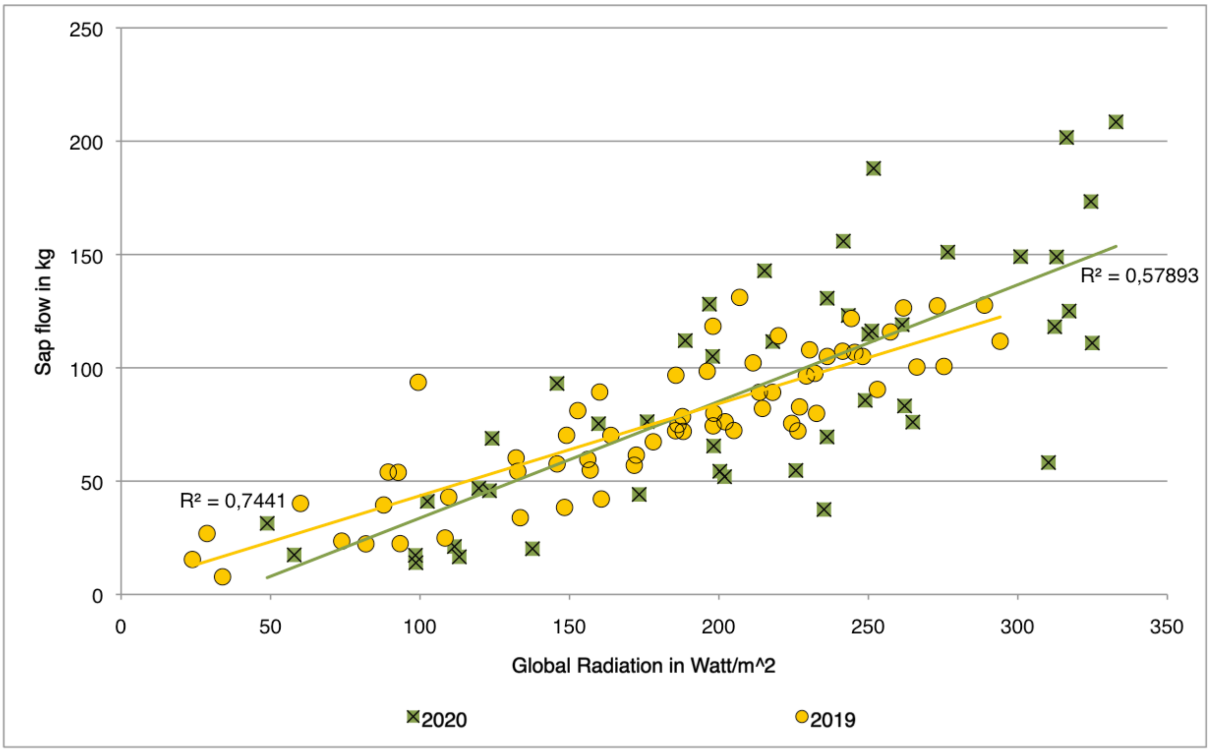


Figure 14: Correlation of global radiation and mean total cumulative sap flow per day (Qt) of all measurement trees on the LTER site Forest Rosalia in 2019 and 2020. The yellow and the green line show the correlation line of 2019 and 2020.

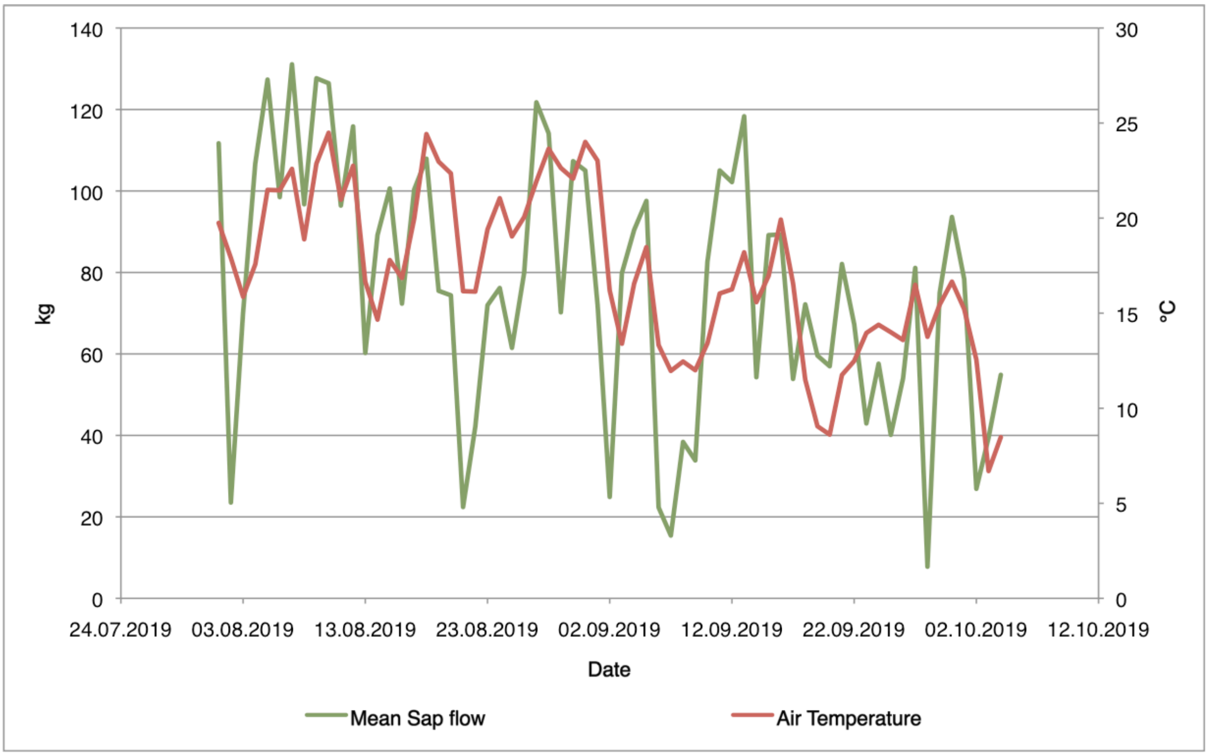


Figure 15: Mean total cumulative sap flow per day (Q_t) of all measurement trees on the LTER site Forest Rosalia and mean daily temperature in 2019

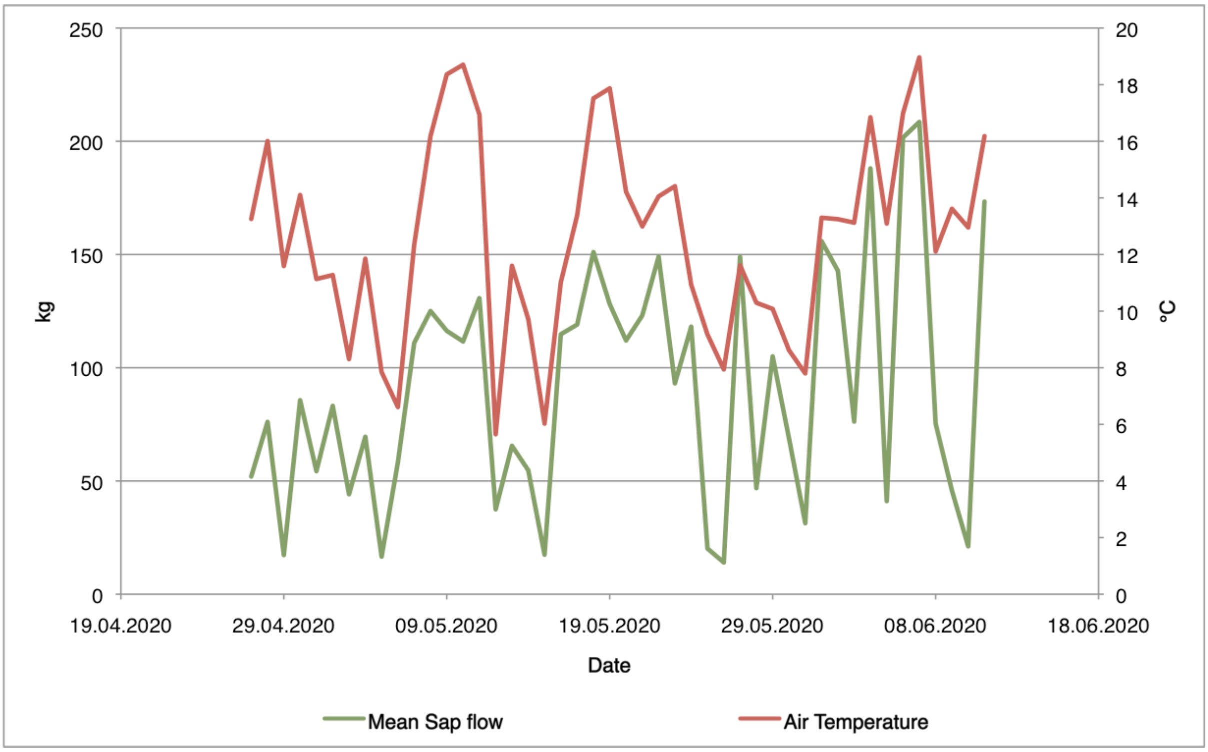


Figure 16: Mean total cumulative sap flow per day (Q_t) of all measurement trees on the LTER site Forest Rosalia and the mean daily temperature in the year 2020

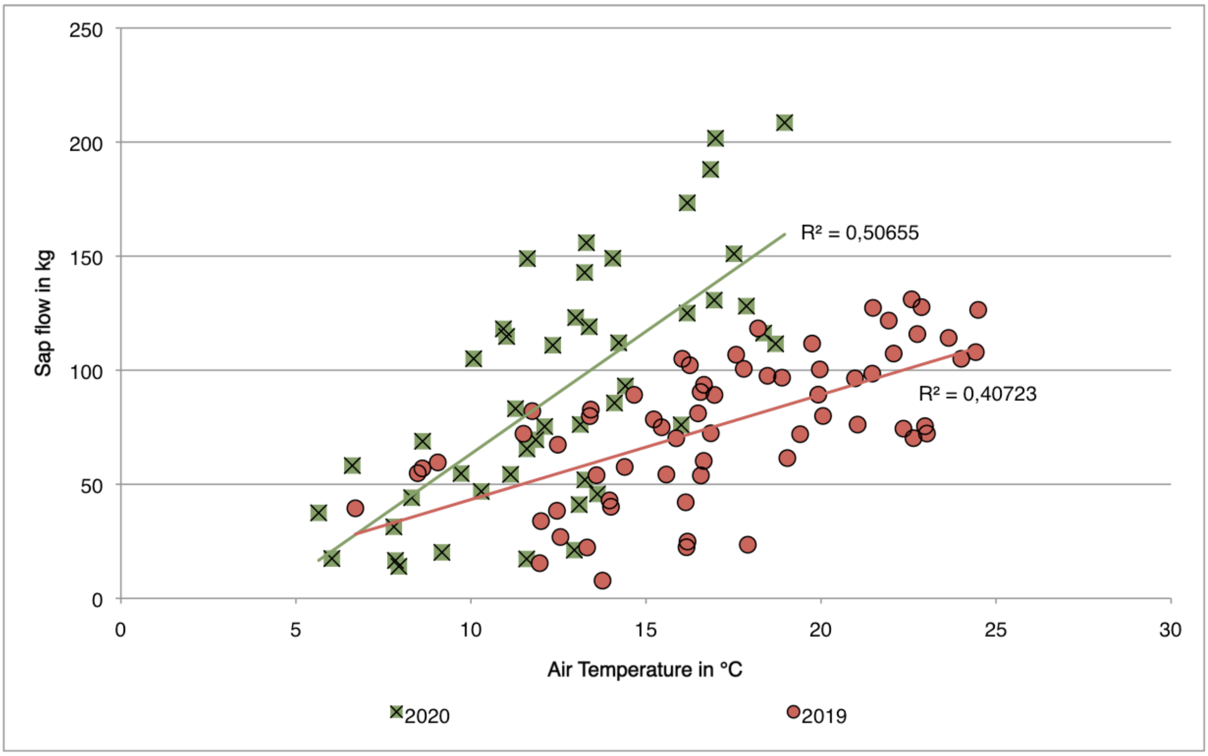


Figure 17: Correlation between air temperature and mean total cumulative sap flow per day (Qt) of all measurement trees on the LTER site Forest Rosalia in 2019 and 2020. The yellow and the green line show the correlation line of 2019 and 2020.

I compared the pattern of the precipitation and mean Q_t (Figure 18, Figure 19). Precipitation had a negative influence on the amount of the mean Q_t which dropped during precipitation events and reached the highest levels during periods of no rain. When the interrupting precipitation event was small, Q_t remained high. The same phenomenon could be seen in 2020 (Figure 19). In the end of May and beginning of June 2020, for example (Figure 19), each precipitation event corresponded with a drop in the mean Q_t.

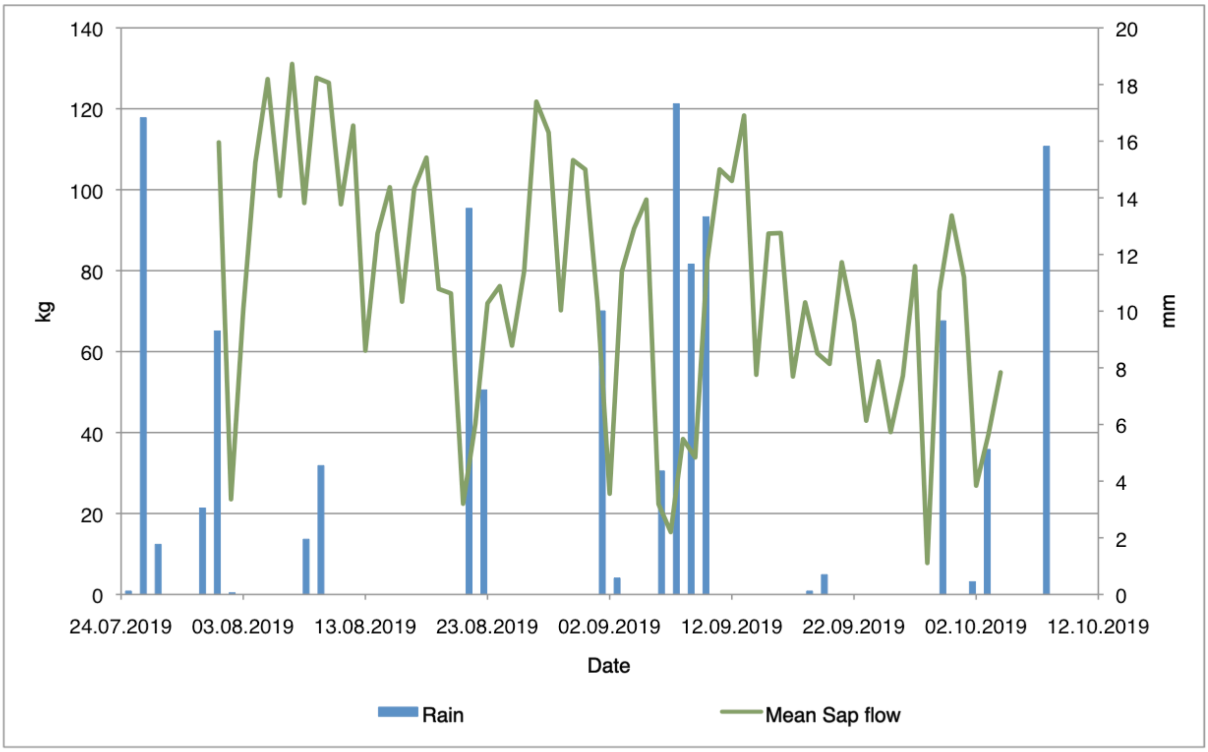


Figure 18: Mean total cumulative sap flow per day (Q_t) of all measurement trees on the LTER site Forest Rosalia and the daily sum of rain amount in the year 2019.

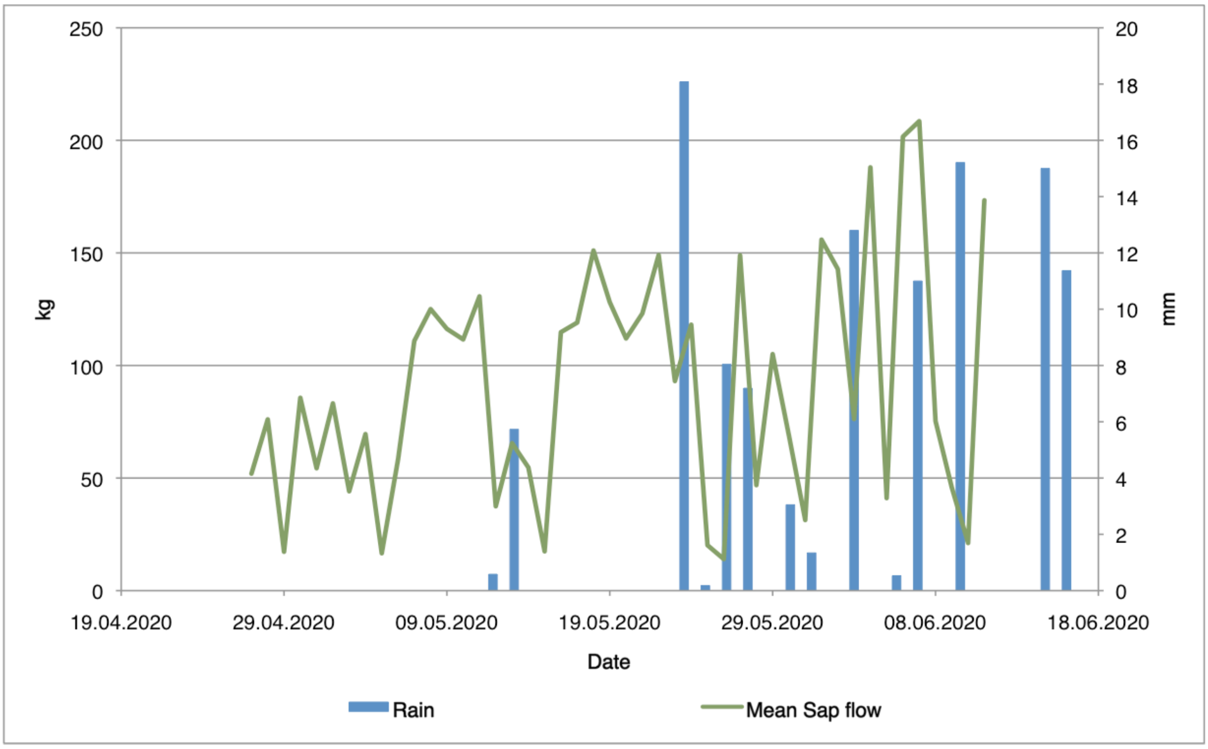


Figure 19: Mean total cumulative sap flow per day (Q_t) of the measurement trees on the LTER site Forest Rosalia and the daily sum of rain amount in the year 2020.

4.3. Comparison between experiment and control trees

4.3.1. 2019

The influenced trees showed significant higher Q_t than the control trees, regardless of whether outliers were excluded, and this difference increased along the observation period. The average Q_t (+/- standard deviation) in 2019 was 108.5 kg for the influenced group (+/- 43.6), or 90.1 kg without outliers (+/- 39.5). Both values were significantly higher than the control group with a Q_t of 50.58 kg (+/- of 23.3). The influenced Q_t was therefore 114.4% higher than the control Q_t, or 78.2% when calculated without outliers. This phenomenon can easily be seen in Figure 20, where the mean Q_t of the influenced trees is most of the time twice as high as the Q_t of the control group. This difference between the treatments increased over time (Figure 21). In the cumulative graph from 2019 we can clearly see that the curves, despite being quite similar in behaviour, drift apart from each other. After the big irrigation event on the 21st of August 2019 (Table 2) a slightly steeper rise in the Q_t of the influenced group and the influenced group without outliers could be noticed as compared to the control group (Figure 21). But such differences could also be detected around the 10th of September where no irrigation took place.

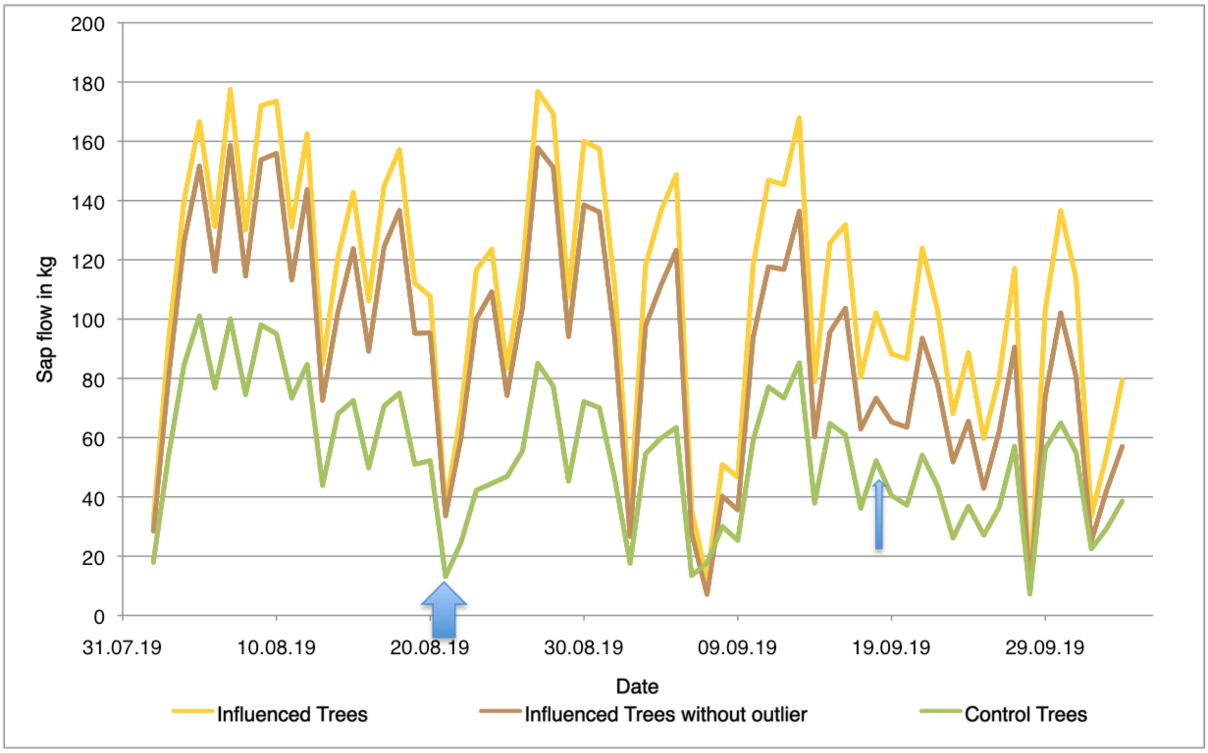


Figure 20: Graphical comparison of treatment group means displayed in the total cumulative sap flow per day (Q_t) in 2019. The blue arrows mark the irrigation dates with 75mm and 150mm water on the 21st of August and 75mm water on the 18th of September.

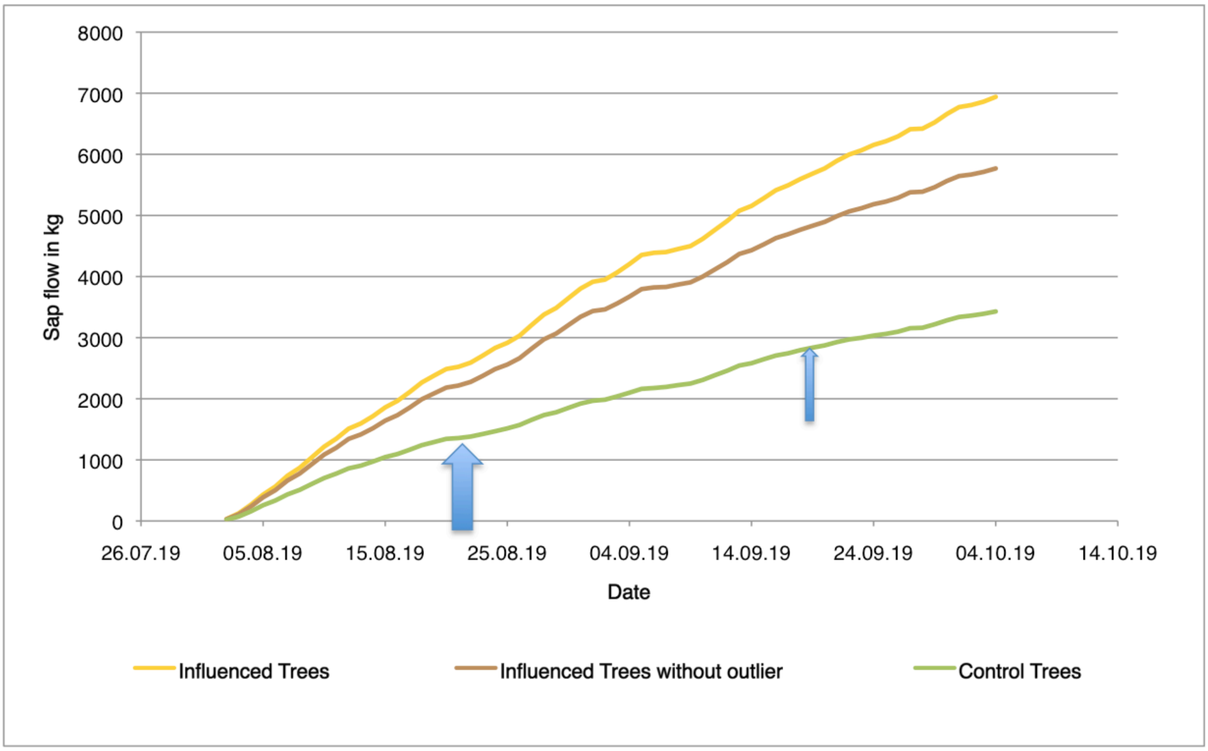


Figure 21:Cumulative display of treatment group means displayed in the total cumulative sap flow per day (Q_t) in 2019. The blue arrows mark the irrigation dates with 75mm and 150mm water on the 21st of August and 75mm water on the 18th of September.

4.3.2. 2020

In 2020 the Q_t of the influenced trees, with and without outliers, was also significantly higher than the control group (Figure 22) and the difference increased during the measurement. The average Q_t (+/- standart deviation) of the influenced group with and without outliers were 138.9 kg (+/- 81.1) and 117.3 kg respectively (+/- 71.4) while the mean control Q_t was 77.7 kg (+/- 43.3). In 2020 the influenced Q_t exceeded the control sap flow about 78.7% or about 51% when calculated without outliers (Figure 22). The cumulative display (Figure 23) shows as in 2019 that the different treatments drifted apart from each other with time. Q_t stagnated after a small irrigation event on the 25th of May 2020, likely due to cloudy or rainy weather. Afterwards, there was a slight increase of the influenced and influenced without outliers compared to the control Q_t. There was no large irrigation event in an uninterrupted period. Thus, it was not possible to capture the reaction of the different trees to a large irrigation event on the cumulative Q_t display.

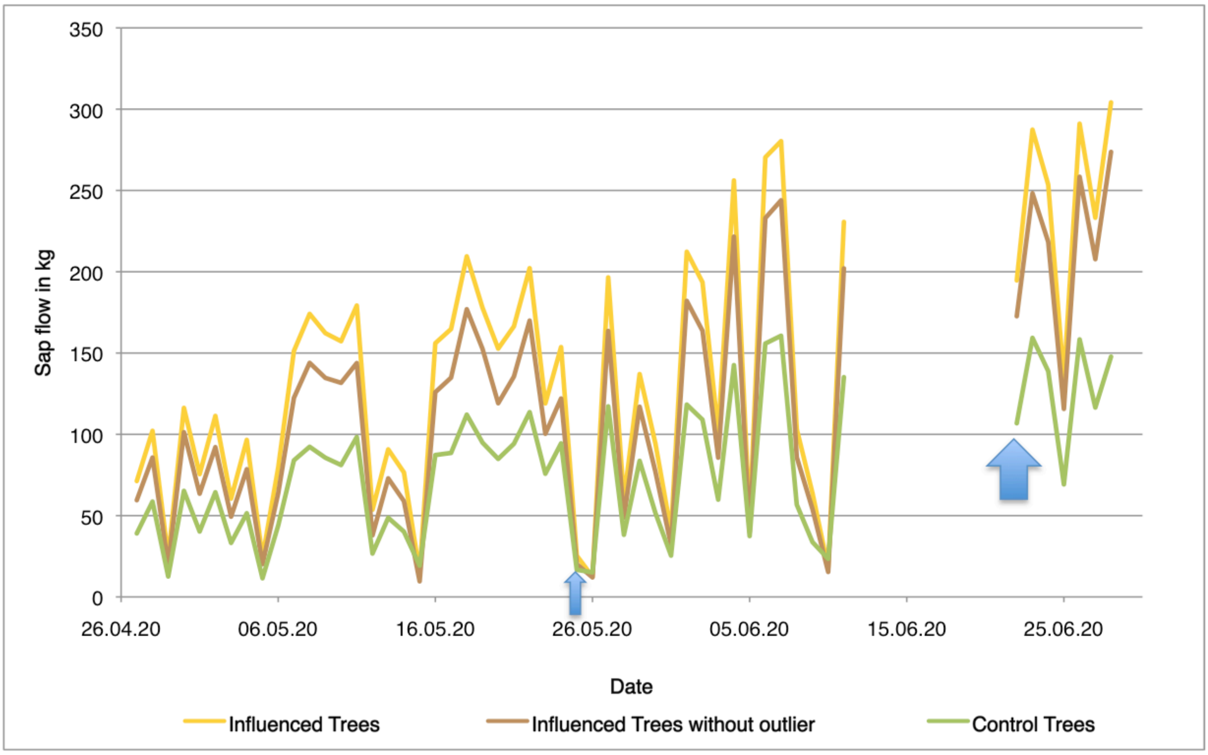


Figure 22: Graphical comparison of treatment group means displayed in the total cumulative sap flow per day (Q_t) in 2020. The blue arrows mark the irrigation dates with 75mm water on the 25th of May and 150mm water on the 22nd of June.

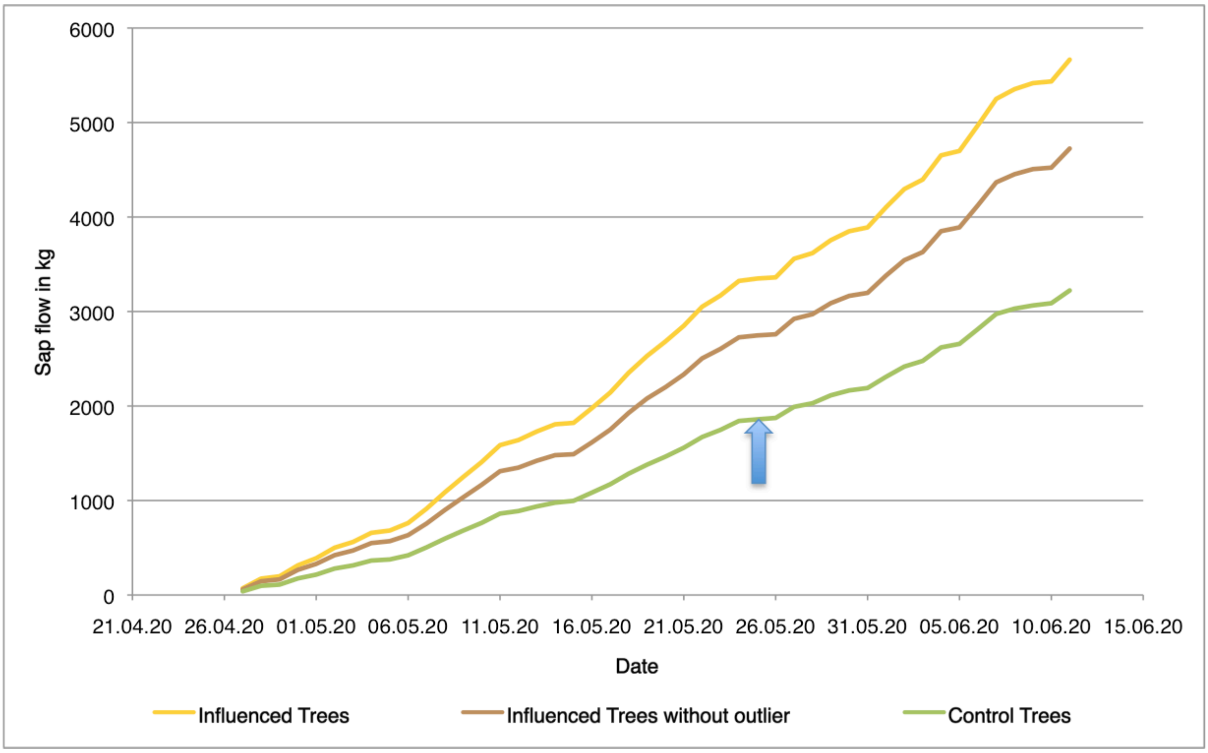


Figure 23:Cumulative display of the treatment group means displayed in the total cumulative sap flow per day (Q_t) in 2020. The blue arrow marks the irrigation date, with 75mm water on the 25th of May.

4.4. Sap flow and soil moisture

4.4.1. Soil moisture content general behaviour

The soil moisture content decreased at first at all measuring points and in all depths, and recovered during a rainy period in the above and the below plots. At the start of the experiment on 27th of April 2020, the soil moisture content was the highest between the plots and in all depths (Figure 24, Figure 25). Until 24th of May, the soil moisture content decreased in all depths in the total measuring site (Figure 24, Figure 25). A small recovery could be seen in the above and the below plots after a small rain event on the 14th of May (Figure 24). Thereof affected were only the soil moisture content in depths of 10 cm (above and below plots) and 20cm (below plots) (Figure 24). The soil moisture content between the plots or in deeper layers showed no sudden increase at this date. Despite this rain event, the soil moisture content decreased further in all plots (Figure 24, Figure 25). With the beginning of a rainy period from 24th of May to 12th of June the soil moisture content recovered in all measuring sites except the one between the plots (Figure 24, Figure 25). In the depth of 10-20 cm the above plots reached the highest soil moisture content, while the below plots reached it in the depth of 30-40 cm.

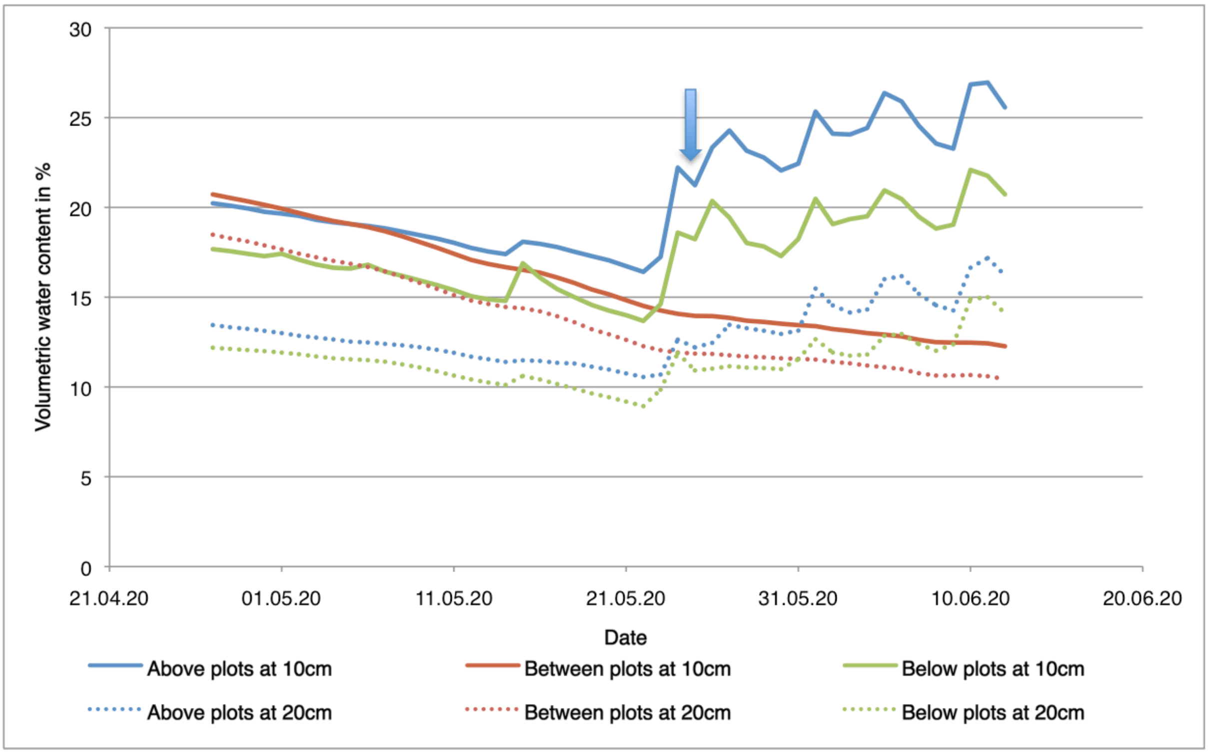


Figure 24: Soil moisture content in 2020 for the depth 10cm and 20cm. The blue arrow mark the irrigation date with 75mm water on the 25th of May.

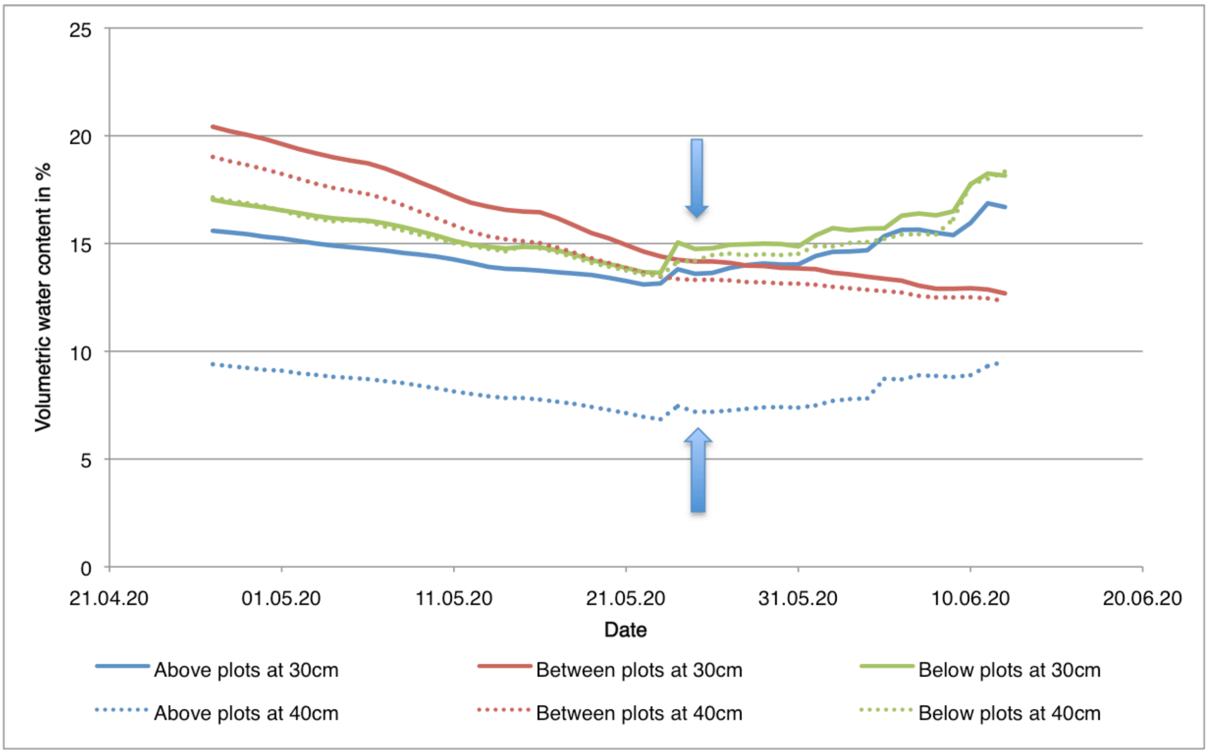


Figure 25: Soil moisture content in 2020 for the depth 30cm and 40cm. The blue arrows mark the irrigation date with 75mm water on the 25th of May.

4.4.2. Correlations between sap flow and soil moisture content or temperature

The correlation between temperature and Q_t was much higher (r = 0.67) than the correlation between the soil moisture and Q_t (0.13-0.36). The correlation between temperature and influenced group with and without outliers did not differ so much with correlation coefficients of 0.67 and 0.68 respectively (Table 3). The control group showed a similar correlation between Q_t and temperature (r= 0.64). Both correlations were significant (p=0.01). Both groups showed a positive, significant correlation with the soil moisture measurements above the plots, and were unaffected by the drought stress experiment. In general, the influenced Q_t without outliers had more significant results than the influenced Q_t data including outliers. The influenced Q_t showed significant correlations mostly with soil moisture values from the above plots with the highest correlation coefficient values compared to the others (coefficient values 0.22-0.36). Soil moisture from in between the plots showed only a weak positive correlation both with and without outliers (coefficient values 0.14-0.19). The plots below the experiment setup also showed a weak positive correlation (values from 0.17- 0.28). The control group showed mostly a significant correlation with the measurements above with correlation coefficients in the range of 0.26-0.31. The Bravais-Pearson Correlation coefficient was lowest at measurements in 10 cm depth (Table 3). The highest significant correlation (p=0.01) was between the soil moisture in 30 cm depth of the plots above and the influenced Q_t without outliers (0.36). The lowest correlation was between the plots below in 40 cm depth and the influenced Q_t data (0.053).

Table 3: Correlation coefficients between the total cumulative sap flow per day (Q_t) and mean daily temperature (MDT) and mean daily soil moisture content (MDSMC) in (10, 20,30, 40) cm depth. np= (Spearman correlation coefficient); otherwise Pearson correlation coefficient * = significant on the level 0.05 (both sides); ** = significant on the level of 0.01 (both sides)

Treatment	**MDSMC Above plots depth in cm**				**MDSMC Between plots depth in cm**				**MDSMC Below plots depth in cm**				**MDT in °C**
	10	20	30	40	10	20	30	40	10	20	30	40	
Influenced Q_t	0,22	0,29*	0,33*	0,31*	0.14	0.14	0.13	0.18	0.17	0.22	0.24	0.05^{np}	0,67**
Influenced Q_t w.o outliers	0.26	0.33*	0.36**	0.34*	0.14	0.15	0.14	0.19	0.21	0.26	0.28*	0.07^{np}	0.68**
Control Q_t	0.26	0.31*	0.31*	0.28*	-	-	-	-	-	-	-	-	0.64**

4.5. Nocturnal sap flow

4.5.1. Mean nocturnal sap flow

The mean Q_n was only a small fraction of the Q_d: 8% in 2019 and 4,7% in 2020. The Q_n ranges between zero and 14 kg while the mean Q_d ranges between zero and 140 kg in 2019 and 250 kg in 2020 (Figure 26, Figure 27). High unexplainable nocturnal values were zeroed in the raw data handling, thus this information about differences between Q_d and Q_n is just an approximation. The graphs (Figure 26, Figure 27) do not show a clear pattern or relationship between nocturnal and diurnal values.

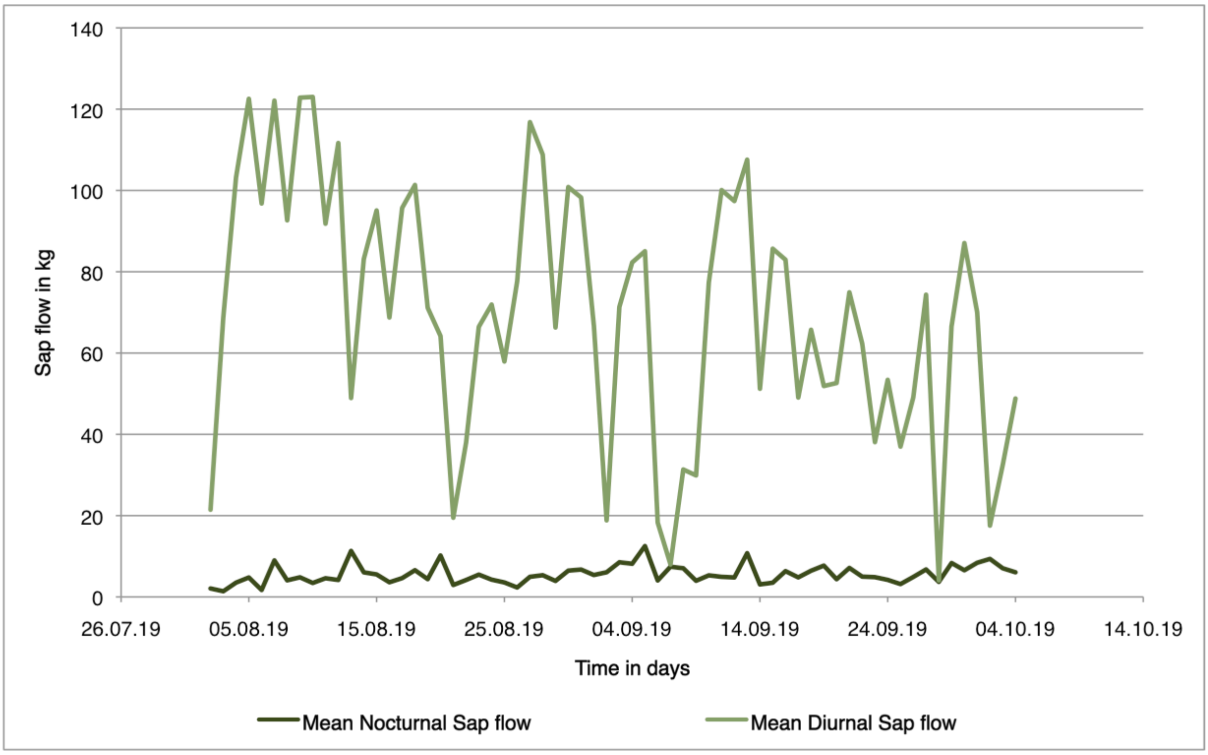


Figure 26: Mean cumulative nocturnal sap flow (Q_n) and mean cumulative diurnal sap flow (Q_d) of all measurement trees on the LTER site Forest Rosalia in 2019

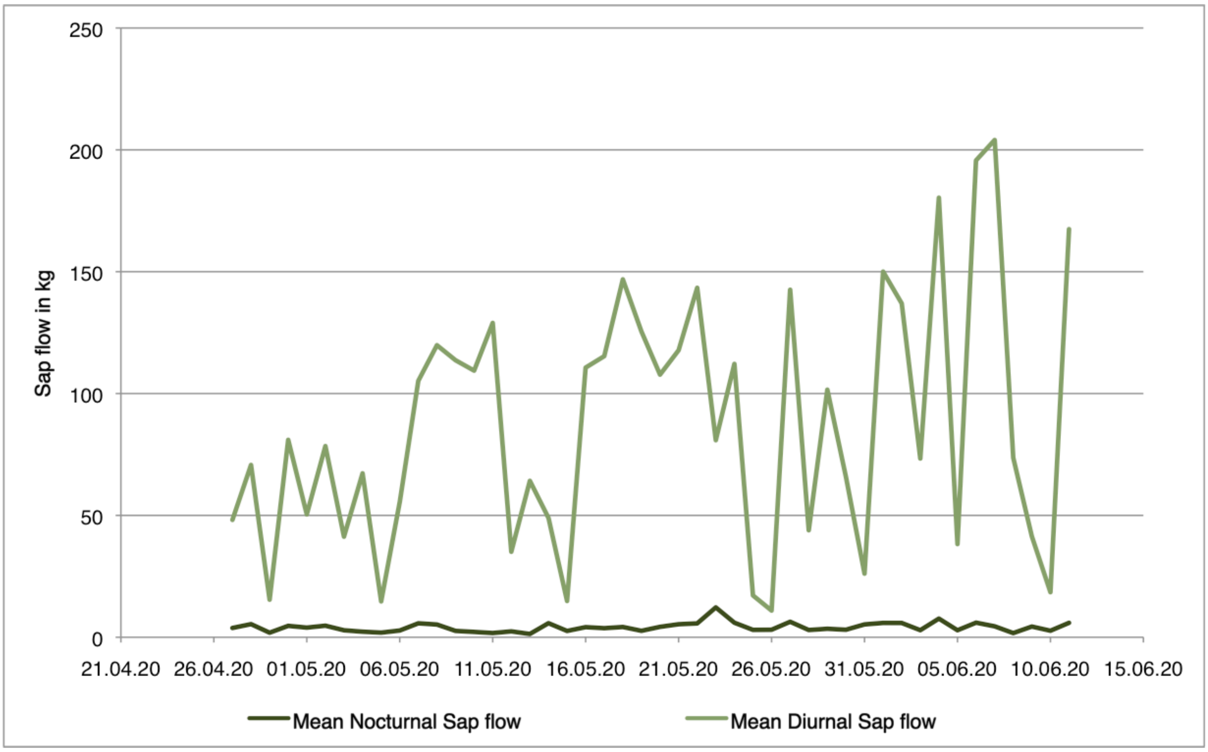


Figure 27: Mean cumulative nocturnal sap flow (Q_n) and mean diurnal sap flow (Q_d) of all measurement trees on the LTER site Forest Rosalia in 2020.

4.5.2. Nocturnal values and precipitation

No significant correlation could be found between the Q_n and the cumulative daily rainfall (R_{cd}), neither did the influenced Q_n differ from the control Q_n. Nocturnal sap flows of the control group showed no relationship with precipitation in 2019 (r= 0.034, p = 0.82) and a non-significant positive trend in 2020(r= 0.317, p-value = 0.08). For the influenced groups, there was an non-significant negative reaction. The influenced Q_n had a negative correlation coefficient of -0.187, (p=0.19) and -0.21 (p=0.14) without outliers in 2019. In 2020 the correlation coefficients of the influenced trees were still non-significant with -0.14 (p=0.45) and -0.13 (p=0.48) without outliers. The Q_n of the influenced and the control group after rain events did not differ significantly. When comparing the treatment group means of the Q_n graphically, no clear tendency is revealed between 2019 (Figure 28) and 2020 (Figure 29). The Mann-Whitney-U test also showed no differences (significance level of 0.583 in 2019 and of 0.387 in 2020), therefore, the hypothesis (H_0) that means are alike could not be rejected.

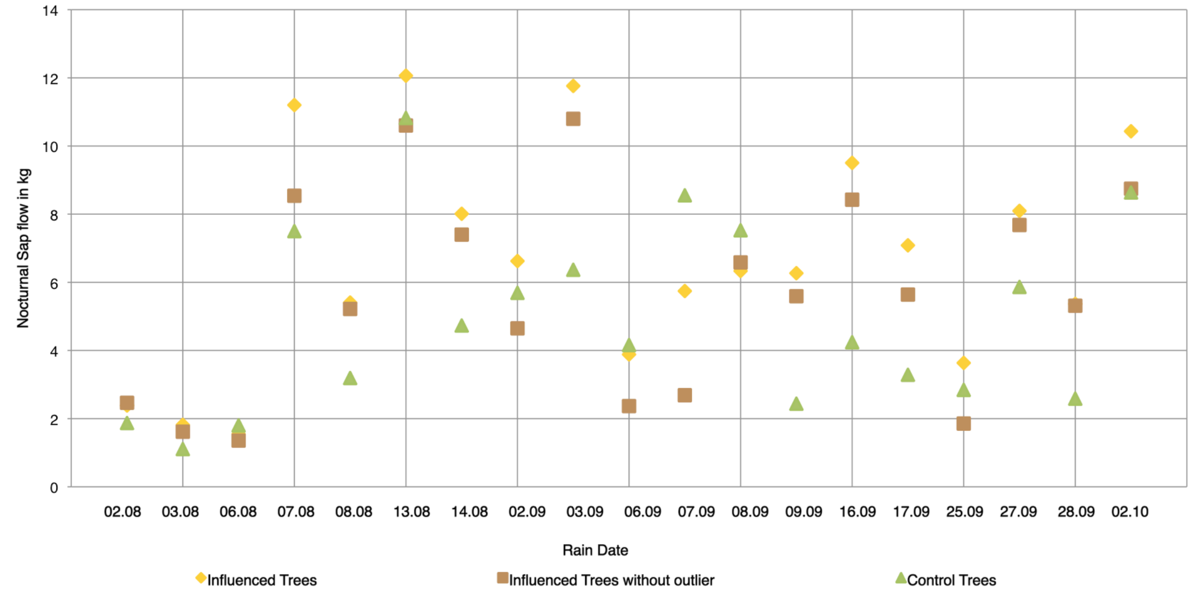


Figure 28: Treatment group means displayed in the cumulative nocturnal sap flow (Q_n) of the measurement trees on the LTER site Forest Rosalia in 2019

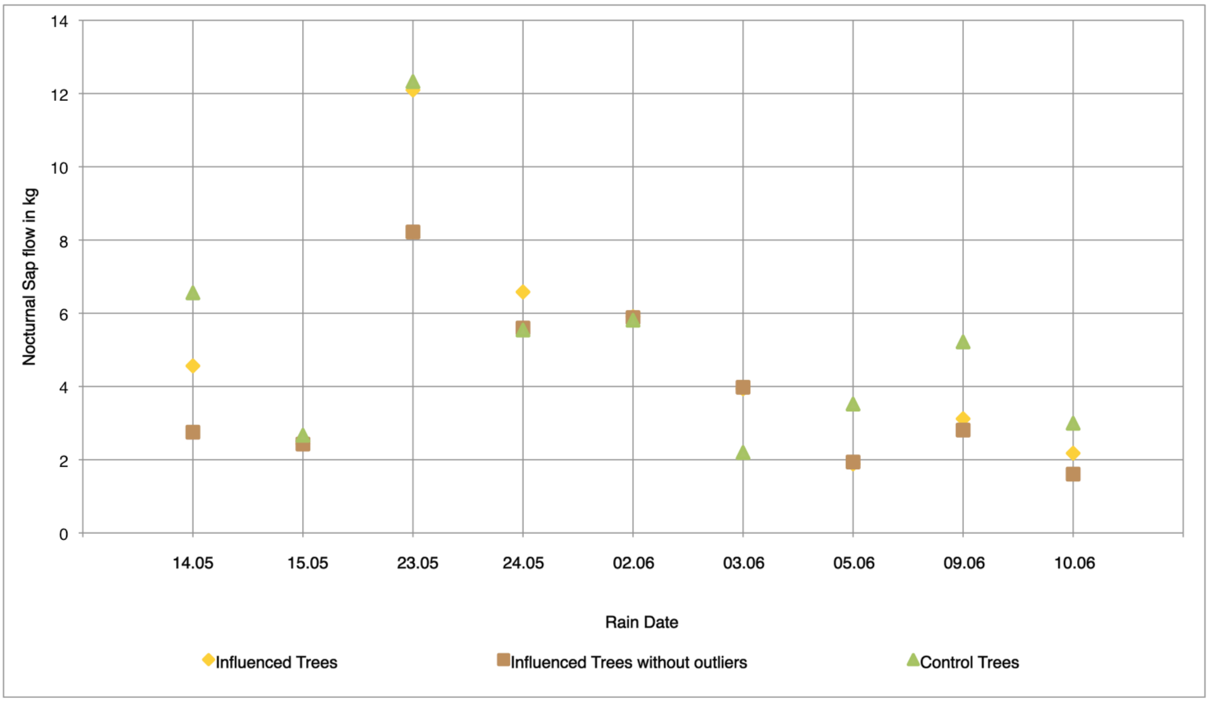


Figure 29: Treatment group means displayed in the cumulative nocturnal sap flow (Q_n) of the measurement trees on the LTER site Forest Rosalia in 2020

4.5.3. Nocturnal values and irrigation

The graphical and statistical analyses distinguish Q_n after irrigation values. The graphical interpretation of Q_n after irrigation events shows a slight difference, where the influenced trees tend to show higher values (Figure 30). However, that trend could not be proven by the Mann-Whitney-U test. The test levels were not significant and H_0, the means are alike as to be valid. But the significant levels were, with 0.065 with and 0.18 without outliers, close to significant level. Due to the total sample size of 12 and the large variability, the analysis was prone to result in non-significant outcomes. If a significant outcome were assumed, the effect of the difference between the control group and the experiment with outliers would be medium (r=0,160).

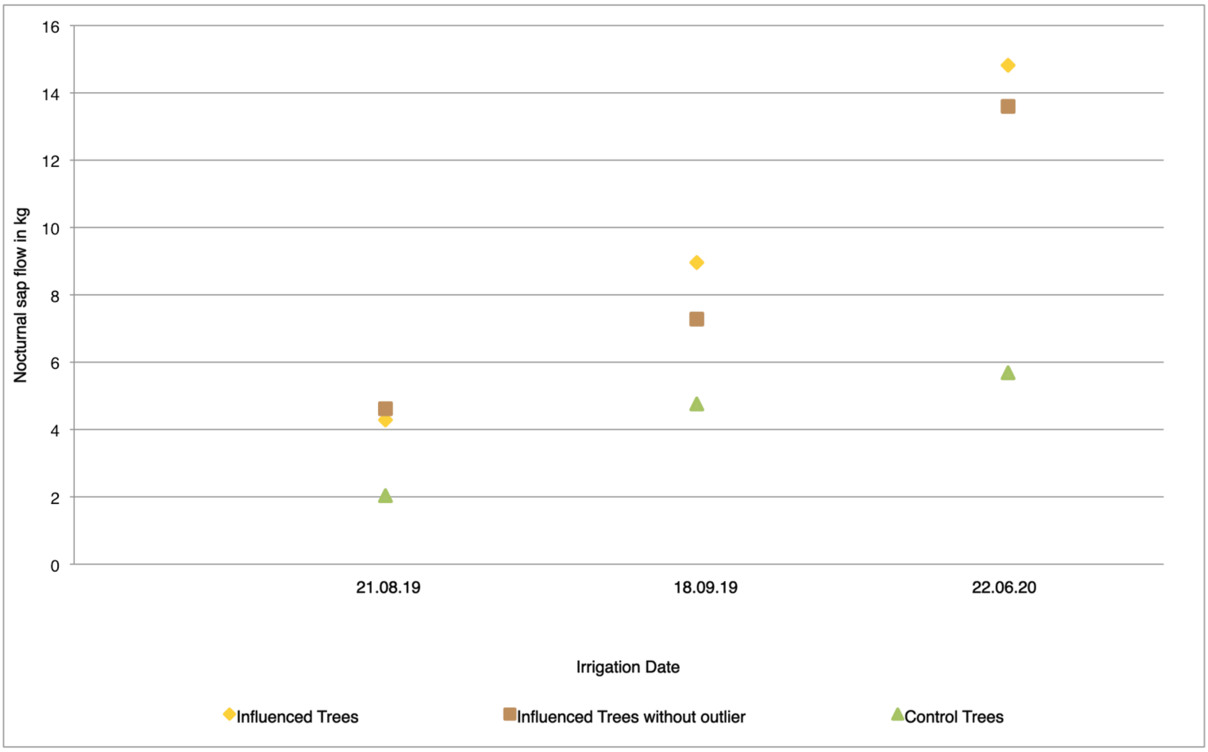


Figure 30:Treatment group means displayed in the cumulative nocturnal sap flow (Q_n) of the measurement trees on the LTER site Forest Rosalia

5. Discussion

The main aim of this thesis is to find out if the DRAIN experiment setup introduced drought stress in trees and if valuable information about drought stress behaviour of beech could be gained. Beech is one of the most wide-spread tree species in Europe (Leuschner, 2020) and its response to climate change has important ecological as well as economical consequences (Chakraborty et al., 2017). Recent studies discovered that the anticipated increase in temperature will reduce the productivity of beech and will limit the beech distribution in Europe (Martinez del Castillo et al., 2022). However, beech is more sensitive to changes in precipitations than temperature (Gennaretti et al., 2020). Thus, beech could cope with higher temperatures with increased precipitation amounts (Martinez del Castillo et al., 2022). However the climate change scenarios predict an increase in extreme weather events including severe droughts for Europe (Grillakis, 2019; IPCC, 2013; Lindner et al., 2010). Beech is rather vulnerable to drought stress (Leuschner, 2020; Rubio-Cuadrado et al., 2018). Walthert et al. (2021) discovered the different stages of beech related drought stress from early defoliation and to crown dieback due to embolism. Those drought vulnerable characteristics are threatening beeches with ongoing climate change. The necessity to investigate beech under drought stress is therefore high, and a better understanding of response behaviour and the general vulnerability to drought is needed to estimate the ecological as well as economical consequences. As the DRAIN experiment is introducing soil drought and shows high similarities to a throughfall-exclusion-experiment, information about beech reaction to soil drought could be gained.

5.1. Discussion of the hypotheses

5.1.1. Regarding aim 1

Investigate the effect of the DRAIN infrastructure on the sap flow of beech trees.

The first hypothesis assumed that the experiment is able to introduce drought stress in the so-called influenced trees; based on the data, it has to be clearly dismissed, as reduction of the sap flow as considered in the hypothesis was found. The reduction of sap flow was the tested indicator for water limitations in the influenced trees compared to the control trees. But the influenced Q_t was in 2019 about 114,4% or 78,2% higher than the control Q_t, and in 2020 about 78,7% or 51%, if calculated with or without outliers. This phenomenon is not supported by other drought stress investigations on beech trees (Dietrich and Kahmen, 2019; Leuzinger et al., 2005).

The second hypothesis stated that Q_t of influenced trees would decrease more steeply in the course of the experiment in a monthly comparison. Due to unexpected data gaps, we could not cover one complete vegetation period, so that this hypothesis could be tested appropriately. As a consequence, we can only evaluate the temporal dynamics of the sap flow during one spring (2020) and one late summer (2019). The available data indicate that this hypothesis is also not likely to come true, considering that the influenced trees show higher Q_t values than the control trees. Comparing the two treatments in cumulative graphs (Figure 21, Figure 23) shows that the treatments are drifting apart. However, this is either through an increase in the Q_t of the influenced trees or a decrease of the Q_t of the control trees for both years. Therefore it is more likely that both treatments followed the seasonal pattern, of an increase of the sap flow in spring 2020 (Figure 8) and a decrease in autumn of 2019 (Figure 7).

5.1.2. Regarding aim 2

Understand the relationship between sap flow and soil moisture

The third hypothesis, stated that the soil moisture in the experimental area would be correlated with sap flow of the influenced trees. It could not be confirmed by the results either. No significant correlation could be found between the soil moisture content measurements between plots and the influenced trees. The correlation coefficients of the mean daily soil moisture content (MDSMC) between the plots and the influenced Q_t were the lowest of all MDSMC correlations (Table 3). The influenced Q_t did also not correlate with below plots MDSMC, only one significant correlation could be found between the soil moisture below the plots and the Q_t of influenced trees without outliers at 30cm depth. In this depth the below plot soil moisture was the highest of all three depths measured (Figure 25). In the depths 20, 30 and 40 cm all measurement groups showed significant positive correlations with the MDSMC of above plots (Table 3). Such behaviour was expected for the control trees, which grow above the experiment and should not be influenced. The influenced trees showed significant positive correlation with the soil moisture content in areas not affected by the experiment, which further contradicts the second hypothesis.

The forth hypothesis, that the influenced trees become stronger correlated to soil water content than to temperature in the course of the experiment could due to an unforeseen lack of data not be tested completely. Data that could be acquired indicate that this hypothesis too has to be rejected. As stated above the influenced trees did not correlate with the experiment soil moisture content at all. The correlation between the temperature and Q_t of the influenced trees was significant and their correlation coefficients of 0,67 or 0,68, depending if measured with or without outliers, were very high (Table 3). As expected, the control trees showed higher temperature correlations as well. Water was therefore for none of the groups the limiting factor.

5.1.3. Regarding aim 3

Investigate the nocturnal sap flow behaviour after rain events and artificial irrigation events

The outcomes of the nocturnal sap flow investigation show that the DRAIN experiment infrastructure did neither limit the influenced trees in their access of rain water nor exclude the control trees from the irrigation water. Hypothesis five, that the nocturnal sap flow (Q_n) of the influenced trees is significantly lower than the ones of the control trees and that the influenced trees have a negative and the control trees a positive correlation with the rain amount of the previous day, could not be confirmed by the data. There was no prove that the influenced trees get significant less water after precipitation events. As the Q_n values of the treatments after rain events were not significantly different. So the data showed that the influenced trees were not excluded from natural precipitation by the DRAIN infrastructure. The same conclusion can be drawn from the results of the correlation between Q_n and the rain amount of the previous day (R_{cd}). Indeed did the control group showed a positive correlation coefficient between Q_n and precipitation and the influenced group showed a negative correlation as expected, but these findings were not significant. Albeit the correlations were non-significant these results were quite interesting. In case the influenced trees would not be affected at all by the rain-out-shelters of the experiment, their Q_n should had shown a positive correlation with the R_{cd} as the control trees had. However, those results might be explained through the behaviour of the Q_n to the VPD. During precipitation events, the VPD drops, but not necessarily the Q_n which is positively affected by precipitation as well, as the trees use the water to fill up their inner reservoirs (Wu et al., 2020). When trees do not suffer water limitations at all, as the results suggest for the influenced trees, they do not have to fill up their inner reservoirs more than the daily consumption (Forster, 2014). Their Q_n drops according to the VPD, as well as according on the diurnal sap flow (Wu et al., 2020).

Also the sixth hypothesis, that the influenced trees have higher Q_n after irrigation events and show a positive correlation with the irrigation amount could not be confirmed by the data. Through the unexpected lack of data I could not investigate the correlation of the irrigation amount and the Q_n of the influenced trees. The statistical comparison analysis between the treatments did not reveal significant higher Q_n values in the influenced trees than in the control trees. So there is no confirmation that the control trees are completely excluded from the irrigation. However, the sample size was very small and the results prone to be non significant. The graphical interpretation (Figure 30) would suggest that the influenced Q_n is higher in the night after irrigation. Further investigations with a lager data set would be necessary to test this hypothesis satisfactory.

However unexpected nocturnal sap flow behaviour could be detected in the course of this study. When searching among the nocturnal sap flow for unexplainable high nocturnal values in nights with VPD smaller than 0,10kP (Forster, 2014; Wu et al., 2020), I became aware of some irregular slow decreasing nocturnal sap flow pattern resulting in high nocturnal values in the later halves of the nights, as displayed in the results (Figure 10). This phenomenon often happened in a row of nights which indicated that there might be a collective reason behind these results. Coincidentally, I figured out that this sort of high nocturnal values often occurred around full moon. Moonlight is known to have an effect on primary photosynthetic machinery in coffee plants (Breitler et al., 2020), and might have in beech. Limitations of the experiment and the scope of this master thesis did not allow a deeper investigation to test this theory. Full moon investigations are quite tricky to do, as the rise of the moon is varying and cloudy weather could disturb the investigations (Breitler et al., 2020). A deeper investigation could enlighten if this phenomenon was just coincidence or if beech trees are affected by the full moon.

5.2. Possible reasons for the absence of drought stress in the beech trees

The obvious question to ask is: Why did the influenced trees not show drought symptoms, e.g. by reducing sap flow, even if they were in the area of the influence of the drought plots? The reason for these unexpected results was not the main focus of my work, but I concluded a few assumptions from my results.

5.2.1. Access to deep water reservoirs

One major assumption could be, that the DRAIN experiment could introduce a certain level of drought stress in the beech trees, but the beech could cope with it, as beech is able to use deep water reservoirs (Granier et al., 2000; Kovalčíková et al., 2012; Magh et al., 2020). Beeches have the highest root density in the top 20 cm roots (Magh et al., 2020), however, small root occurrences have been found down to 1.5 m (Granier et al., 2000). Even when less than 5% of the fine root biomass is located below 1m (Leuschner, 2020), it can bring a beech through droughts (Walthert et al., 2021)When water is available again in the topsoil layers beeches quickly change their water consumption behaviour again (Magh et al., 2020). The influenced trees in the experiment setup could have used their access to such deep-water sources. A similar behaviour was documented by Walthert et al. (2021), who found beech trees on deep soils less vulnerable to drought. However, this does not explain why the Q_t of the control trees was significant lower than the Q_t of the influenced trees. They would also use their deep root system, if water in the top layers was limited. Also, the found correlation of the Q_t of influenced trees and the measured soil water content above the experiment setup contradict this line of argumentation.

5.2.2. Water supply through the DRAIN experiment setup

Another reasonable explanation is that the influenced trees might got more water than the control trees through the DRAIN experiment. This is supported by the fact that the Q_t of the influenced trees was significantly higher than the Q_t of control trees. There are two possible explanations, which are not mutually exclusive. First, the influenced trees did get a greater deal of water through irrigation than the control trees while not being excluded enough from rainfall. The slope of the hill logically supports this assumption. The insignificant correlations of the Q_n after precipitation fit as well. But the Q_n of the treatments did not differ after irrigations. Would the Q_n of the influenced trees after irrigation be significantly higher than the Q_n of control trees this assumption would be out of doubt. Here, we should not neglect the fact that this hypothesis was tested with a very small data set and was prone to be insignificant. The graphical comparison of the two treatments Q_n after irrigations (Figure 30) supports this explanation. Therefore, more data is required to determine whether the influenced trees get more water from the irrigation than the control trees or not.

Secondly, the influenced trees got more water from precipitation through discharge coming from rain-out-shelters. This is plausible because roof water was not collected but went down the slope and ran directly to the influenced trees beneath. A rain collection could prevent this phenomenon but was not installed initially as this was not necessary for the forest soil experiment to work. If this assumption was true, the influenced trees would get more water than would naturally fall in their root area This could explain the tremendous outlier behaviour of the influenced tree 1.3 which grows directly beneath a roof end. The positive correlation between sap flow and soil moisture content from above the plots would also fit very well: The time when the soil moisture content changes is the same for the influenced trees as for control trees but the amount of available soil moisture content would be different. To fully validate this theory further measurements of soil moisture content directly at the influenced trees are needed. However, the shown positive correlation between influenced trees and soil moisture content in 30 cm depth (Table 3), which was the location with the highest soil moisture content amongst the deeper layers (20-40cm) (Figure 24, Figure 25), reinforce the theory. It is thus likely that the influenced trees were additionally irrigated by the experiment setup instead of being excluded from precipitation.

5.3. Possible future options to investigate beech drought stress on the DRAIN experiment

The second part of the main research aim was, if valuable information about beech behaviour under drought stress could be gained. This question cannot be answered currently. Drought stress in mature trees could be measured in two ways as explained in the introduction, either by a throughfall-exclusion-experiment or by waiting for a natural drought to occur. Therefore I discuss the possibilities of either, alterations in the experiment setup or investigations under natural drought.

5.3.1. Possible alterations on the existing DRAIN experiment

If the experiment of drying and rewetting forest soil should ever be used to investigate drought stress on trees there are some fundamental improvements necessary in advance. First, a rain collection must be installed to prevent that roof water irrigates the influenced trees additionally. The success of this measure needs to be examined by testing both, the general sap flow behaviour of the influenced trees and their sap flow after rain events. Secondly, it will be necessary to test if the influenced trees can use the irrigation water better than the control trees. Third, soil moisture content should be measured in greater depth as well, up to 0,8m depth, as Magh et al. (2020) did. This would take into account that beech trees use deeper water reservoirs (Leuschner, 2020; Leuzinger et al., 2005; Magh et al., 2020). An effective operation would be to enlarge the roof area, and to create a proper throughfall-exclusion-experiments for trees. However, this would be very expensive (Cranston et al., 2020) and it is not realistic to expect that valuable resources are put into the modification of an already good working soil drought experiment to fullfill a not foreseen purpose. However, the new, cheaper and more efficient throughfall-exclusion technique for mature trees by Cranston et al. (2020) could be used in order to obtain valuable information about trees under drought stress.

5.3.2. Investigation on natural droughts on beech trees

If the effects of a natural drought should be investigated on the site, the now control trees would suffer under the natural water limiting conditions while the now influenced trees would be additionally irrigated (as discussed above). Such an experiment setup can be found by many natural drought examine studies (Kovalčíková et al., 2012; Nalevanková et al., 2018; Sitková et al., 2014). Information about behaviour of trees under drought stress might be gained. This would also require previous investigations of the extent to which the now control trees are affected by the irrigations of the experiment. The trees are probably not much affected as the experiment site is sloped and the trees are growing above of the experiment. Also, Kovalčíková et al. (2012) found that even irrigations on purpose of relieving drought stress do not necessarily influence the sap flow behaviour of drought induced trees.

Unfortunately, only limited information could be gained about drought for the years 2019 and 2020. July and August of 2019 were dry and hot, creating the second hottest summer since start of the measurement (Chimani et al., 2020). However, with 1st of August, the sap flow measurements started too late and the soil moisture content measurement were not operative until October. In 2020, the data was very limited due to a multitude of power breakdowns. Data of soil moisture content and sap flow measurements available were only available for May 2020. The precipitation abundance of May is important for beech growth as (Michelot et al., 2012) explained. There was an uncommon drought from January 2020 to April 2020 which ended with May (Hiebl et al., 2021). In general, data from June and July would be of greatest interest as beech is most sensitive to the precipitation in these months (Gennaretti et al., 2020), but data is missing. Even with available data, however, no information about drought behaviour could be obtained because the whole summer of 2020 was, despite of being warm, also very wet (Hiebl et al., 2021).

5.3.3. Further research opportunities

The manipulation to increase frequency and intensity of drought and rewetting events has worked well on the forest soil, which was its foreseen domain. Therfore the DRAIN experiment offers tremendous opportunities to investigate drought effects on soil microbes (Liu et al., 2019), soil hydrophobicity (Schwen et al., 2015), nutrient (Leitner, 2017) or green house gas fluxes (Díaz-Pinés et al., 2018) as to mention a few. However, the data suggest that the setup was not able to induce the expected drought response in the so-called influenced trees. I therefore deduce that the soil experiment is not able to limit the surrounding trees in their water consumption. On the contrary the observed data responses pointing out to the opposite direction, that the DRAIN experiment is enhancing the amount of available water for the trees nearby. The DRAIN experiment setup can therefore not be used as throughfall-exclusion experiment for trees in the current setting and would need some lager alterations. To check if the experiment setting could investigate drought stress under a natural drought a lot more data, which were limited through a row of power cuts failured the sensors, is required. In case either setup improvements or natural drought provoked water limitations, there is plenty of research about beech drought behaviour that can be investigated. Ozone uptake, for example, as all relevant environment data, as temperature, VPD, light and soil moisture are already measured. The sap flow measurements could help to validate the findings (Braun et al., 2010). The findings could also be compared to the behaviour of other tree species. There was another drought stress experiment done in the Rosalia forest with focus on spruce (Netherer et al., 2015). A comparison would give a possibility to investigate the different drought responses of mature trees of these two species. Investigations in nocturnal sap flow behaviour during drought could be investigated, as nocturnal sap flow is in general insufficiently probed (Forster, 2014).

6. Conclusion

Despite the huge similarities of the soil drought experiment to a throughfall-exclusion-experiment on trees, the current experiment setting was not able to introduce drought stress in the trees. No reduction of the sap flow in the experiment trees nor a correlation between sap flow and the experiment soil water content were measured. Also, the nocturnal values after rain or irrigation events did not differ between the experiment and the control group.

There were two major theories for the inefficacy of the experiment setup. First, that the experiment trees got more water from the experiment, possibly from the irrigation or from the roofs. This would explain the significant higher sap flow rates of the experiment trees. Secondly, the ability of beeches to use water in deep layers could also prevent them from suffering drought stress.

I consider some modifications need to be done before the forest soil drought and rewetting experiment would work for trees as well. Rainwater should be collected to prevent rainwater from the roofs of being led to the experiment trees; roofs could be enlarged to obtain a real throughfall-exclusion-experiment; or new technique such as developed by (Cranston et al., 2020) could be used. Alternatively, the experiment could be used to investigate the drought stress behaviour under a naturally occurring drought. Thereby the so far unaffected control trees would suffer water limitations while the trees influenced by the experiment could count as the additionally irrigated control group. This would of course inquire also further testing, especially after precipitation or irrigation events. Unfortunate circumstances, like power break downs causing an unexpected lack of data or non-occurrence of drought during the measuring period inhibited the investigations on natural drought related behaviour in this study. After successful alterations of the experiment setup or naturally occurring drought, valuable information of beech sap flow behaviour during drought stress or full moon may be obtained in the future.

References

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D., Hogg, E.H. (Ted), Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.-H., Allard, G., Running, S.W., Semerci, A., Cobb, N., 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For. Ecol. Manag. 259, 660–684. https://doi.org/10.1016/j.foreco.2009.09.001

Aranda, I., Gil, L., Pardos, J.A., 2005. Seasonal changes in apparent hydraulic conductance and their implications for water use of European beech (Fagus sylvatica L.) and sessile oak [Quercus petraea (Matt.) Liebl] in South Europe. Plant Ecol. 179, 155–167. https://doi.org/10.1007/s11258-004-7007-1

Arend, M., Sever, K., Pflug, E., Gessler, A., Schaub, M., 2016. Seasonal photosynthetic response of European beech to severe summer drought: Limitation, recovery and post-drought stimulation. Agric. For. Meteorol. 220, 83–89. https://doi.org/10.1016/j.agrformet.2016.01.011

Bamberg, G., Baur, F., 2001. Statistik, 11., überarb. Aufl. ed, Oldenbourgs Lehr- und Handbücher der Wirtschafts- und Sozialwissenschaften. Oldenbourg, München Wien.

Benesch, T., Schuch, K., 2009. Der Schlüssel zur Statistik: Datenbeurteilung mithilfe von SPSS, 2., überarb. Aufl. ed, Manual. Facultas.Wuv, Wien.

Bennett, A.C., McDowell, N.G., Allen, C.D., Anderson-Teixeira, K.J., 2015. Larger trees suffer most during drought in forests worldwide. Nat. Plants 1, 15139. https://doi.org/10.1038/nplants.2015.139

Betsch, P., Bonal, D., Breda, N., Montpied, P., Peiffer, M., Tuzet, A., Granier, A., 2011. Drought effects on water relations in beech: The contribution of exchangeable water reservoirs. Agric. For. Meteorol. 151, 531–543. https://doi.org/10.1016/j.agrformet.2010.12.008

Blöschl, G., Blaschke, A.P., Haslinger, K., Hofstätter, M., Parajka, J., Salinas, J., Schöner, W., 2018. Auswirkungen der Klimaänderung auf Österreichs Wasserwirtschaft – ein aktualisierter Statusbericht. Österr. Wasser- Abfallwirtsch. 70, 462–473. https://doi.org/10.1007/s00506-018-0498-0

Bosela, M., Štefančík, I., Marčiš, P., Rubio-Cuadrado, Á., Lukac, M., 2021. Thinning decreases above-ground biomass increment in central European beech forests but does not change individual tree resistance to climate events. Agric. For. Meteorol. 306, 108441. https://doi.org/10.1016/j.agrformet.2021.108441

Braun, S., Schindler, C., Leuzinger, S., 2010. Use of sap flow measurements to validate stomatal functions for mature beech (Fagus sylvatica) in view of ozone uptake calculations. Environ. Pollut. 158, 2954–2963. https://doi.org/10.1016/j.envpol.2010.05.028

Breitler, J.-C., Djerrab, D., Leran, S., Toniutti, L., Guittin, C., Severac, D., Pratlong, M., Dereeper, A., Etienne, H., Bertrand, B., 2020. Full moonlight-induced circadian clock entrainment in Coffea arabica. BMC Plant Biol. 20, 24. https://doi.org/10.1186/s12870-020-2238-4

Campbell, G.S., Norman, J.M., 1998. Introduction to environmental biophysics, 2nd ed. ed. Springer, New York.

Chakraborty, T., Saha, S., Matzarakis, A., Reif, A., 2017. Influence of multiple biotic and abiotic factors on the crown die-back of European beech trees at their drought limit. Flora 229, 58–70. https://doi.org/10.1016/j.flora.2017.02.012

Chen, Z., Zhang, Z., Sun, G., Chen, L., Xu, H., Chen, S., 2020. Biophysical controls on nocturnal sap flow in plantation forests in a semi-arid region of northern China. Agric. For. Meteorol. 284, 107904. https://doi.org/10.1016/j.agrformet.2020.107904

Chimani, B., Ganekind, M., Hiebl, J., Höfler, A., Orlik, A., 2020. Österreichisches Klimabulletin Jahr 2019.

Choat, B., Brodribb, T.J., Brodersen, C.R., Duursma, R.A., López, R., Medlyn, B.E., 2018. Triggers of tree mortality under drought. Nature 558, 531–539. https://doi.org/10.1038/s41586-018-0240-x

Cranston, B.M., Powers, B.F., Macinnis‐Ng, C., 2020. Inexpensive throughfall exclusion experiment for single large trees. Appl. Plant Sci. 8. https://doi.org/10.1002/aps3.11325

Creek, D., Blackman, C.J., Brodribb, T.J., Choat, B., Tissue, D.T., 2018. Coordination between leaf, stem, and root hydraulics and gas exchange in three arid-zone angiosperms during severe drought and recovery: Coordination between hydraulics and gas exchange during drought and recovery. Plant Cell Environ. 41, 2869–2881. https://doi.org/10.1111/pce.13418

Díaz-Pinés, E., Leitner, S., Keiblinger, K.M., Saronjic, N., Zimmermann, M., Zechmeister-Boltenstern, S., 2018. Impact of droughts and heavy rain on greenhouse gas emissions and soil microbial communities, ACRP Project (Final Report No. B368577), ACRP Project. BOKU, Wien.

Dietrich, L., Kahmen, A., 2019. Water relations of drought-stressed temperate trees benefit from short drought-intermitting rainfall events. Agric. For. Meteorol. 265, 70–77. https://doi.org/10.1016/j.agrformet.2018.11.012

DroughtNet, n.d. Drought-Net | [WWW Document]. URL https://drought-net.colostate.edu/ (accessed 3.11.22).

Eid, M., Gollwitzer, M., Schmitt, M., 2013. Statistik und Forschungsmethoden: Lehrbuch ; mit Online-Materialien, 3., korrigierte Aufl. ed. Beltz, Weinheim Basel.

Eilmann, B., Rigling, A., 2012. Tree-growth analyses to estimate tree species' drought tolerance. Tree Physiol. 32, 178–187. https://doi.org/10.1093/treephys/tps004

Fagerland, M.W., Sandvik, L., 2009. Performance of five two-sample location tests for skewed distributions with unequal variances. Contemp. Clin. Trials 30, 490–496. https://doi.org/10.1016/j.cct.2009.06.007

Filipović, V., Weninger, T., Filipović, L., Schwen, A., Bristow, K.L., Zechmeister-Boltenstern, S., Leitner, S., 2018. Inverse estimation of soil hydraulic properties and water repellency following artificially induced drought stress. J. Hydrol. Hydromech. 66, 170–180. https://doi.org/10.2478/johh-2018-0002

Flo, V., Martinez-Vilalta, J., Steppe, K., Schuldt, B., Poyatos, R., 2019. A synthesis of bias and uncertainty in sap flow methods. Agric. For. Meteorol. 271, 362–374. https://doi.org/10.1016/j.agrformet.2019.03.012

Förster, A., Culmsee, H., Leuschner, C., 2021. Thinned northern German Scots pine forests have a low carbon storage and uptake potential in comparison to naturally developing beech forests. For. Ecol. Manag. 479, 118575. https://doi.org/10.1016/j.foreco.2020.118575

Forster, M.A., 2014. How significant is nocturnal sap flow? Tree Physiol. 34, 757–765. https://doi.org/10.1093/treephys/tpu051

Fürst, J., 2020. Forsthydrologisches Versuchsgebiet Rosalia::Institut für Hydrologie und Wasserwirtschaft (HyWa)::Department für Wasser-Atmosphäre-Umwelt (WAU)::BOKU [WWW Document]. URL https://boku.ac.at/wau/hywa/forschungsstandorte/forsthydrologisches-versuchsgebiet-rosalia (accessed 1.23.22).

Gasch, J., Díaz-Pinés, E., 2021. Rosalia Lehrforst AUSTRIA - Meteorological Data 2001-2020. https://doi.org/10.23728/B2SHARE.681966BE29A34F3EBC6015AC255AB143

Gasch, J., Díaz-Pinés, E., 2019. LTER_site_data_from_EURO-CORDEX-RCMs_rel1_77c127c4-2ebe-453b-b5af-61858ff02e31. https://doi.org/10.23728/B2SHARE.3A43E4D6EAD04C54867197E3375B0B13

Gennaretti, F., Ogée, J., Sainte-Marie, J., Cuntz, M., 2020. Mining ecophysiological responses of European beech ecosystems to drought. Agric. For. Meteorol. 280, 107780. https://doi.org/10.1016/j.agrformet.2019.107780

Giménez, C., Gallardo, M., Thompson, R.B., 2013. Plant–Water Relations, in: Reference Module in Earth Systems and Environmental Sciences. Elsevier, p. B978012409548905257X. https://doi.org/10.1016/B978-0-12-409548-9.05257-X

Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J., Stoffel, M., 2014. 21st century climate change in the European Alps—A review. Sci. Total Environ. 493, 1138–1151. https://doi.org/10.1016/j.scitotenv.2013.07.050

Granier, A., Biron, P., Lemoine, D., 2000. Water balance, transpiration and canopy conductance in two beech stands. Agric. For. Meteorol. 100, 291–308. https://doi.org/10.1016/S0168-1923(99)00151-3

Grillakis, M.G., 2019. Increase in severe and extreme soil moisture droughts for Europe under climate change. Sci. Total Environ. 660, 1245–1255. https://doi.org/10.1016/j.scitotenv.2019.01.001

Grime, V.L., Sinclair, F.L., 1999. Sources of error in stem heat balance sap ¯ow measurements. Agric. For. Meteorol. 94, 103–121.

Haase, P., Frenzel, M., Klotz, S., Musche, M., Stoll, S., 2016. The long-term ecological research (LTER) network: Relevance, current status, future perspective and examples from marine, freshwater and terrestrial long-term observation. Ecol. Indic. 65, 1–3. https://doi.org/10.1016/j.ecolind.2016.01.040

Hansen, J., Sato, M., Ruedy, R., Lo, K., Lea, D.W., Medina-Elizade, M., 2006. Global temperature change. Proc. Natl. Acad. Sci. 103, 14288–14293. https://doi.org/10.1073/pnas.0606291103

Hiebl, J., Chimani, B., Ganekind, M., Höfler, A., Orlik, A., 2021. Österreichisches Klimabulletin Jahr 2020.

Hoelscher, M.-T., Kern, M.A., Wessolek, G., Nehls, T., 2018. A new consistent sap flow baseline-correction approach for the stem heat balance method using nocturnal water vapour pressure deficits and its application in the measurements of urban climbing plant transpiration. Agric. For. Meteorol. 248, 169–176. https://doi.org/10.1016/j.agrformet.2017.09.014

ILTER, 2021. Network - Global Coverage - ILTER - International long term ecological research [WWW Document]. URL https://www.ilter.network/network/global-coverageFound%20on:%2030.06.2021 (accessed 1.23.22).

IPCC, 2013. Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change[Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jacobs, K., Bonal, D., Collet, C., Muys, B., Ponette, Q., 2021. Mixing increases drought exposure through a faster growth in beech, but not in oak. For. Ecol. Manag. 479, 118593. https://doi.org/10.1016/j.foreco.2020.118593

Konôpka, B., Pajtík, J., Noguchi, K., Lukac, M., 2013. Replacing Norway spruce with European beech: A comparison of biomass and net primary production patterns in young stands. For. Ecol. Manag. 302, 185–192. https://doi.org/10.1016/j.foreco.2013.03.026

Kovalčíková, D., Střelcová, K., Ditmarová, Ľ., 2012. Measurement of European beech transpiration rate under drought stress. FOLIA OECOLOGICA 39, 36–44.

Kučera, J., 2015. Sap flow system EMS 81 User's manual – 2-nd issue.

Leitner, M., Babcicky, P., Schinko, T., Glas, N., 2020. The status of climate risk management in Austria. Assessing the governance landscape and proposing ways forward for comprehensively managing flood and drought risk. Clim. Risk Manag. 30, 100246. https://doi.org/10.1016/j.crm.2020.100246

Leitner, S., 2017. Impact of Extreme Weather Events on Soil Nitrogen Cycling and Greenhouse Gas Emissions (Doctoral Thesis). University of Natural Resources and Life Sciences, Vienna.

Leitner, S., Minixhofer, P., Inselsbacher, E., Keiblinger, K.M., Zimmermann, M., Zechmeister-Boltenstern, S., 2017. Short-term soil mineral and organic nitrogen fluxes during moderate and severe drying–rewetting events. Appl. Soil Ecol. 114, 28–33. https://doi.org/10.1016/j.apsoil.2017.02.014

Leitner, S., Sae-Tun, O., Kranzinger, L., Zechmeister-Boltenstern, S., Zimmermann, M., 2016. Contribution of litter layer to soil greenhouse gas emissions in a temperate beech forest. Plant Soil 403, 455–469. https://doi.org/10.1007/s11104-015-2771-3

Leuschner, C., 2020. Drought response of European beech (Fagus sylvatica L.)—A review. Perspect. Plant Ecol. Evol. Syst. 47, 125576. https://doi.org/10.1016/j.ppees.2020.125576

Leuzinger, S., Zotz, G., Asshoff, R., Korner, C., 2005. Responses of deciduous forest trees to severe drought in Central Europe. Tree Physiol. 25, 641–650. https://doi.org/10.1093/treephys/25.6.641

Li, S.-N., Lu, S.W., Zhao, Y.-G., Zhao, N., Chen, B., 2019. Characteristics and influencing factors in sap flow of four broadleaved tree species for typical weather conditions of Beijing. J. Ecol. Rural Environ. 35, 189–196.

Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R., Delzon, S., Corona, P., Kolström, M., Lexer, M.J., Marchetti, M., 2010. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. For. Ecol. Manag. 259, 698–709. https://doi.org/10.1016/j.foreco.2009.09.023

Liu, D., Keiblinger, K.M., Leitner, S., Wegner, U., Zimmermann, M., Fuchs, S., Lassek, C., Riedel, K., Zechmeister-Boltenstern, S., 2019. Response of Microbial Communities and Their Metabolic Functions to Drying–Rewetting Stress in a Temperate Forest Soil. Microorganisms 7, 129. https://doi.org/10.3390/microorganisms7050129

LTER Austria, 2021. LTER Sites und LTSER Plattformen | LTER Austria. URL https://www.lter-austria.at/lter-sites-und-ltser-plattformen/ (accessed 1.23.22).

LTER Austria, n.d. Ökologische Langzeitforschung [WWW Document]. Umweltbundesamt. URL https://www.umweltbundesamt.at/umweltthemen/oekosystemmonitoring/langzeitforschung (accessed 3.17.22).

Magh, R.-K., Eiferle, C., Burzlaff, T., Dannenmann, M., Rennenberg, H., Dubbert, M., 2020. Competition for water rather than facilitation in mixed beech-fir forests after drying-wetting cycle. J. Hydrol. 587, 124944. https://doi.org/10.1016/j.jhydrol.2020.124944

Martinez del Castillo, E., Zang, C.S., Buras, A., Hacket-Pain, A., Esper, J., Serrano-Notivoli, R., Hartl, C., Weigel, R., Klesse, S., Resco de Dios, V., Scharnweber, T., Dorado-Liñán, I., van der Maaten-Theunissen, M., van der Maaten, E., Jump, A., Mikac, S., Banzragch, B.-E., Beck, W., Cavin, L., Claessens, H., Čada, V., Čufar, K., Dulamsuren, C., Gričar, J., Gil-Pelegrín, E., Janda, P., Kazimirovic, M., Kreyling, J., Latte, N., Leuschner, C., Longares, L.A., Menzel, A., Merela, M., Motta, R., Muffler, L., Nola, P., Petritan, A.M., Petritan, I.C., Prislan, P., Rubio-Cuadrado, Á., Rydval, M., Stajić, B., Svoboda, M., Toromani, E., Trotsiuk, V., Wilmking, M., Zlatanov, T., de Luis, M., 2022. Climate-change-driven growth decline of European beech forests. Commun. Biol. 5, 163. https://doi.org/10.1038/s42003-022-03107-3

Massonnet, C., Chuste, P.-A., Levillain, J., Gérémia, F., E Silva, D., Maillard, P., Dreyer, E., Dupouey, J.-L., Bréda, N., 2021. Leafy season length is reduced by a prolonged soil water deficit but not by repeated defoliation in beech trees (Fagus sylvatica L.): comparison of response among regional populations grown in a common garden. Agric. For. Meteorol. 297, 108228. https://doi.org/10.1016/j.agrformet.2020.108228

Mausolf, K., Wilm, P., Härdtle, W., Jansen, K., Schuldt, B., Sturm, K., von Oheimb, G., Hertel, D., Leuschner, C., Fichtner, A., 2018. Higher drought sensitivity of radial growth of European beech in managed than in unmanaged forests. Sci. Total Environ. 642, 1201–1208. https://doi.org/10.1016/j.scitotenv.2018.06.065

Michelot, A., Bréda, N., Damesin, C., Dufrêne, E., 2012. Differing growth responses to climatic variations and soil water deficits of Fagus sylvatica, Quercus petraea and Pinus sylvestris in a temperate forest. For. Ecol. Manag. 265, 161–171. https://doi.org/10.1016/j.foreco.2011.10.024

Michener, W.K., Porter, J., Servilla, M., Vanderbilt, K., 2011. Long term ecological research and information management. Ecol. Inform. 6, 13–24. https://doi.org/10.1016/j.ecoinf.2010.11.005

Nalevanková, P., Ježík, M., Sitková, Z., Vido, J., Leštianska, A., Střelcová, K., 2018. Drought and irrigation affect transpiration rate and morning tree water status of a mature European beech (*Fagus sylvatica* L.) forest in Central Europe: Ecophysiology of European beech exposed to drought. Ecohydrology 11, e1958. https://doi.org/10.1002/eco.1958

Netherer, S., Matthews, B., Katzensteiner, K., Blackwell, E., Henschke, P., Hietz, P., Pennerstorfer, J., Rosner, S., Kikuta, S., Schume, H., Schopf, A., 2015. Do water‐limiting conditions predispose N orway spruce to bark beetle attack? New Phytol. 205, 1128–1141. https://doi.org/10.1111/nph.13166

Rais, A., Uhl, E., van de Kuilen, J.-W.G., Pretzsch, H., 2021. Short-term reaction of European beech stem taper due to weather extremes. For. Ecol. Manag. 480, 118653. https://doi.org/10.1016/j.foreco.2020.118653

Rohner, B., Kumar, S., Liechti, K., Gessler, A., Ferretti, M., 2021. Tree vitality indicators revealed a rapid response of beech forests to the 2018 drought. Ecol. Indic. 120, 106903. https://doi.org/10.1016/j.ecolind.2020.106903

Rötzer, T., Biber, P., Moser, A., Schäfer, C., Pretzsch, H., 2017. Stem and root diameter growth of European beech and Norway spruce under extreme drought. For. Ecol. Manag. 406, 184–195. https://doi.org/10.1016/j.foreco.2017.09.070

Rubio-Cuadrado, Á., Camarero, J.J., del Río, M., Sánchez-González, M., Ruiz-Peinado, R., Bravo-Oviedo, A., Gil, L., Montes, F., 2018. Long-term impacts of drought on growth and forest dynamics in a temperate beech-oak-birch forest. Agric. For. Meteorol. 259, 48–59. https://doi.org/10.1016/j.agrformet.2018.04.015

Ryan, M.G., 2011. Tree responses to drought. Tree Physiol. 31, 237–239. https://doi.org/10.1093/treephys/tpr022

Schwen, A., Zimmermann, M., Leitner, S., Woche, S.K., 2015. Soil Water Repellency and its Impact on Hydraulic Characteristics in a Beech Forest under Simulated Climate Change. Vadose Zone J. 14, vzj2015.06.0089. https://doi.org/10.2136/vzj2015.06.0089

Sinha, R.K., 2004. Modern plant physiology. Alpha Science International, Pangbourne, England.

Sitková, Z., Nalevanková, P., Střelcová, K., Fleischer Jr., P., Ježík, M., Sitko, R., Pavlenda, P., Hlásny, T., 2014. How does soil water potential limit the seasonal dynamics of sap flow and circumference changes in European beech? For. J. 60, 19–30. https://doi.org/10.2478/forj-2014-0002

Spinoni, J., Naumann, G., Vogt, J., Barbosa, P., 2015. European drought climatologies and trends based on a multi-indicator approach. Glob. Planet. Change 127, 50–57. https://doi.org/10.1016/j.gloplacha.2015.01.012

Steppe, K., De Pauw, D.J.W., Doody, T.M., Teskey, R.O., 2010. A comparison of sap flux density using thermal dissipation, heat pulse velocity and heat field deformation methods. Agric. For. Meteorol. 150, 1046–1056. https://doi.org/10.1016/j.agrformet.2010.04.004

Taiz, L., Zeiger, E., Møller, I.M., Murphy, A., 2018. Plant physiology and development, Sixth edition. ed. Oxford University Press, Oxford.

Tomasella, M., Beikircher, B., Häberle, K.-H., Hesse, B., Kallenbach, C., Matyssek, R., Mayr, S., 2018. Acclimation of branch and leaf hydraulics in adult Fagus sylvatica and Picea abies in a forest through-fall exclusion experiment. Tree Physiol. 38, 198–211. https://doi.org/10.1093/treephys/tpx140

Walthert, L., Ganthaler, A., Mayr, S., Saurer, M., Waldner, P., Walser, M., Zweifel, R., von Arx, G., 2021. From the comfort zone to crown dieback: Sequence of physiological stress thresholds in mature European beech trees across progressive drought. Sci. Total Environ. 753, 141792.

https://doi.org/10.1016/j.scitotenv.2020.141792

Way, D.A., Domec, J.-C., Jackson, R.B., 2013. Elevated growth temperatures alter hydraulic characteristics in trembling aspen (*Populus tremuloides*) seedlings: implications for tree drought tolerance: Temperature and tree hydraulics. Plant Cell Environ. 36, 103–115. https://doi.org/10.1111/j.1365-3040.2012.02557.x

Wimmer, R., 2006. 100 Liter am Tag. zuschnitt 14–15.

Wu, J., Liu, H., Zhu, J., Gong, L., Xu, L., Jin, G., Li, J., Hauer, R., Xu, C., 2020. Nocturnal sap flow is mainly caused by stem refilling rather than nocturnal transpiration for Acer truncatum in urban environment. Urban For. Urban Green. 56, 126800. https://doi.org/10.1016/j.ufug.2020.126800

List of abbreviations

LTER…Long term ecological research

MDSMC… mean daily soil moisture content

Q …sap flow per 1cm stem circumference

Q_d …cumulative day sap flow

Q_n …cumulative nocturnal sap flow

Q_t …total cumulative sap flow per day

Q_{tree} …total sap flow per tree

$Q(t_{i/2})$… numerically integrated sap flow per tree (Q_{tree}) in half hours steps

R_{cd} …cumulative daily rainfall

VPD …vapor pressure deficit

List of figures, formulas and tables

Appendix

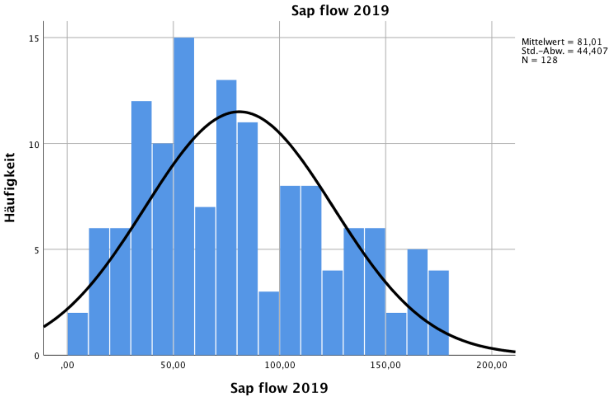
Comparison between experiment and control trees

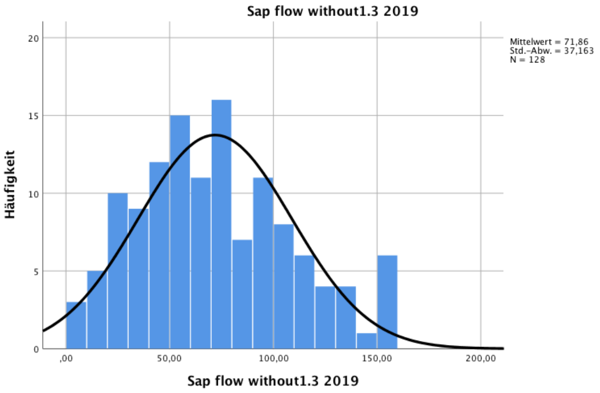
⇨ 2019

Test for Gauss distribution:

Statistiken

		Sap flow 2019	Sap flow without1.3 2019
N	Gültig	128	128
	Fehlend	2	2
Schiefe		,453	,464
Standardfehler der Schiefe		,214	,214
Kurtosis		-,715	-,408
Standardfehler der Kurtosis		,425	,425





Test for variance homogentity

ONEWAY deskriptive Statistiken

		N	Mittelwert	Std.-Abweichung	Std.-Fehler	95%-Konfidenzintervall für den Mittelwert		Minimum	Maximum
						Untergrenze	Obergrenze		
Sap flow 2019	control	64	53,5750	23,29946	2,91243	47,7550	59,3951	7,20	101,12
	experiment	64	108,4472	43,62311	5,45289	97,5505	119,3439	8,64	177,49
	Gesamt	128	81,0111	44,40672	3,92504	73,2442	88,7780	7,20	177,49
Sap flow without1.3 2019	control	64	53,5750	23,29946	2,91243	47,7550	59,3951	7,20	101,12

	experiment	64	90,1415	39,52296	4,94037	80,2690	100,0140	7,11	158,62
	Gesamt	128	71,8583	37,16297	3,28477	65,3583	78,3582	7,11	158,62

Test der Homogenität der Varianzen

		Levene-Statistik	df1	df2	Signifikanz
Sap flow 2019	Basiert auf dem Mittelwert	20,844	1	126	,000
	Basiert auf dem Median	18,352	1	126	,000
	Basierend auf dem Median und mit angepaßten df	18,352	1	92,803	,000
	Basiert auf dem getrimmten Mittel	20,281	1	126	,000
Sap flow without1.3 2019	Basiert auf dem Mittelwert	16,770	1	126	,000
	Basiert auf dem Median	15,021	1	126	,000
	Basierend auf dem Median und mit angepaßten df	15,021	1	100,478	,000
	Basiert auf dem getrimmten Mittel	16,515	1	126	,000

Einfaktorielle ANOVA

		Quadratsumme	df	Mittel der Quadrate	F	Signifikanz
Sap flow 2019	Zwischen den Gruppen	96350,523	1	96350,523	78,787	,000
	Innerhalb der Gruppen	154087,981	126	1222,920		
	Gesamt	250438,504	127			
Sap flow without1.3 2019	Zwischen den Gruppen	42787,418	1	42787,418	40,654	,000
	Innerhalb der Gruppen	132610,531	126	1052,465		
	Gesamt	175397,949	127			

no Variance homogentiy-therefore no Students T- Test

Welch-test

Einfaktorielle ANOVA

		Quadratsumme	df	Mittel der Quadrate	F	Signifikanz
Sap flow 2019	Zwischen den Gruppen	96350,523	1	96350,523	78,787	,000

	Innerhalb der Gruppen	154087,981	126	1222,920		
	Gesamt	250438,504	127			
Sap flow without1.3 2019	Zwischen den Gruppen	42787,418	1	42787,418	40,654	,000
	Innerhalb der Gruppen	132610,531	126	1052,465		
	Gesamt	175397,949	127			

Robuste Testverfahren zur Prüfung auf Gleichheit der Mittelwerte

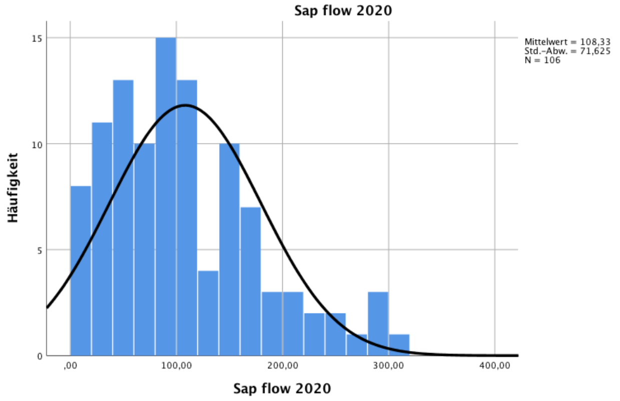
		Statistik	df1	df2	Sig.
Sap flow 2019	Welch-Test	78,787	1	96,239	,000
Sap flow without1.3 2019	Welch-Test	40,654	1	102,070	,000

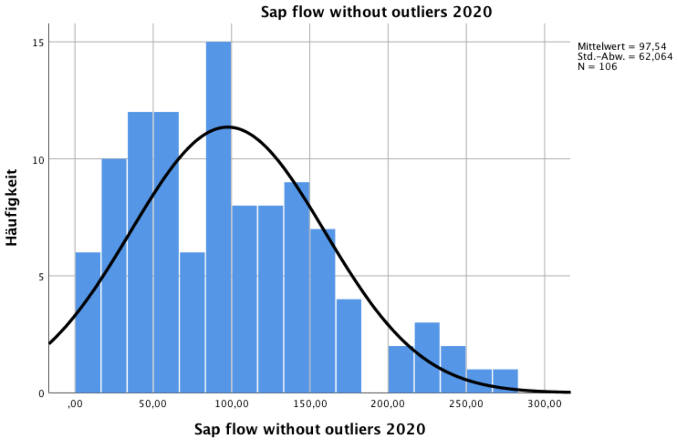
=>2020

Test for Gauss distribution:

Statistiken

		Sap flow 2020	Sap flow without outliers 2020
N	Gültig	106	106
	Fehlend	0	0
Schiefe		,822	,751
Standardfehler der Schiefe		,235	,235
Kurtosis		,135	,123
Standardfehler der Kurtosis		,465	,465





Test for variance homogentity

ONEWAY deskriptive Statistiken

		N	Mittelwert	Std.-Abweichung	Std.-Fehler	95%-Konfidenzintervall für den Mittelwert		Minimum	Maximum
						Untergrenze	Obergrenze		
Sap flow 2020	control	53	77,7317	43,29571	5,94712	65,7979	89,6655	11,48	160,64
	experiment	53	138,9242	81,09411	11,13913	116,5718	161,2765	12,39	304,14
	Gesamt	106	108,3279	71,62534	6,95687	94,5337	122,1221	11,48	304,14
Sap flow without outliers 2020	control	53	77,7317	43,29571	5,94712	65,7979	89,6655	11,48	160,64
	experiment	53	117,3448	71,44081	9,81315	97,6533	137,0364	9,60	273,71
	Gesamt	106	97,5383	62,06417	6,02820	85,5855	109,4911	9,60	273,71

Test der Homogenität der Varianzen

		Levene-Statistik	df1	df2	Signifikanz
Sap flow 2020	Basiert auf dem Mittelwert	21,927	1	104	,000
	Basiert auf dem Median	21,742	1	104	,000
	Basierend auf dem Median und mit angepaßten df	21,742	1	79,758	,000
	Basiert auf dem getrimmten Mittel	21,789	1	104	,000
Sap flow without outliers 2020	Basiert auf dem Mittelwert	12,241	1	104	,001
	Basiert auf dem Median	12,204	1	104	,001
	Basierend auf dem Median und mit angepaßten df	12,204	1	83,616	,001
	Basiert auf dem getrimmten Mittel	12,276	1	104	,001

Einfaktorielle ANOVA

		Quadratsumme	df	Mittel der Quadrate	F	Signifikanz
Sap flow 2020	Zwischen den Gruppen	99229,728	1	99229,728	23,484	,000
	Innerhalb der Gruppen	439440,209	104	4225,387		
	Gesamt	538669,937	105			

Sap flow without outliers 2020	Zwischen den Gruppen	41583,874	1	41583,874	11,918	,001
	Innerhalb der Gruppen	362871,993	104	3489,154		
	Gesamt	404455,867	105			

⇨ no Variance homogentiy-therefore no Students T- Test

⇨ Welch-test

Einfaktorielle ANOVA

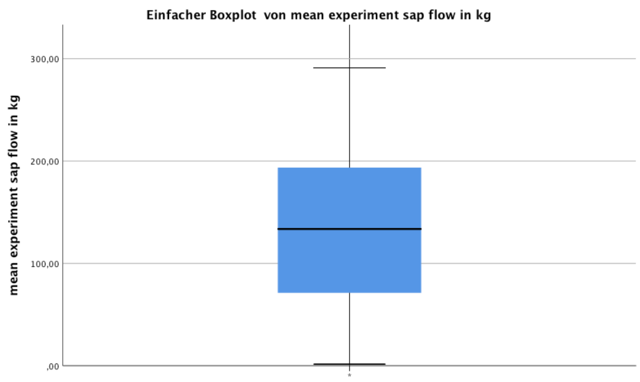
		Quadratsumme	df	Mittel der Quadrate	F	Signifikanz
Sap flow 2020	Zwischen den Gruppen	99229,728	1	99229,728	23,484	,000
	Innerhalb der Gruppen	439440,209	104	4225,387		
	Gesamt	538669,937	105			
Sap flow without outliers 2020	Zwischen den Gruppen	41583,874	1	41583,874	11,918	,001
	Innerhalb der Gruppen	362871,993	104	3489,154		
	Gesamt	404455,867	105			

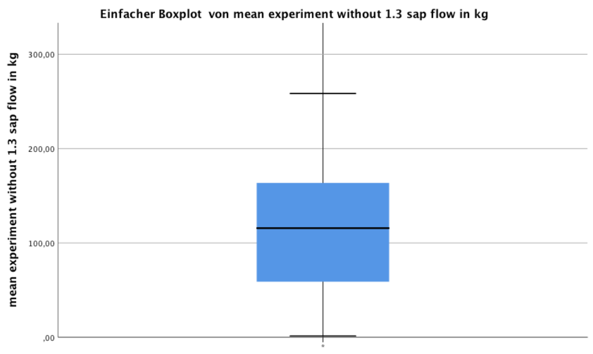
Robuste Testverfahren zur Prüfung auf Gleichheit der Mittelwerte

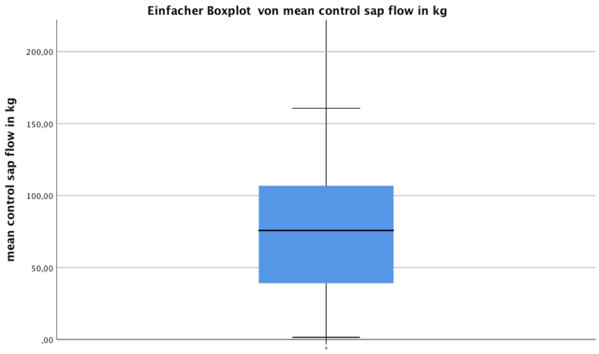
		Statistik	df1	df2	Sig.
Sap flow 2020	Welch-Test	23,484	1	79,417	,000
Sap flow without outliers 2020	Welch-Test	11,918	1	85,657	,001

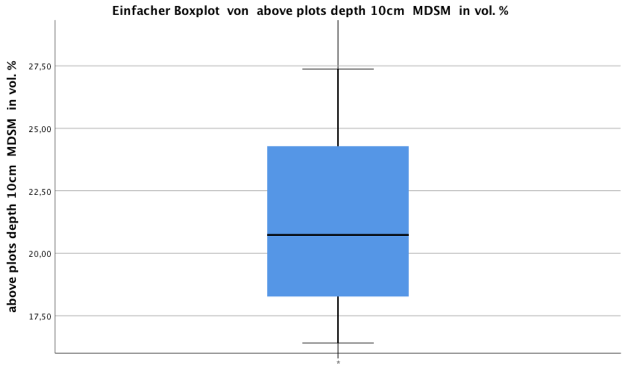
Correlation between soil moisture content and temperature to the sap flow rate

Detection of outliers






Einfacher Boxplot von mean control sap flow in kg
mean control sap flow in kg
200,00
150,00
100,00
50,00
,00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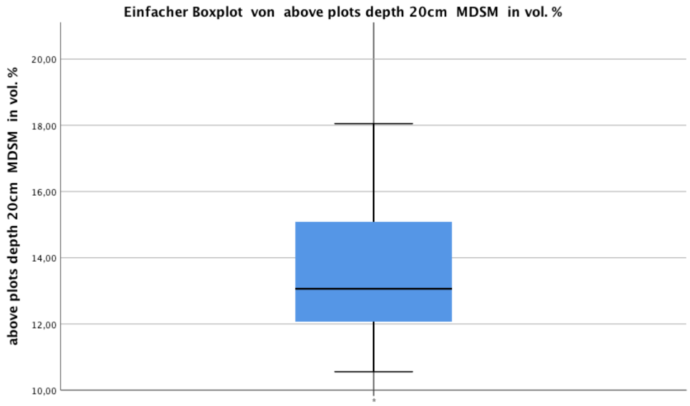
above plots depth 10cm MDSM in vol. %
27,50
25,00
22,50
20,00
17,50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above plots depth 20cm MDSM in vol. %
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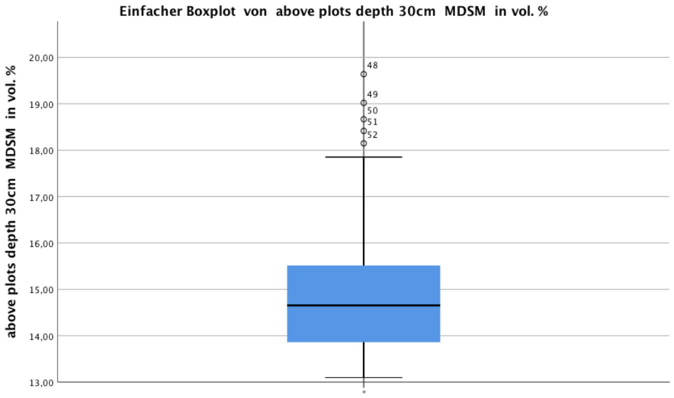
18,00
16,00
14,00
12,00
10,00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above plots depth 30cm MDSM in vol. %
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19,00
18,00
17,00
16,00
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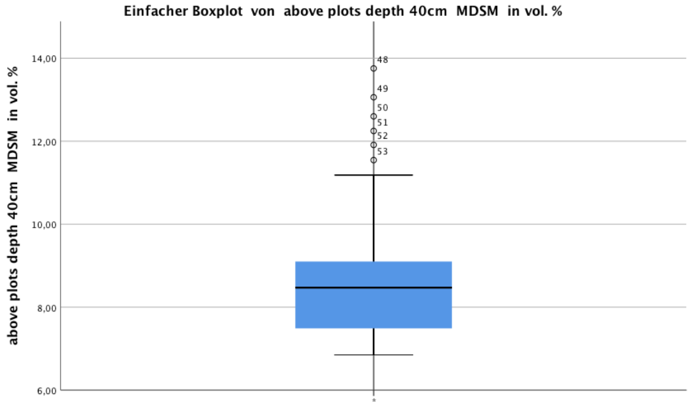
13,00
48
49
50
51
52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above plots depth 40cm MDSM in vol. %
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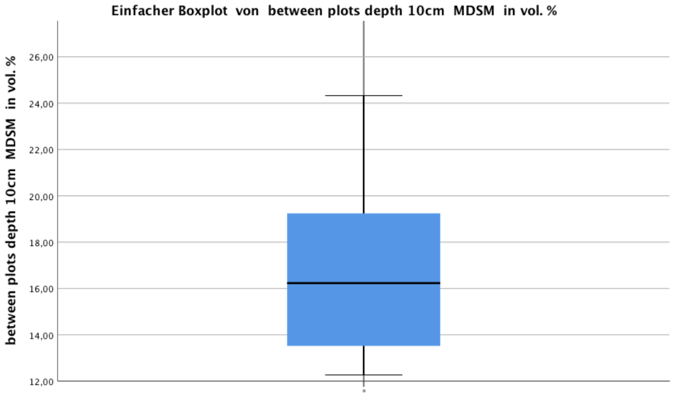
12,00
10,00
8,00
6,00
48
49
50
51
52
53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between plots depth 10cm MDSM in vol. %
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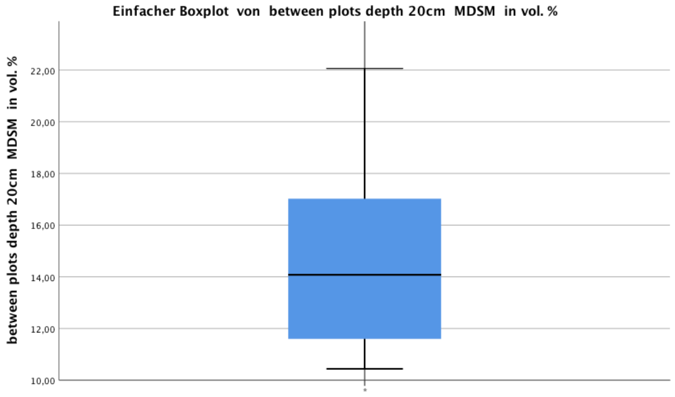
24,00
22,00
20,00
18,00
16,00
14,00
12,00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between plots depth 20cm MDSM in vol. %
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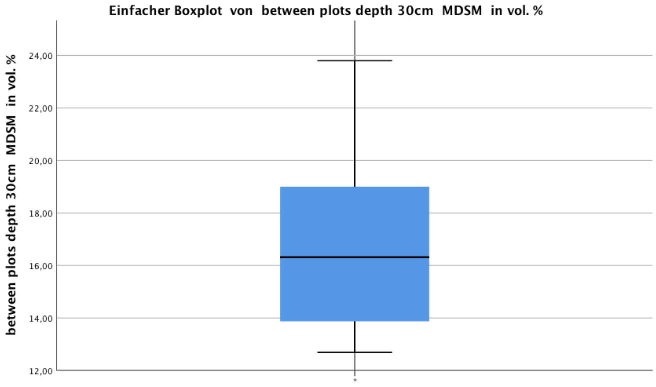
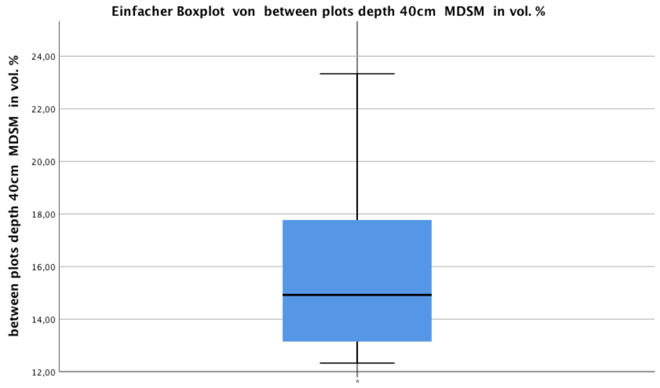
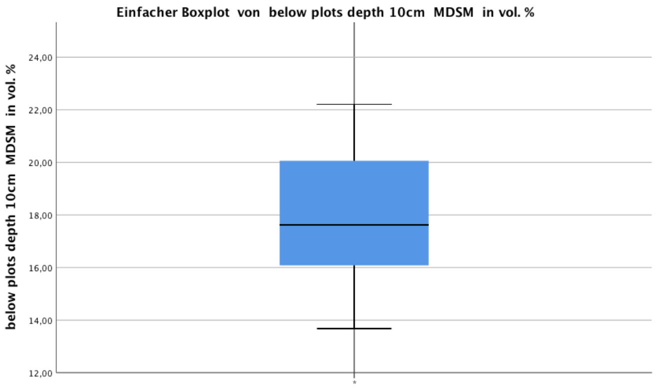
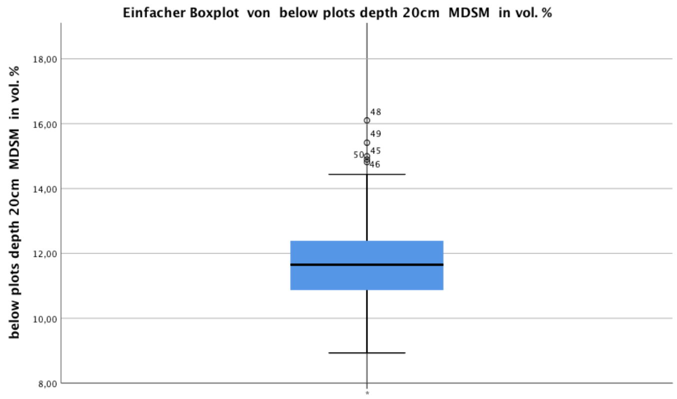
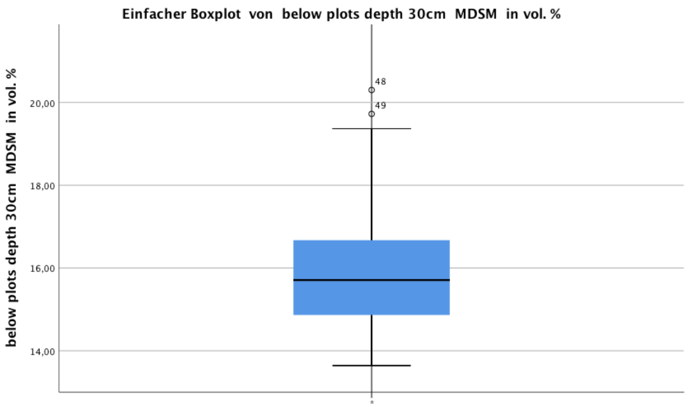
20,00
18,00
16,00
14,00
12,00
10,00

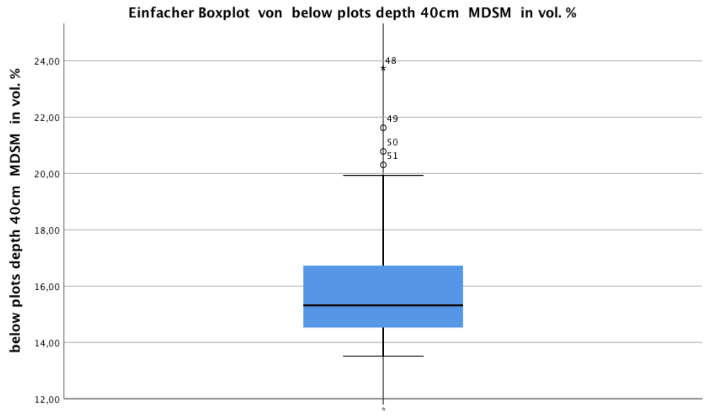

Einfacher Boxplot von between plots depth 30cm MDSM in vol. %
between plots depth 30cm MDSM in vol. %
24,00
22,00
20,00
18,00
16,00
14,00
12,00

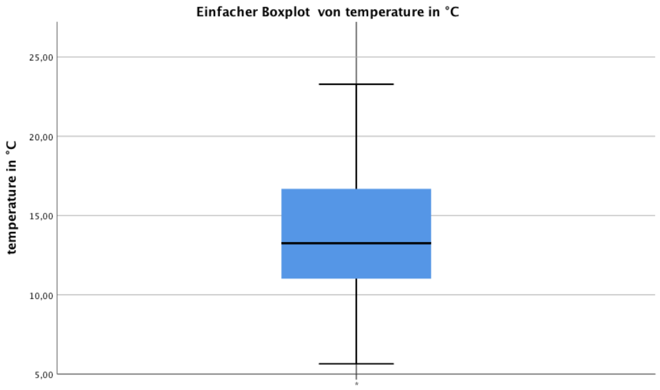












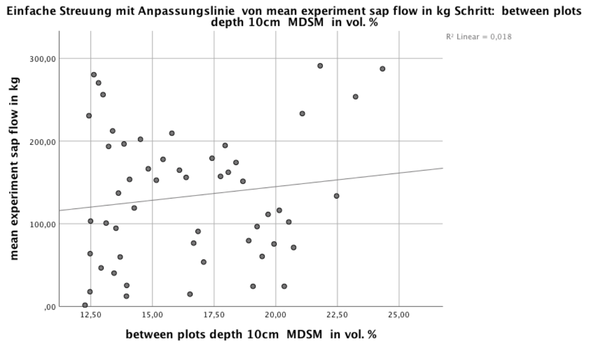
=> extreme outlier no Bravis- Pearson Correlation

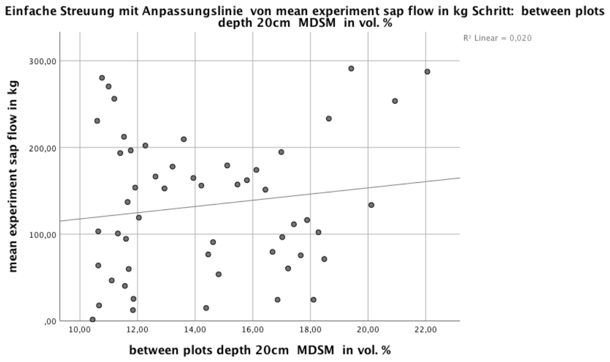
Test for Gauss distribution

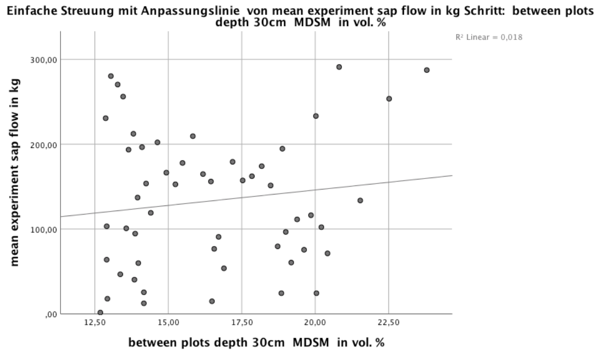
Statistiken

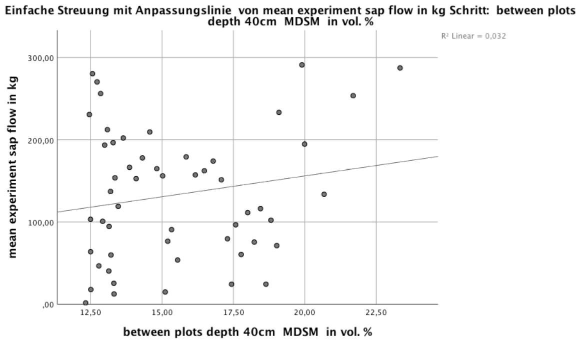
		mean experiment sap flow in kg	mean experiment without 1.3 sap flow in kg	mean control sap flow in kg	above plots depth 10cm MDSM in vol. %	above plots depth 20cm MDSM in vol. %	above plots depth 30cm MDSM in vol. %	above plots depth 40cm MDSM in vol. %	between plots depth 10cm MDSM in vol. %	between plots depth 20cm MDSM in vol. %	between plots depth 30cm MDSM in vol. %	between plots depth 40cm MDSM in vol. %	below plots depth 10cm MDSM in vol. %	below plots depth 20cm MDSM in vol. %	below plots depth 30cm MDSM in vol. %	below plots depth 40cm MDSM in vol. %	temperature in °C
N	Gültig	53	53	53	54	54	54	54	54	54	54	54	54	54	54	54	54
	Fehlend	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Schiefe		,237	,343	,309	,183	,574	1,292	1,569	,457	,501	,467	,766	,081	,701	,903	1,625	,133
Standardfehler der Schiefe		,327	,327	,327	,325	,325	,325	,325	,325	,325	,325	,325	,325	,325	,325	,325	,325
Kurtosis		-,848	-,754	-,791	-1,397	-,646	1,067	2,071	-,894	-,864	-,849	-,288	-1,057	,173	,213	2,539	-,341
Standardfehler der Kurtosis		,644	,644	,644	,639	,639	,639	,639	,639	,639	,639	,639	,639	,639	,639	,639	,639

Test for Liniar Corellation:

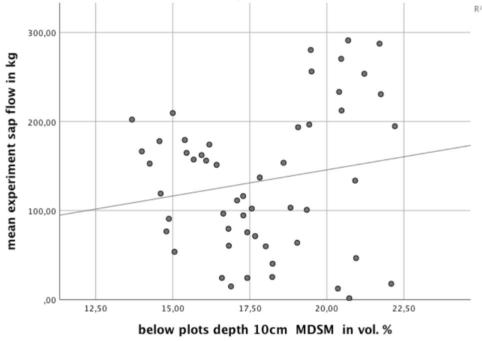




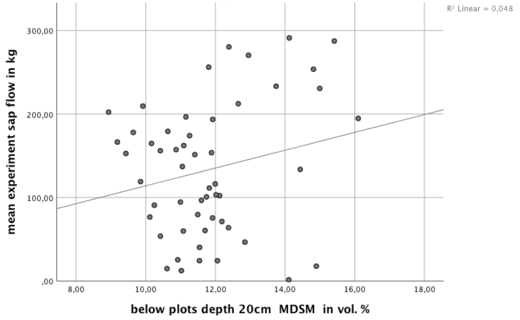




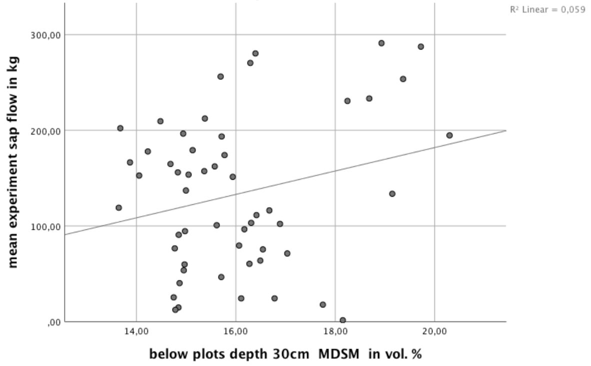
Einfache Streuung mit Anpassungslinie von mean experiment sap flow in kg Schritt: below plots depth 10cm MDSM in vol. %



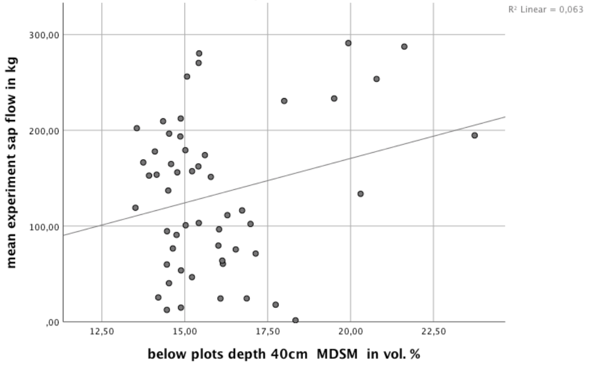
Einfache Streuung mit Anpassungslinie von mean experiment sap flow in kg Schritt: below plots depth 20cm MDSM in vol. %



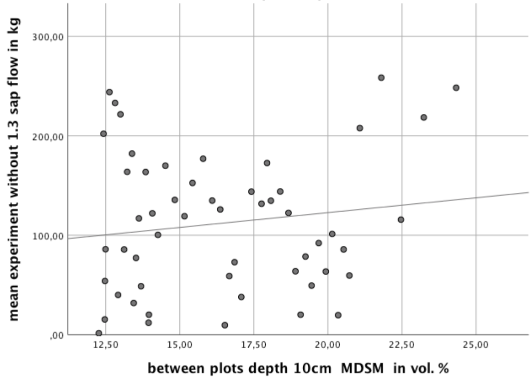
Einfache Streuung mit Anpassungslinie von mean experiment sap flow in kg Schritt: below plots depth 30cm MDSM in vol. %



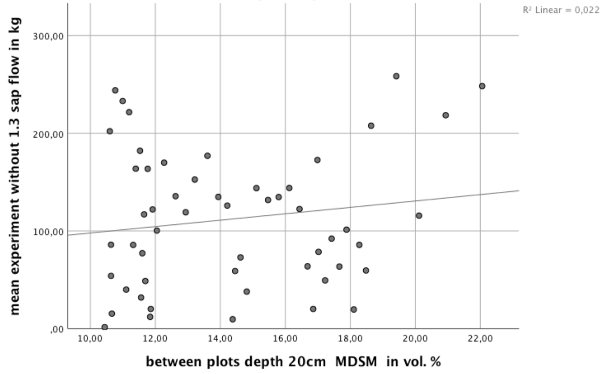
Einfache Streuung mit Anpassungslinie von mean experiment sap flow in kg Schritt: below plots depth 40cm MDSM in vol. %



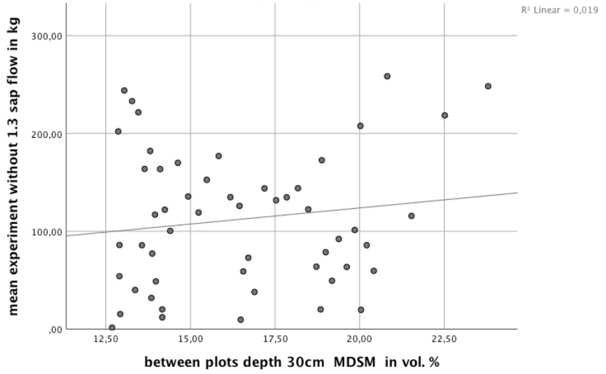
Einfache Streuung mit Anpassungslinie von mean experiment without 1.3 sap flow in kg Schritt: between plots depth 10cm MDSM in vol. %



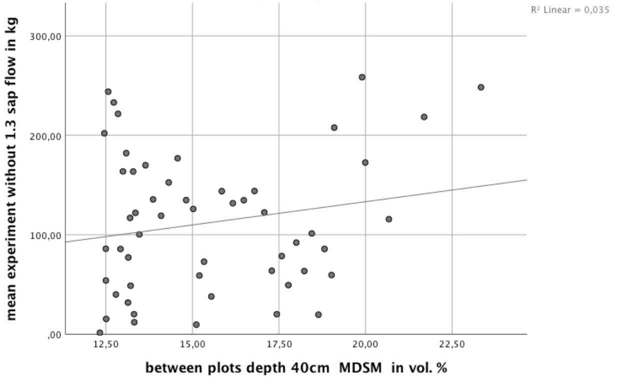
Einfache Streuung mit Anpassungslinie von mean experiment without 1.3 sap flow in kg Schritt: between plots depth 20cm MDSM in vol. %

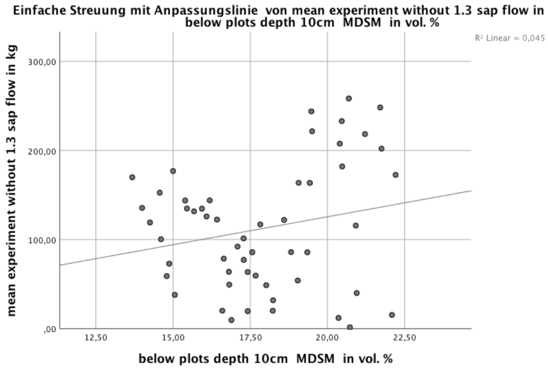


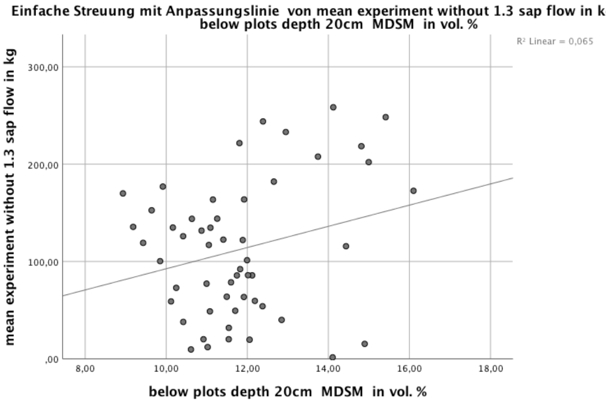
Einfache Streuung mit Anpassungslinie von mean experiment without 1.3 sap flow in kg Schritt: between plots depth 30cm MDSM in vol. %

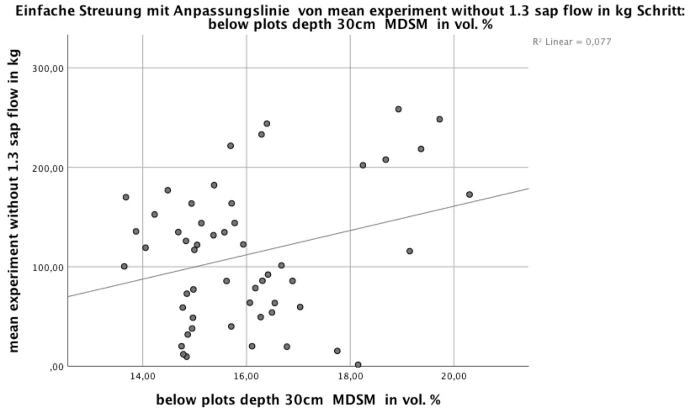


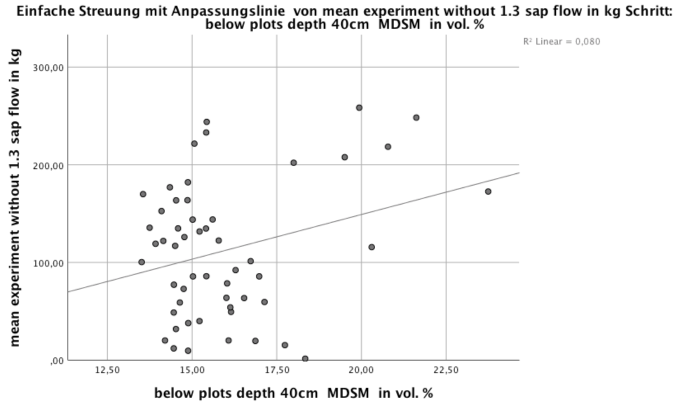
Einfache Streuung mit Anpassungslinie von mean experiment without 1.3 sap flow in kg Schritt: between plots depth 40cm MDSM in vol. %

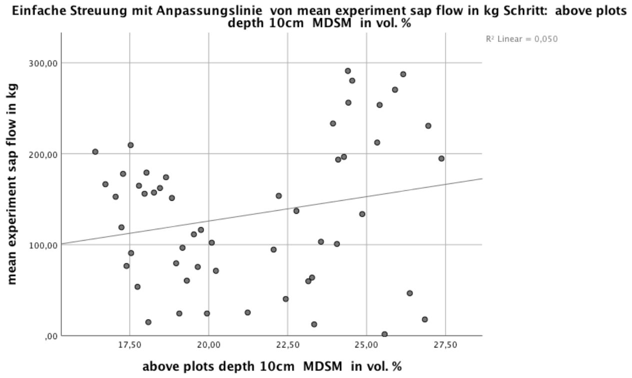


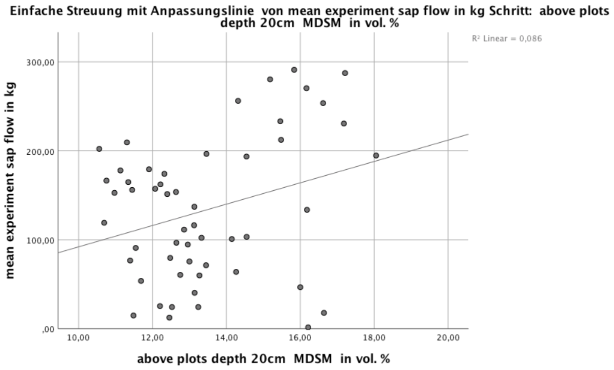

Einfache Streuung mit Anpassungslinie von mean experiment without 1.3 sap flow in kg Schritt: below plots depth 10cm MDSM in vol. %
R² Linear = 0,045
mean experiment without 1.3 sap flow in kg
300,00
200,00
100,00
,00
12,50
15,00
17,50
20,00
22,50
below plots depth 10cm MDSM in vol. %

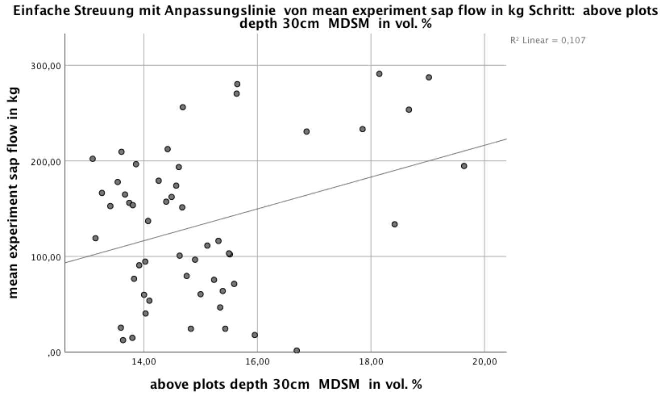

Einfache Streuung mit Anpassungslinie von mean experiment without 1.3 sap flow in kg Schritt: below plots depth 20cm MDSM in vol. %
R² Linear = 0,065
mean experiment without 1.3 sap flow in kg
300,00
200,00
100,00
,00
8,00
10,00
12,00
14,00
16,00
18,00
below plots depth 20cm MDSM in vol. %

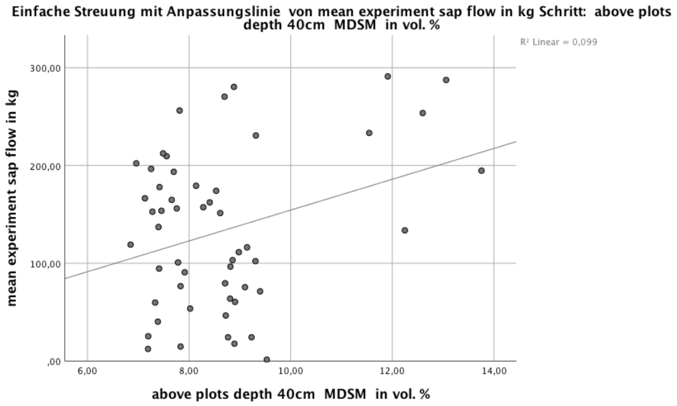

Einfache Streuung mit Anpassungslinie von mean experiment without 1.3 sap flow in kg Schritt: below plots depth 30cm MDSM in vol. %
R² Linear = 0,077
mean experiment without 1.3 sap flow in kg
300,00
200,00
100,00
,00
14,00
16,00
18,00
20,00
below plots depth 30cm MDSM in vol. %


Einfache Streuung mit Anpassungslinie von mean experiment without 1.3 sap flow in kg Schritt: below plots depth 40cm MDSM in vol. %
R² Linear = 0,080
mean experiment without 1.3 sap flow in kg
300,00
200,00
100,00
,00
12,50
15,00
17,50
20,00
22,50
below plots depth 40cm MDSM in vol. %

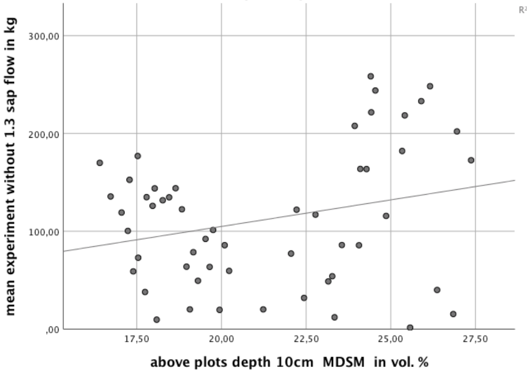

Einfache Streuung mit Anpassungslinie von mean experiment sap flow in kg Schritt: above plots depth 10cm MDSM in vol. %
R² Linear = 0,050
mean experiment sap flow in kg
300,00
200,00
100,00
,00
17,50
20,00
22,50
25,00
27,50
above plots depth 10cm MDSM in vol. %


Einfache Streuung mit Anpassungslinie von mean experiment sap flow in kg Schritt: above plots depth 20cm MDSM in vol. %
R² Linear = 0,086
mean experiment sap flow in kg
300,00
200,00
100,00
,00
10,00
12,00
14,00
16,00
18,00
20,00
above plots depth 20cm MDSM in vol. %

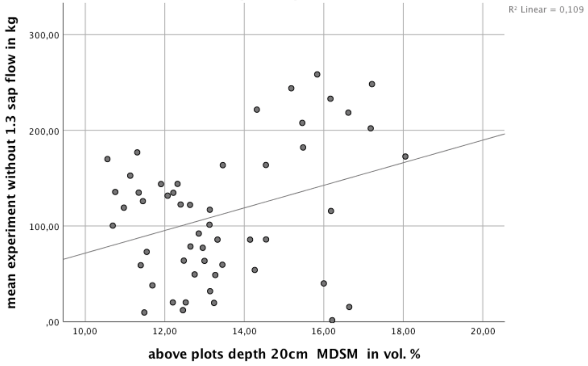

Einfache Streuung mit Anpassungslinie von mean experiment sap flow in kg Schritt: above plots depth 30cm MDSM in vol. %
R² Linear = 0,107
mean experiment sap flow in kg
300,00
200,00
100,00
,00
14,00
16,00
18,00
20,00
above plots depth 30cm MDSM in vol. %


Einfache Streuung mit Anpassungslinie von mean experiment sap flow in kg Schritt: above plots depth 40cm MDSM in vol. %
R² Linear = 0,099
mean experiment sap flow in kg
300,00
200,00
100,00
,00
6,00
8,00
10,00
12,00
14,00
above plots depth 40cm MDSM in vol. %

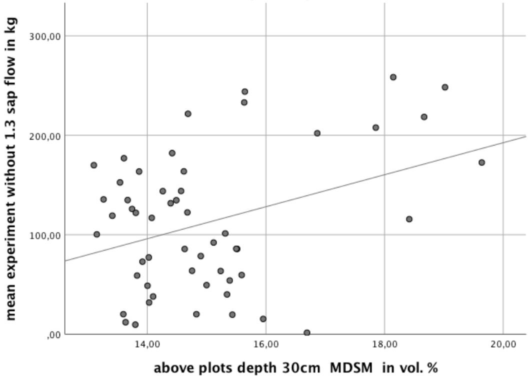
Einfache Streuung mit Anpassungslinie von mean experiment without 1.3 sap flow in kg Schritt: above plots depth 10cm MDSM in vol. %



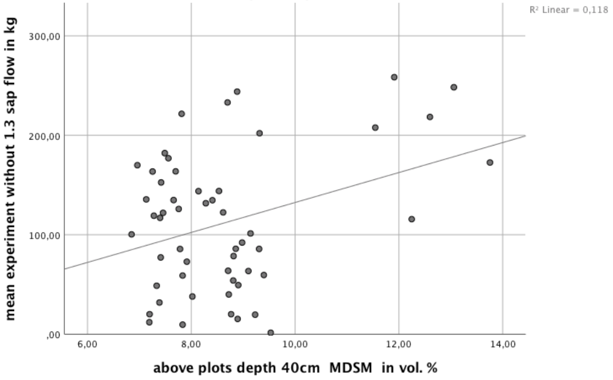
Einfache Streuung mit Anpassungslinie von mean experiment without 1.3 sap flow in kg Schritt: above plots depth 20cm MDSM in vol. %



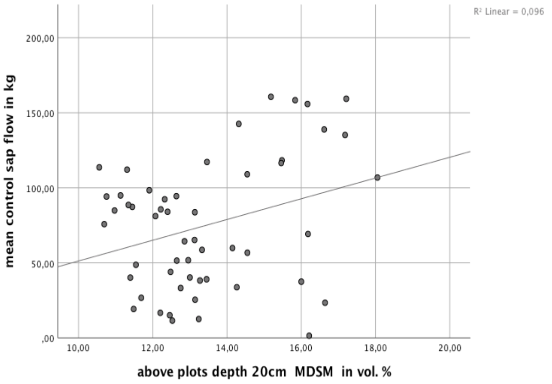
Einfache Streuung mit Anpassungslinie von mean experiment without 1.3 sap flow in kg Schritt: above plots depth 30cm MDSM in vol. %



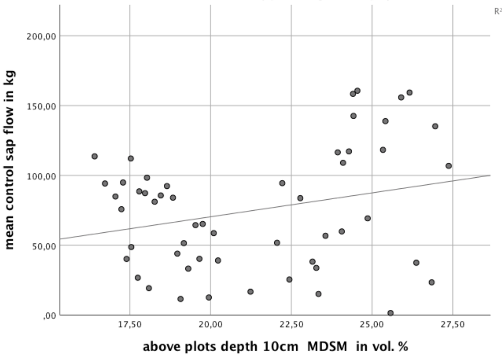
Einfache Streuung mit Anpassungslinie von mean experiment without 1.3 sap flow in kg Schritt: above plots depth 40cm MDSM in vol. %



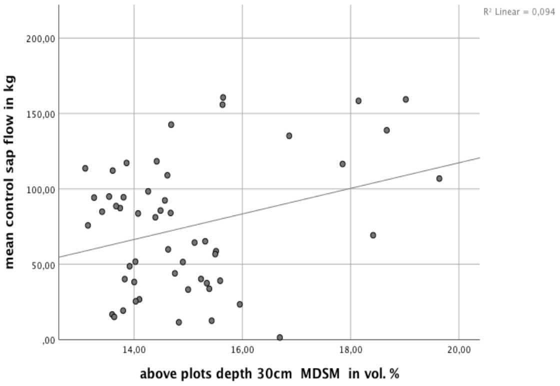
Einfache Streuung mit Anpassungslinie von mean control sap flow in kg Schritt: above plots depth 20cm MDSM in vol. %



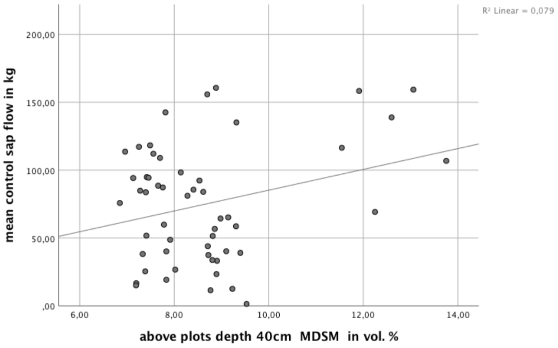
Einfache Streuung mit Anpassungslinie von mean control sap flow in kg Schritt: above plots depth 10cm MDSM in vol. %

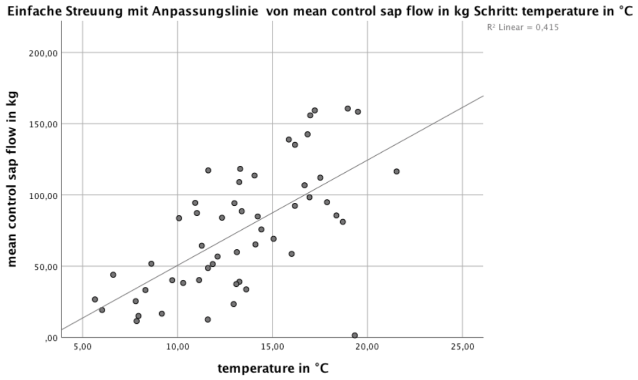


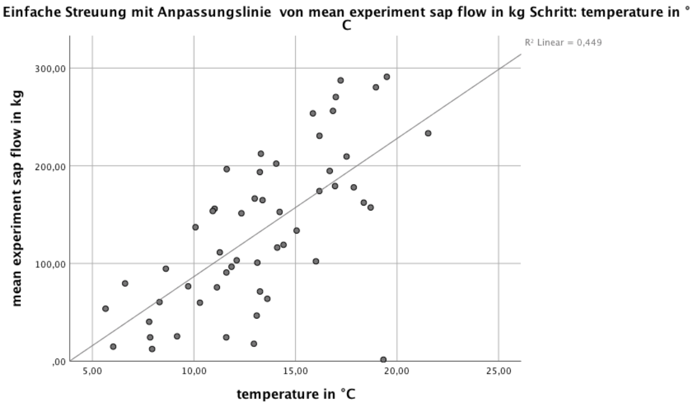
Einfache Streuung mit Anpassungslinie von mean control sap flow in kg Schritt: above plots depth 30cm MDSM in vol. %

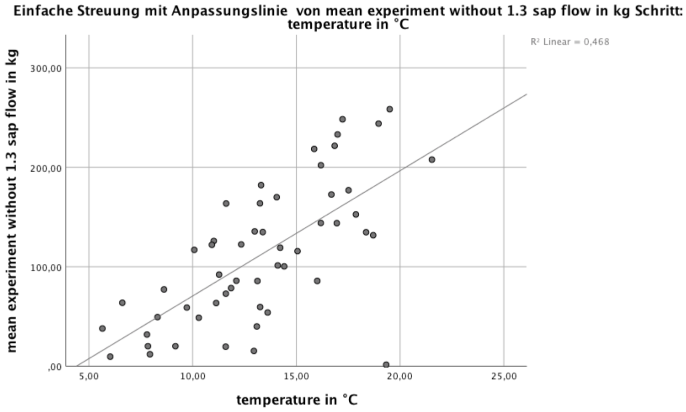


Einfache Streuung mit Anpassungslinie von mean control sap flow in kg Schritt: above plots depth 40cm MDSM in vol. %









Only for below plots depth 40cm a bravis –Pearson-Correlation is not possible

Spearmann- Correlation

CORRELATIONS

Korrelationen

		mean experiment sap flow in kg	between plots depth 10cm MDSM in vol. %	between plots depth 20cm MDSM in vol. %	between plots depth 30cm MDSM in vol. %	between plots depth 40cm MDSM in vol. %	below plots depth 10cm MDSM in vol. %	below plots depth 20cm MDSM in vol. %	below plots depth 30cm MDSM in vol. %	temperature in °C
mean experiment sap flow in kg	Korrelation nach Pearson	1	,136	,142	,134	,178	,174	,218	,243	,670
	Signifikanz (2-seitig)		,332	,312	,339	,202	,212	,116	,080	,000
	N	53	53	53	53	53	53	53	53	53
between plots depth 10cm MDSM in vol. %	Korrelation nach Pearson	,136	1	,998	,997	,980	-,025	,270	,521	,177
	Signifikanz (2-seitig)	,332		,000	,000	,000	,860	,048	,000	,201

	N	53	54	54	54	54	54	54	54	54
between plots depth 20cm MDSM in vol. %	Korrelation nach Pearson	,142	,998	1	,999	,990	,011	,310	,556	,181
	Signifikanz (2-seitig)	,312	,000		,000	,000	,937	,023	,000	,191
	N	53	54	54	54	54	54	54	54	54
between plots depth 30cm MDSM in vol. %	Korrelation nach Pearson	,134	,997	,999	1	,988	-,013	,287	,533	,161
	Signifikanz (2-seitig)	,339	,000	,000		,000	,924	,035	,000	,244
	N	53	54	54	54	54	54	54	54	54
between plots depth 40cm MDSM in vol. %	Korrelation nach Pearson	,178	,980	,990	,988	1	,102	,401	,631	,211
	Signifikanz (2-seitig)	,202	,000	,000	,000		,465	,003	,000	,126
	N	53	54	54	54	54	54	54	54	54
below plots depth 10cm MDSM in vol. %	Korrelation nach Pearson	,174	-,025	,011	-,013	,102	1	,900	,749	,272
	Signifikanz (2-seitig)	,212	,860	,937	,924	,465		,000	,000	,047
	N	53	54	54	54	54	54	54	54	54
below plots depth 20cm MDSM in vol. %	Korrelation nach Pearson	,218	,270	,310	,287	,401	,900	1	,940	,384
	Signifikanz (2-seitig)	,116	,048	,023	,035	,003	,000		,000	,004
	N	53	54	54	54	54	54	54	54	54
below plots depth 30cm MDSM in vol. %	Korrelation nach Pearson	,243	,521	,556	,533	,631	,749	,940	1	,453
	Signifikanz (2-seitig)	,080	,000	,000	,000	,000	,000	,000		,001
	N	53	54	54	54	54	54	54	54	54
temperature in °C	Korrelation nach Pearson	,670	,177	,181	,161	,211	,272	,384	,453	1

	Signifikanz (2-seitig)	,000	,201	,191	,244	,126	,047	,004	,001	
	N	53	54	54	54	54	54	54	54	54

Korrelationen

		mean experiment without 1.3 sap flow in kg	between plots depth 10cm MDSM in vol. %	between plots depth 20cm MDSM in vol. %	between plots depth 30cm MDSM in vol. %	between plots depth 40cm MDSM in vol. %	below plots depth 10cm MDSM in vol. %	below plots depth 20cm MDSM in vol. %	below plots depth 30cm MDSM in vol. %	temperature in °C
mean experiment without 1.3 sap flow in kg	Korrelation nach Pearson	1	,141	,148	,139	,188	,213	,255	,278	,684
	Signifikanz (2-seitig)		,315	,290	,320	,178	,126	,065	,044	,000
	N	53	53	53	53	53	53	53	53	53
between plots depth 10cm MDSM in vol. %	Korrelation nach Pearson	,141	1	,998	,997	,980	-,025	,270	,521	,177
	Signifikanz (2-seitig)	,315		,000	,000	,000	,860	,048	,000	,201
	N	53	54	54	54	54	54	54	54	54
between plots depth 20cm MDSM in vol. %	Korrelation nach Pearson	,148	,998	1	,999	,990	,011	,310	,556	,181
	Signifikanz (2-seitig)	,290	,000		,000	,000	,937	,023	,000	,191
	N	53	54	54	54	54	54	54	54	54
between plots depth 30cm MDSM in vol. %	Korrelation nach Pearson	,139	,997	,999	1	,988	-,013	,287	,533	,161
	Signifikanz (2-seitig)	,320	,000	,000		,000	,924	,035	,000	,244
	N	53	54	54	54	54	54	54	54	54
between plots depth 40cm MDSM in vol. %	Korrelation nach Pearson	,188	,980	,990	,988	1	,102	,401	,631	,211
	Signifikanz (2-seitig)	,178	,000	,000	,000		,465	,003	,000	,126

	N	53	54	54	54	54	54	54	54	54
below plots depth 10cm MDSM in vol. %	Korrelation nach Pearson	,213	-,025	,011	-,013	,102	1	,900	,749	,272
	Signifikanz (2-seitig)	,126	,860	,937	,924	,465		,000	,000	,047
	N	53	54	54	54	54	54	54	54	54
below plots depth 20cm MDSM in vol. %	Korrelation nach Pearson	,255	,270	,310	,287	,401	,900	1	,940	,384
	Signifikanz (2-seitig)	,065	,048	,023	,035	,003	,000		,000	,004
	N	53	54	54	54	54	54	54	54	54
below plots depth 30cm MDSM in vol. %	Korrelation nach Pearson	,278	,521	,556	,533	,631	,749	,940	1	,453
	Signifikanz (2-seitig)	,044	,000	,000	,000	,000	,000	,000		,001
	N	53	54	54	54	54	54	54	54	54
temperature in °C	Korrelation nach Pearson	,684	,177	,181	,161	,211	,272	,384	,453	1
	Signifikanz (2-seitig)	,000	,201	,191	,244	,126	,047	,004	,001	
	N	53	54	54	54	54	54	54	54	54

Korrelationen

			below plots depth 40cm MDSM in vol. %	mean experiment sap flow in kg
Spearman-Rho	below plots depth 40cm MDSM in vol. %	Korrelationskoeffizient	1,000	,053
		Sig. (2-seitig)	.	,706
		N	54	53
	mean experiment sap flow in kg	Korrelationskoeffizient	,053	1,000
		Sig. (2-seitig)	,706	.
		N	53	53

Korrelationen

			below plots depth 40cm MDSM in vol. %	mean experiment without 1.3 sap flow in kg
Spearman-Rho	below plots depth 40cm MDSM in vol. %	Korrelationskoeffizient	1,000	,071
		Sig. (2-seitig)	.	,615
		N	54	53
	mean experiment without 1.3 sap flow in kg	Korrelationskoeffizient	,071	1,000
		Sig. (2-seitig)	,615	.
		N	53	53

Korrelationen

		mean experiment sap flow in kg	above plots depth 10cm MDSM in vol. %	above plots depth 20cm MDSM in vol. %	above plots depth 30cm MDSM in vol. %	above plots depth 40cm MDSM in vol. %
mean experiment sap flow in kg	Korrelation nach Pearson	1	,224	,293	,327	,314
	Signifikanz (2-seitig)		,107	,033	,017	,022
	N	53	53	53	53	53
above plots depth 10cm MDSM in vol. %	Korrelation nach Pearson	,224	1	,935	,662	,499
	Signifikanz (2-seitig)	,107		,000	,000	,000
	N	53	54	54	54	54
above plots depth 20cm MDSM in vol. %	Korrelation nach Pearson	,293	,935	1	,854	,726
	Signifikanz (2-seitig)	,033	,000		,000	,000
	N	53	54	54	54	54
above plots depth 30cm MDSM in vol. %	Korrelation nach Pearson	,327	,662	,854	1	,973
	Signifikanz (2-seitig)	,017	,000	,000		,000
	N	53	54	54	54	54
above plots depth 40cm MDSM in vol. %	Korrelation nach Pearson	,314	,499	,726	,973	1
	Signifikanz (2-seitig)	,022	,000	,000	,000	
	N	53	54	54	54	54

Korrelationen

		mean experiment without 1.3 sap flow in kg	above plots depth 10cm MDSM in vol. %	above plots depth 20cm MDSM in vol. %	above plots depth 30cm MDSM in vol. %	above plots depth 40cm MDSM in vol. %
mean experiment without 1.3 sap flow in kg	Korrelation nach Pearson	1	,259	,330	,362	,344
	Signifikanz (2-seitig)		,061	,016	,008	,012
	N	53	53	53	53	53
above plots depth 10cm MDSM in vol. %	Korrelation nach Pearson	,259	1	,935	,662	,499
	Signifikanz (2-seitig)	,061		,000	,000	,000
	N	53	54	54	54	54
above plots depth 20cm MDSM in vol. %	Korrelation nach Pearson	,330	,935	1	,854	,726
	Signifikanz (2-seitig)	,016	,000		,000	,000
	N	53	54	54	54	54
above plots depth 30cm MDSM in vol. %	Korrelation nach Pearson	,362	,662	,854	1	,973
	Signifikanz (2-seitig)	,008	,000	,000		,000
	N	53	54	54	54	54
above plots depth 40cm MDSM in vol. %	Korrelation nach Pearson	,344	,499	,726	,973	1
	Signifikanz (2-seitig)	,012	,000	,000	,000	
	N	53	54	54	54	54

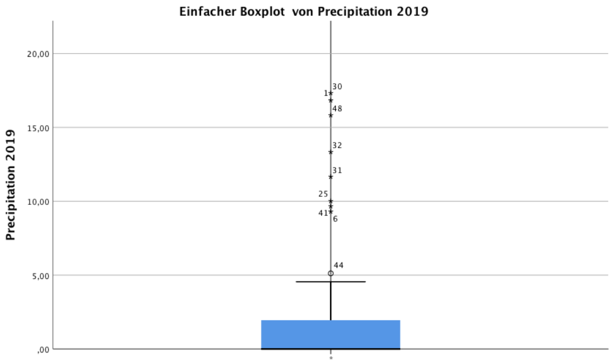
Korrelationen

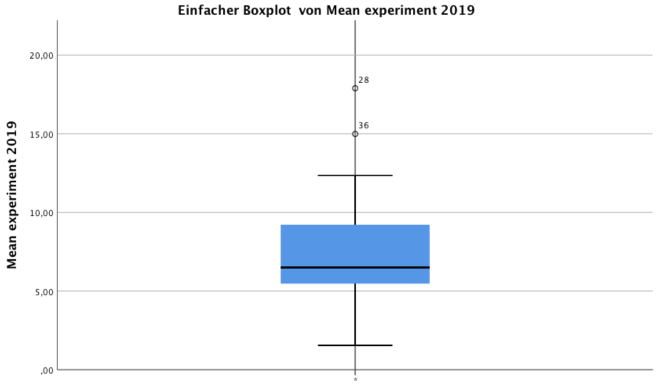
		mean control sap flow in kg	above plots depth 10cm MDSM in vol. %	above plots depth 20cm MDSM in vol. %	above plots depth 30cm MDSM in vol. %	above plots depth 40cm MDSM in vol. %	temperature i °C
mean control sap flow in kg	Korrelation nach Pearson	1	,262	,310	,306	,281	,64
	Signifikanz (2-seitig)		,058	,024	,026	,042	,00
	N	53	53	53	53	53	5
above plots depth 10cm MDSM in vol. %	Korrelation nach Pearson	,262	1	,935	,662	,499	,27
	Signifikanz (2-seitig)	,058		,000	,000	,000	,04
	N	53	54	54	54	54	5

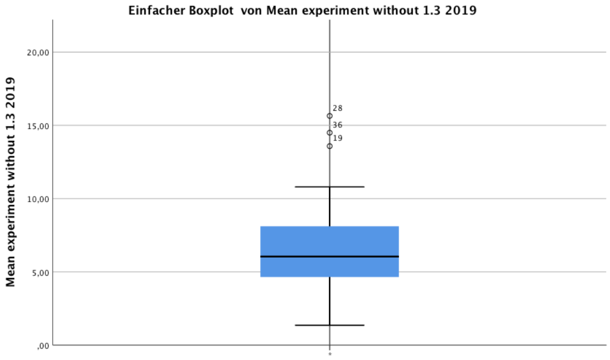
Analysis of night values after irrigation and heavy rainfall events

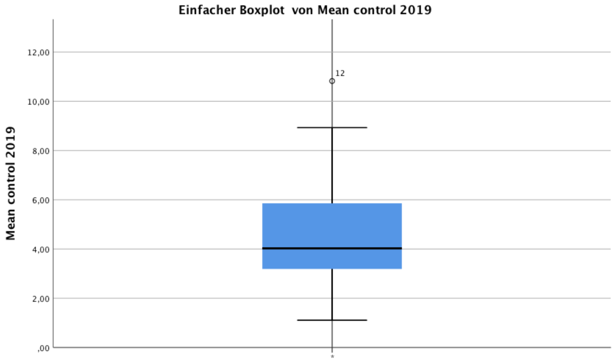
Detction of outliers

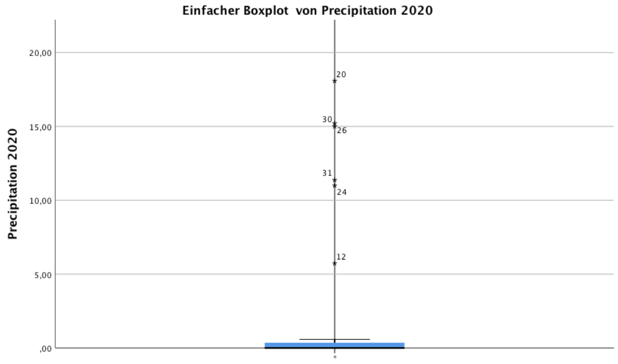
above plots depth 20cm MDSM in vol. %	Korrelation nach Pearson	,310	,935	1	,854	,726	,41
	Signifikanz (2-seitig)	,024	,000		,000	,000	,00
	N	53	54	54	54	54	5
above plots depth 30cm MDSM in vol. %	Korrelation nach Pearson	,306	,662	,854	1	,973	,50
	Signifikanz (2-seitig)	,026	,000	,000		,000	,00
	N	53	54	54	54	54	5
above plots depth 40cm MDSM in vol. %	Korrelation nach Pearson	,281	,499	,726	,973	1	,46
	Signifikanz (2-seitig)	,042	,000	,000	,000		,00
	N	53	54	54	54	54	5
temperature in °C	Korrelation nach Pearson	,644	,277	,412	,502	,467	
	Signifikanz (2-seitig)	,000	,043	,002	,000	,000	
	N	53	54	54	54	54	5

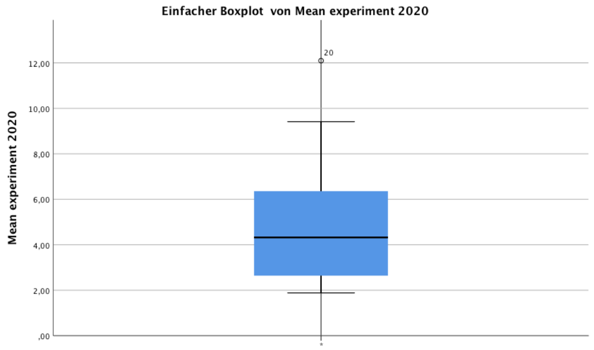


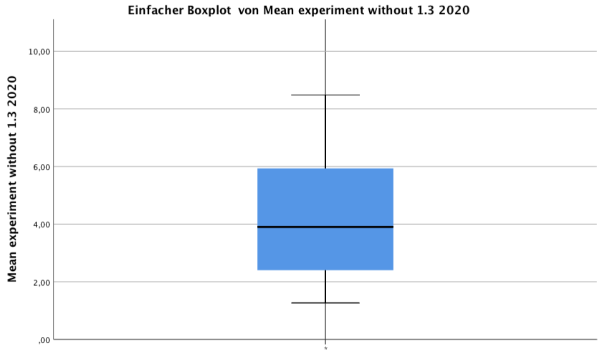


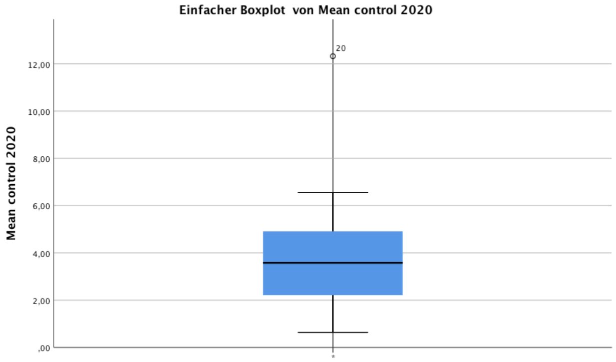








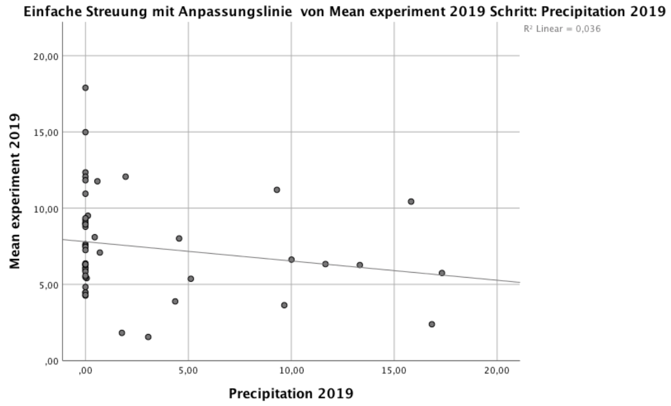


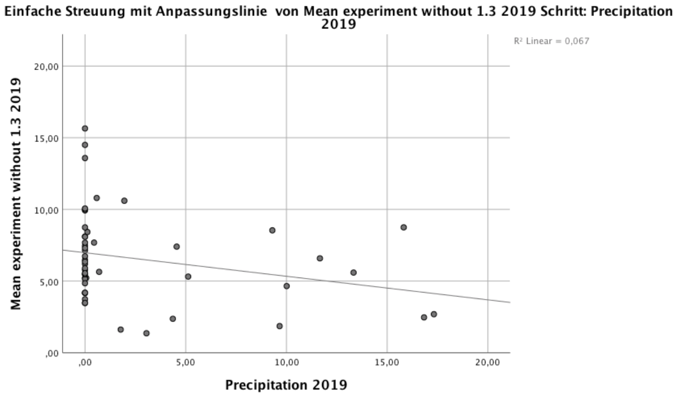


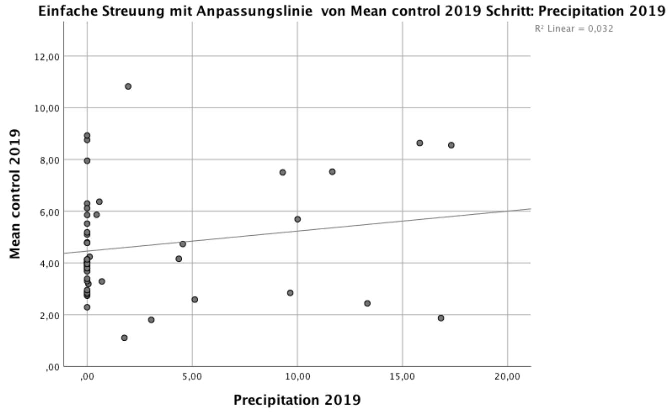
=> extreme outliers

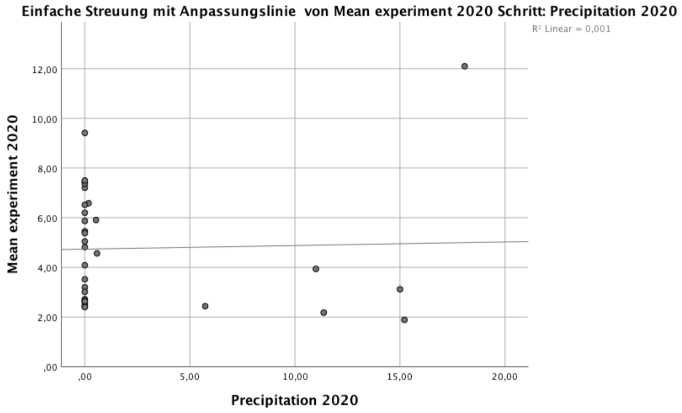
=> no Bravis-Pearson Correltation

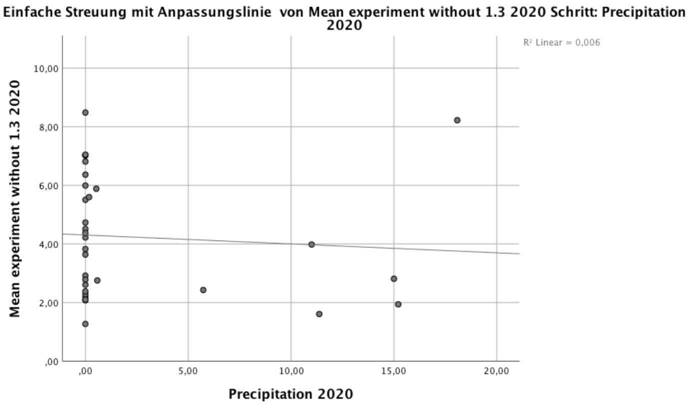
Test for liniar Correlation

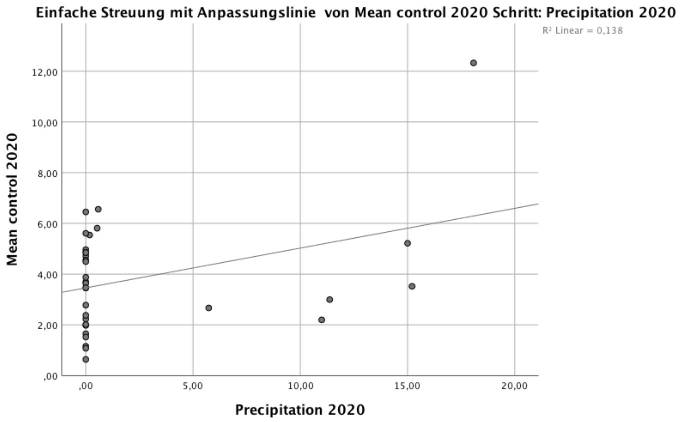












Not all Critaria fulfilled for Bravis- Pearson-Correlation

Spearmann- Correlation

Korrelationen

			Precipitation 2019	Mean experiment 2019	Mean experiment without 1.3 2019	Mean control 2019
Spearman-Rho	Precipitation 2019	Korrelationskoeffizient	1,000	-,187	-,210	,034
		Sig. (2-seitig)	.	,193	,144	,816
		N	50	50	50	50
	Mean experiment 2019	Korrelationskoeffizient	-,187	1,000	,968	,847
		Sig. (2-seitig)	,193	.	,000	,000
		N	50	50	50	50
	Mean experiment without 1.3 2019	Korrelationskoeffizient	-,210	,968	1,000	,787
		Sig. (2-seitig)	,144	,000	.	,000
		N	50	50	50	50
	Mean control 2019	Korrelationskoeffizient	,034	,847	,787	1,000
		Sig. (2-seitig)	,816	,000	,000	.
		N	50	50	50	50

Korrelationen

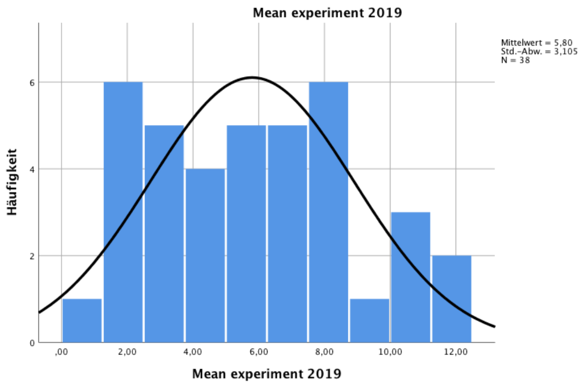
			Precipitation 2020	Mean experiment 2020	Mean experiment without 1.3 2020	Mean control 2020
Spearman-Rho	Precipitation 2020	Korrelationskoeffizient	1,000	-,140	-,130	,317
		Sig. (2-seitig)	.	,445	,477	,077

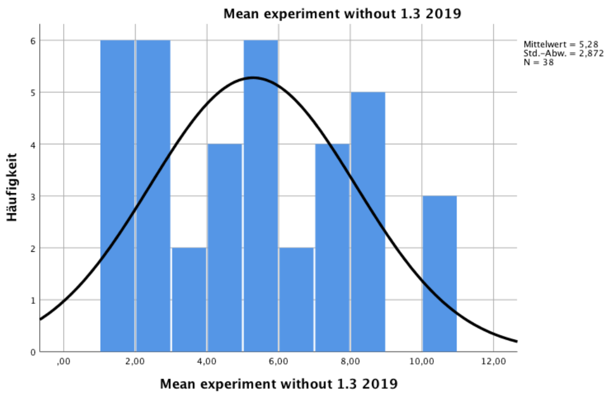
		N	32	32	32	32
	Mean experiment 2020	Korrelationskoeffizient	-,140	1,000	,961	,761
		Sig. (2-seitig)	,445	.	,000	,000
		N	32	32	32	32
	Mean experiment without 1.3 2020	Korrelationskoeffizient	-,130	,961	1,000	,742
		Sig. (2-seitig)	,477	,000	.	,000
		N	32	32	32	32
	Mean control 2020	Korrelationskoeffizient	,317	,761	,742	1,000
		Sig. (2-seitig)	,077	,000	,000	.
		N	32	32	32	32

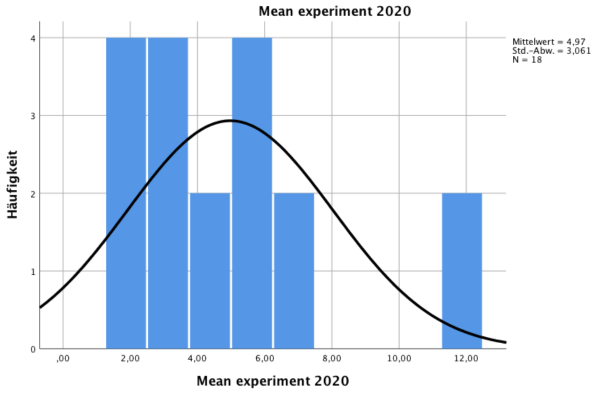
Test for Gauss distribution

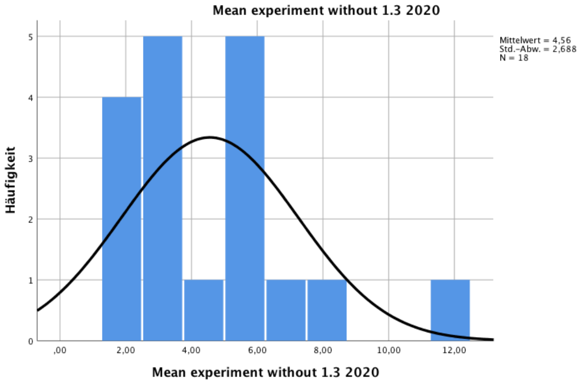
Statistiken

		Mean experiment 2019	Mean experiment without 1.3 2019	Mean experiment 2020	Mean experiment without 1.3 2020
N	Gültig	38	38	18	18
	Fehlend	0	0	20	20
Mittelwert		5,7995	5,2828	4,9744	4,5583
Std.-Abweichung		3,10488	2,87248	3,06139	2,68835
Varianz		9,640	8,251	9,372	7,227
Schiefe		,388	,326	1,495	1,505
Standardfehler der Schiefe		,383	,383	,536	,536
Kurtosis		-,771	-,979	1,940	2,882
Standardfehler der Kurtosis		,750	,750	1,038	1,038









⇨ Limited Number of N => only partly Gauss distributed
⇨ No T- Test possible
⇨ No Welch test possible
⇨ Mann- Whitney- U- Test

Mann-Whitney-U- Test

Ränge

	Treatment 2019	N	Mittlerer Rang	Rangsumme
Mean experiment 2019	control	19	16,63	316,00
	experiment	19	22,37	425,00
	Gesamt	38		
Mean experiment without 1.3 2019	control	19	18,47	351,00
	experiment	19	20,53	390,00
	Gesamt	38		

Statistik für Test

	Mean experiment 2019	Mean experiment without 1.3 2019
Mann-Whitney-U	126,000	161,000

Wilcoxon-W	316,000	351,000
Z	-1,591	-,569
Asymptotische Signifikanz (2-seitig)	,112	,569
Exakte Signifikanz [2*(1-seitige Sig.)]	,116	,583

Ränge

	Treatment 2020	N	Mittlerer Rang	Rangsumme
Mean experiment 2020	control	9	10,11	91,00
	experiment	9	8,89	80,00
	Gesamt	18		
Mean experiment without 1.3 2020	control	9	10,67	96,00
	experiment	9	8,33	75,00
	Gesamt	18		

Statistik für Test

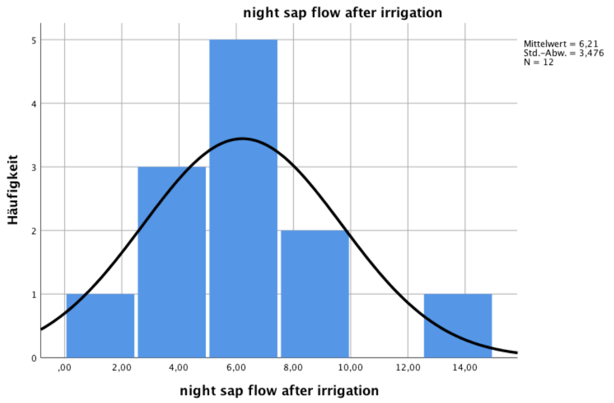
	Mean experiment 2020	Mean experiment without 1.3 2020
Mann-Whitney-U	35,000	30,000
Wilcoxon-W	80,000	75,000
Z	-,486	-,927
Asymptotische Signifikanz (2-seitig)	,627	,354
Exakte Signifikanz [2*(1-seitige Sig.)]	,666	,387

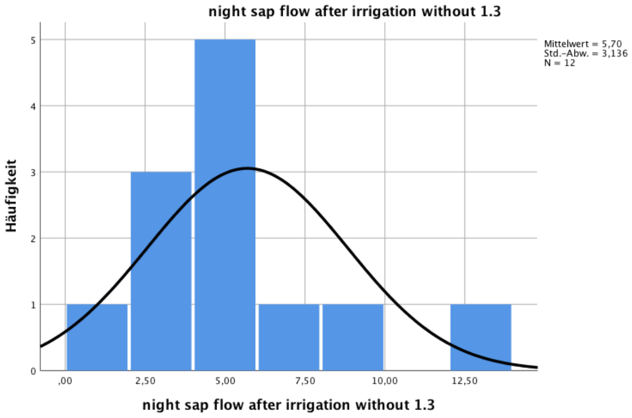
⇨ Irrigation
⇨ Test for Gauss distributon

Statistiken

		night sap flow after irrigation	night sap flow after irrigation without 1.3
N	Gültig	12	12
	Fehlend	0	0
Mittelwert		6,2142	5,6992

Varianz	12,084	9,832
Schiefe	1,403	1,476
Standardfehler der Schiefe	,637	,637
Kurtosis	2,643	3,026
Standardfehler der Kurtosis	1,232	1,232
Spannweite	12,99	11,77





- => limited umber of N
- => partly Gauss distributed
- => no Students T- Test
- => No welch-Test
- => Mann- Whitney- U-Test
- Mann- Whitney- U-Test

Ränge

	treatment	N	Mittlerer Rang	Rangsumme
night sap flow after irrigation	control	6	4,50	27,00
	experiment	6	8,50	51,00
	Gesamt	12		
night sap flow after irrigation without 1.3	control	6	5,00	30,00
	experiment	6	8,00	48,00
	Gesamt	12		

Statistik für Test

	night sap flow after irrigation	night sap flow after irrigation without 1.3

Mann-Whitney-U	6,000	9,000
Wilcoxon-W	27,000	30,000
Z	-1,922	-1,441
Asymptotische Signifikanz (2-seitig)	,055	,150
Exakte Signifikanz [2*(1-seitige Sig.)]	,065	,180