Universität Zürich[UZH]

Department of Geography

Spatial and temporal variation in soil moisture and transpiration in the Studibach catchment, Switzerland

GEO 511 Master's Thesis

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Abbreviations

DEM……………………..…………….Digital Elevation Model
dS……………………….…..…………Delta Storage
e………………………………………..Euler’s number
ET……………………………..……….Evapotranspiration
F………………………..…..…..……..Flag
m a.s.l……………………….……….Meter above sea level
P……………………………….…..….Precipitation
Q……………………………..………..Discharge
r………………………………………..Radius
RH…………………………..….…….Relative Humidity
SVP…………………………………..Saturation Vapour Pressure
T……………………………………….Temperature
Transp……………………………….Transpiration
TWI……………………..…………….Topographic Wetness Index
VPD…………………………….…….Vapor Pressure Deficit
VSM………………………..…………Volumetric Soil Moisture
WSL…………………………………..Swiss Federal Institute for Forest, Snow and Landscape Research
Ψsoil…………………………..……..Soil water potential

Abstract

Transpiration is a key process of the water cycle and is influenced by various ecosystem factors. The interplay between the different factors, especially between soil moisture and transpiration, is not fully understood. On top of that, climate change is expected to shift water fluxes by decreasing runoff and increasing evapotranspiration in the pre-Alpine region, with implications for local forest health and water supplies for downstream basins. Therefore, this thesis contributes to the understanding of the temporal and spatial variation of soil moisture and transpiration, across a hillslope. The study was conducted in the Studibach catchment in the Alptal in the pre-Alpine region of Switzerland, during the growing season of 2024. Sap flow of Norway spruce trees was measured at three locations across a slope. At additional location's manual and continuous soil moisture measurements as well as the meteorological conditions were recorded, and sap wood area was estimated from tree cores. Findings show a weak correlation between soil moisture and topographic wetness index. During moderate soil moisture conditions, the correlation is stronger between soil moisture and the topographic wetness index, in comparison to wet conditions. Sap flow was shown to significantly differ between sites with different topographic wetness index at a monthly scale and partially on a weekly scale. Meanwhile transpiration shows a different spatial pattern which is due to the amount of sapwood area per site. For both sap flow and transpiration, a difference across the study sites is found but the explanation for the spatial pattern remains unclear. It is recommended to extend the research with measurements in a dry year and more locations.

1. Introduction

1.1 Importance of transpiration

Evapotranspiration (ET) is a key process of the water cycle that has an influence on local and global climate as it transfers 60-80% of precipitation to the atmosphere (Castelli, 2021; van Meerveld & Seibert, 2024). The fluxes of ET are composed of transpiration of the plants, soil evaporation and interception (Verstraeten, et al., 2008). Globally the terrestrial ET flux is mainly regulated by plant transpiration (Ghimire, et al., 2022). Schlesinger and Jasechko (2014) conclude that globally transpiration accounts for 61% (±15%) of ET. Quantifying the spatial and temporal variation of transpiration is relevant as it impacts the water balance and water availability (Castelli, 2021). This becomes especially relevant, when trying to improve hydrological models in consideration of the changing soil-plant-atmosphere interaction with climate change (Mastrotheodoros, et al., 2020; Berg & Sheffield, 2018). Because transpiration is controlled by multiple variables such as atmospheric conditions, soil moisture, and vegetation, research has been difficult and the interplay of the dynamics between soil moisture and transpiration are not yet fully understood (Bourbia, et al., 2025; Fabiani, et al., 2021; Fabiani, et al., 2024; Hassler, et al., 2018; Koehler, et al., 2023; Novick, et al., 2016; Tromp-van Meerveld & McDonnell, 2006; Vivoni, et al., 2008).

In Europe the average annual value of ET is estimated to be 489 mm with an average precipitation of 789 mm (Novák, 2012). Furthermore, the ET in temperate coniferous forests is assessed to be 458 mm/year and in temperate deciduous forests 549 mm/year (Schlesinger & Jasechko, 2014). In the temperate coniferous forest, the percentage of transpiration of the ET is estimated to be 55% (±15%) (Schlesinger & Jasechko, 2014). Within the Alptal the average annual water balance of the Erlenbach catchment from 1968 to 1993 shows 450 mm ET with precipitation of 2190 mm and 1740 mm of streamflow (Bruch, 1994). However, there not a lot of studies on transpiration in the pre-Alpine region, particularly not field studies on steep slopes (de Jong, et al., 2005; van Meerveld, et al., 2018; Verstraeten, et al., 2008).

With the predicted warming in the Alps the snow cover is declining, which affects the hydrological cycle and seasonal variation in streamflow (Castelli, 2021; Stähli, et al., 2021). The increase in the frequency and intensity of droughts in the Alps could cause a lack of soil moisture in the summer months and influence evapotranspiration and forest health (Brunner, et al., 2023). With climate change, vapor pressure deficit (VPD) is expected to rise and could limit transpiration and impact forest health (Grossiord et al. 2020; Novick et al. 2016). However, the modeling results of Mastrotheodoros et al. (2020) suggested that, during the heatwave and drought of 2003 the evapotranspiration rates in the Alps increased by 45mm, due to the higher radiation and vapor pressure deficit. The increase in ET leads to a decrease in annual runoff, which impacts the water availability in Switzerland (Mastrotheodoros, et al., 2020). Similar findings in Rietholzbach show that ET was the main influence on water storage deficit and the following drought conditions in June 2003 (Seneviratne, et al., 2012). However, during drought conditions the decline in soil moisture can become limiting for ET (Calanca, 2007; Hirschi, et al., 2020). Because transpiration and soil moisture are critical components to investigate land-atmosphere interactions, it is important to study their spatial variation (Liu, et al., 2019). Knowledge of the spatial and temporal patterns of soil moisture and transpiration also helps to understand the pathways of water, and to evaluate impacts of climate change (Grayson, et al., 1997).

1.2 Spatial and temporal patterns in soil moisture

Due to the lateral redistribution of water, topography affects soil moisture distribution (Western, et al., 1999). The Topographic Wetness Index (TWI) introduced by Beven & Kirkby (1979) is due to its simplicity widely used as a proxy for soil moisture (Jarecke, et al., 2021; Mohamedou, et al., 2019; Riihimäki, et al., 2021; Rinderer, et al., 2014; Sørensen, et al., 2006; Winzeler, et al., 2022). The TWI's application potential is high because it can be calculated by only using a digital elevation model (DEM). However, it has been shown to be limited and only have low to moderate predictive power (Winzeler, et al., 2022). It is important to better understand the interrelations of soil moisture and topography as they can explain flooding, erosion, solute transport and pedogenic and geomorphic processes (Western, et al., 1998), as well as the distribution of vegetation (Atchley & Maxwell, 2011). While climate and soil moisture influence vegetation growth, vegetation cover impacts the water balance and feedbacks to the atmosphere (Tromp-van Meerveld & McDonnell, 2006). Depending on the vegetation cover and hillslope, the evapotranspiration and soil moisture varies (Jarecke, et al., 2021; Vivoni, et al., 2008). With climate change soil moisture is predicted to decline in the pre-Alpine region, with more decline expected on steeper slopes and in forests (Jasper, et al., 2006). The soil moisture pattern on slopes has been studied in great detail by several authors, it has been shown that the pattern in soil moisture depends on a lot of different factors such as topography, soil properties, vegetation characteristics, climate and seasonality (Grayson, et al., 1997; Hassler, et al., 2018; Heštera, et al., 2024; Jarecke, et al., 2021, Jasper, et al., 2006; Kolleger, 2011; Liu, et al., 2024; Riihimäki, et al. 2021; Rosenbaum, et al., 2012; Sørensen, et al., 2006; Tromp-van Meerveld & McDonnell, 2006; Western, et al., 1998, Western, et al, 1999; Winzeler, et al., 2022).

In one of the first detailed studies on the spatial variation in soil moisture in the Tarrawarra catchment, Western et al. (1998) showed the influence of topography on soil moisture resulting from lateral distribution of water during the wet season and from the water retention properties of the soil during the dry season. In the Alptal, Kollegger (2011) found soil moisture to be generally high and that the spatial pattern varies with topography and vegetation cover. However, Jarecke et al. (2021) found that during both wet and dry conditions the spatial variation of soil moisture was mainly influenced by soil properties, and not by hillslope topography for a catchment in west-central Cascades Mountains of Oregon USA. Other studies suggested that there is less variation of soil moisture across the hillslope during the wet winter months than in the dry summer months (Tromp-van Meerveld & McDonnell, 2006). Liu et al. (2024) also reported the lack of a relation between the average soil moisture and topography in the wet season for a catchment on the Chinese Loess Plateau. These contrasting findings could be due to site specific factors that vary with topography, soil characteristics, climate conditions, or vegetation (Liu, et al., 2024). Moreover, soil moisture varies dynamically with seasons due to changes in precipitation, temperature, and evapotranspiration (Winzeler, et al., 2022). In this thesis, the focus lies on the impact of the soil moisture pattern across the slope and over the growing season on the resulting transpiration pattern.

1.3 Temporal and spatial variation in transpiration

Transpiration is the process where water is transported from the soil to the atmosphere through the plants and therefore is an important part of plant productivity (Novák, 2012). The temporal and spatial variation of transpiration depends on local factors. The main drivers and limiting factors which influence transpiration can be divided in environmental factors, climatic conditions and biological factors (Ghimire, et al., 2022). Environmental factors entail the ecoregion, altitude, land cover, soil texture, and topography determined by slope and aspect (Calanca, 2007). The biological factors of the plant species, forest structure and composition, tree size and age, rooting depth and leaf surface area all have an impact on transpiration rates (Ghimire, et al., 2022; van Meerveld & Seibert, 2024). On top of that the climatic conditions on different temporal and spatial scales show that transpiration varies with radiation, VPD, wind speed, precipitation, and soil water availability (Castelli, 2021; Ghimire, et al., 2022). The interrelation of these factors and relative importance considering transpiration rates are complicated and difficult to measure (Novák, 2012).

Hirschi et al. (2020) found that in forests the transpiration is higher than for unmanaged grassland or agricultural cropland. Further Castelli (2021) states that transpiration is elevated with increasing leaf surface area. A field study in eastern Madagascar found that VPD and radiation are the factors that explained the variation in transpiration the most (Ghimire et al., 2022). Therefore, at locations with high elevation the transpiration is constrained by the air temperature, VPD and wind speed (Calanca, 2007). Castelli (2021) agrees that radiation plays a major role and adds that precipitation impacts the soil moisture availability for transpiration. On the one hand, during dry periods transpiration is limited by soil moisture availability where it depends on root depth of the plants, on the other hand transpiration is also limited when the relative humidity is too high (Ghimire, et al., 2022; Verstraeten, et al., 2008). Limitation of ET (where transpiration is the dominant component) by soil moisture is also reflected in a global pattern. Berg and Sheffield (2018) show that a significant share of ET variance is explained by soil moisture variability. Globally in drier regions the ET is soil moisture limited and in wetter regions, in the tropics and in the high latitudes, the ET is not soil moisture limited and is shown to be negatively correlated with soil moisture (Berg & Sheffield, 2018). However, Liu et al. (2024) suggest that variation of soil moisture under wet and dry conditions is dominated by the dynamics of evapotranspiration.

Research has investigated the relationship of topography and evapotranspiration (Fabiani, et al., 2022; Fabiani, et al., 2024; Hassler, et al., 2018; Tromp-van Meerveld & McDonnell, 2006). Several studies suggest that the change in ET is impacted by the soil moisture pattern, which in turn is spatially distributed due to the slope (Calanca, 2007; Jasper, et al., 2006). While

Tromp-van Meerveld and McDonnell (2006) observed no difference of sap flow across the hillslope during early summer, in late summer the trees on the upslope showed a decrease in daily sap flow rates with drier soil conditions and a large increase after a rainfall while the decrease did not occur at trees on the midslope and lower slope (Tromp-van Meerveld & McDonnell, 2006). Similarly, Fabiani et al. (2024) observed lower sap velocities and a shorter growing season of trees growing in the upper portions of the hillslope at Lecciona. Which Fabiani et al. (2024) attribute to downslope locations being recharged by water redistribution from the upper slopes. Thus, the downslope can support sap flow in trees during extended dry conditions while sap flow declines at the upslope locations. This pattern was observed but not consistently across landscapes which is why it is important monitoring this relationship at more locations.

1.4 This study

The aim of this thesis is to research the relationship of soil moisture and sap flow as well as transpiration across the hillslope of the Studibach catchment in the Alptal of Switzerland over the growing season in 2024. Thus, this thesis follows one main research question which is divided into three sub-questions and hypotheses:

What is the effect of topography on the spatial and temporal variation in soil moisture and sap flow as well as transpiration in the Studibach catchment in the Alptal in Switzerland?

Research question 1: How does soil moisture vary with topography?

> Hypothesis 1: Soil moisture is higher for the flat areas than on the steeper slopes (Grayson et al., 1997; Jarecke et al., 2021; Liu et al., 2024; Rosenbaum et al., 2012; Tromp-van Meerveld & McDonnell, 2006; Western et al., 1998; Western et al., 1999).

Research question 2: How do sap flow and transpiration rates vary with weather conditions?

> Hypothesis 2: Sap flow and transpiration rates are positively correlated with temperature and radiation, and linearly up to a certain threshold with vapour pressure deficit (Dingman, 2002; Grossiord et al., 2020; Jarvis, 1979; Koehler et al. 2023).

Research question 3: How do sap flow and transpiration rates vary with topography and soil moisture?

> Hypothesis 3: Sap flow and transpiration rates are reduced at both very low and high soil moisture (Fabiani, et al., 2022; Fabiani, et al., 2024; Liu, et al., 2024; Mastrotheodoros, et al., 2020; Novick, et al., 2016; Tromp-van Meerveld & McDonnell, 2006).

3. Study site

3.1 Studibach catchment

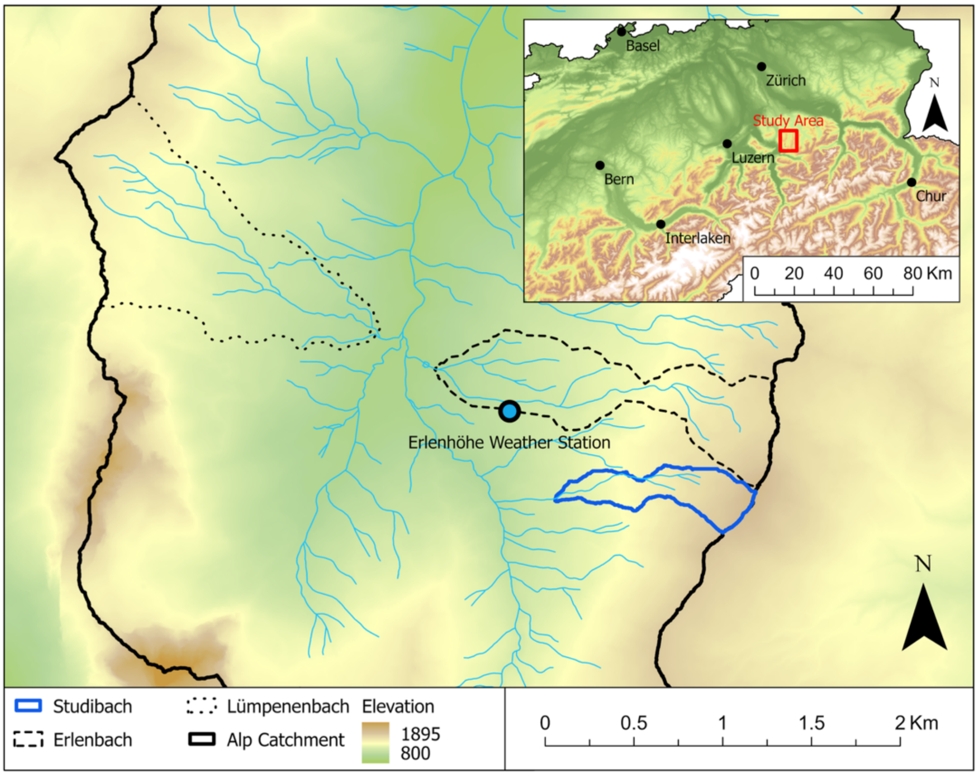

Figure 1. Map of the Alp catchment with the Studibach catchment and the location of the Erlenhöhe Weather station (van Dijk, 2024).

The 20 ha Studibach catchment in the Alptal is located in the pre-Alpine region of Switzerland (N47.038, E8.723). The Studibach catchment is located on a western slope and ranges from 1270 to 1650 m a.s.l. in elevation (van Meerveld, et al., 2018) (Figure 1). The climate is humid, with a mean precipitation of 2300 mm per year (Kiewiet et al., 2019). The mean annual air temperature is 5.7°C at the meteorological station "Erlenhöhe" (Stähli, et al., 2021). Generally, wet grassland areas can be found in the flat parts of the catchment, while the coniferous forest areas are located at the steeper slopes (Rinderer, et al., 2014). The area has an average slope of 21° with a maximum of 47° (van Meerveld, et al., 2018). The gleysols are 0.5-2.5 m deep and overlay flysch bedrock which is poorly permeable (Rinderer, et al., 2014). The soil depth and soil type vary due to differences in the local topography, which shows shallow soils in ridges and deeper soils in depressions (Rinderer, et al., 2014). Land cover consists of 53% forest and 28% wetland cover (van Meerveld, et al., 2018). The forest consists of spruce, silver fir, grey alder and beech (Bruppacher, 2022). The understory varies from blueberries at drier locations, while ferns and Equisetum dominate the wet areas (Bruppacher, 2022).

The Studibach catchment is a suitable study area to investigate the effect of topography on vegetation cover, soil moisture and evapotranspiration because the landscape is heterogenous and consist of forest and grassland across various slopes (van Meerveld, et al., 2018). Currently the Alptal is characterized by mostly wet conditions due to frequent and high precipitation and low permeability soils (van Meerveld, et al., 2018). Furthermore, it is known that topography has a large effect on groundwater levels and water quality (Rinderer, et al., 2014; Kiewiet, et al., 2019). Hydrological research in the Alptal started in 1963 by the Swiss Federal Institute for Forest, Snow and Landscape (WSL) and is still ongoing, a comprehensive summary of the research and the catchment characteristics has been done by van Meerveld, et al., (2018) and Stähli, et al., (2021). While the research started to investigate the effects of forestry on floods and water quality, research concerning geomorphological processes, observations of biogeochemical and ecohydrological processes followed, and in more recent years research has shifted to the effects of climate change on water resources (Stähli, et al., 2021). Additionally, the Studibach catchment is located in the critical elevation range of 1000–1500 m a.s.l, where the snow cover and therefore the hydrological regime is highly sensitive to temperature changes (Stähli, et al., 2021). Over the past 50 years, there has been an increase of about 2°C in mean annual air temperature and a shift towards earlier snowmelt (Stähli, et al., 2021). Therefore, the Studibach catchment is an important study area to research the spatial and temporal effects of soil moisture and evapotranspiration.

3.2 Research site

The study site is in the lower part of the Studibach catchment (Figure 1), which is dominated by forest of silver fir and Norway spruce (van Meerveld, et al., 2018). Locations were chosen along the hillslope including steep and flat parts with wet and dry areas, to cover highly heterogenous landscape (Figure 2). Additionally, accessibility of the research site was important due to heavy field equipment and weekly exchange of batteries. Due to these reasons the locations for installing the field instruments were chosen in the lowest part of the Studibach catchment. The study area range from 1266 to 1328 m a.s.l..

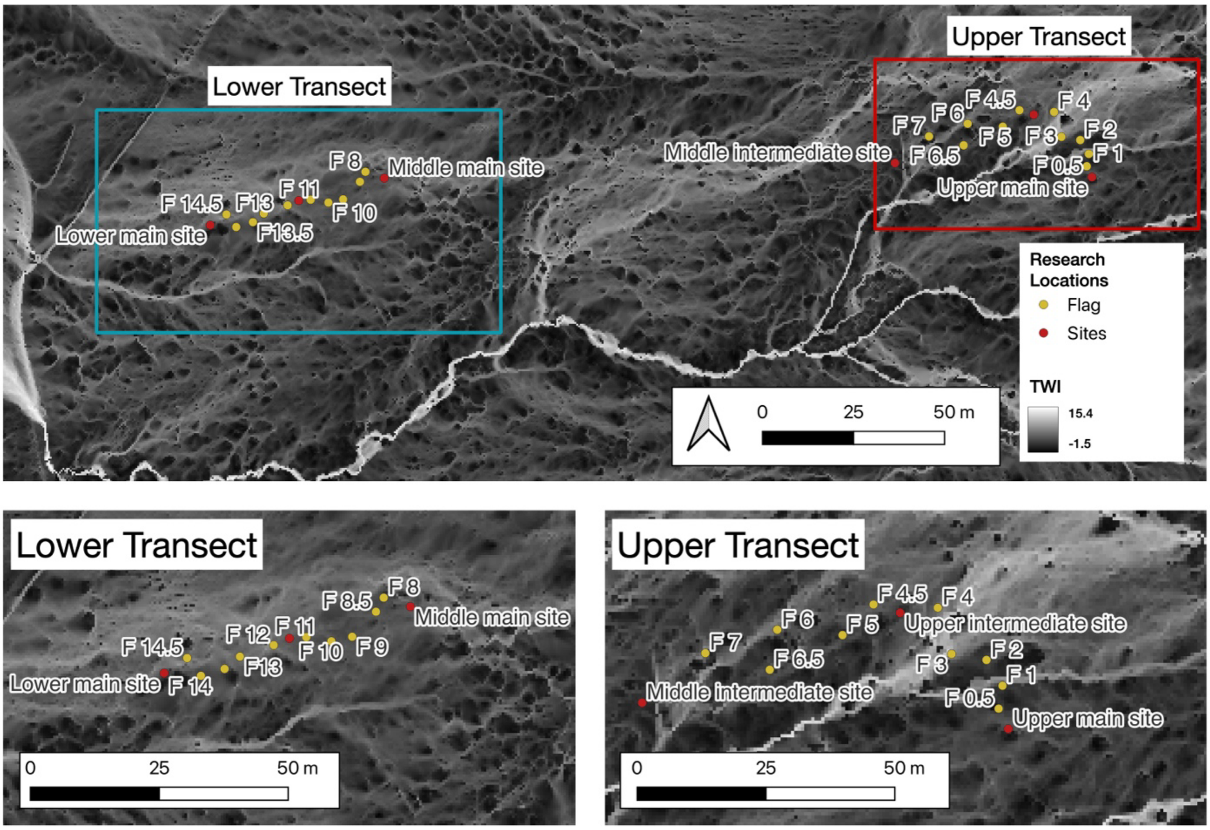

Figure 2. Map of the study site with locations of the measurements. The two lower maps are cutout from the above map to see more detail of the lower and upper transect.

The sites are selected along two transects across the hillslope which contain a steeper upper part and a flatter lower part. The two transects are about 140 m apart, while the lower transect stretches over 70 m and the upper transect over 50 m. Overall, there are three main sites along the transacts (Upper main site, Middle main site and Lower main site) where the most field equipment and in particular the sap flow measurements take place (Figure 3). In between there are three intermediate sites (named Upper intermediate site, Middle intermediate site and Lower intermediate site) and additional locations marked by flags (named F0.5 to F14.5). At the highest and lowest location, a meteorological measurement equipment was added. In Table 2 there is an overview of all sites with the according names, GPS location, measurement instruments, TWI, slope and aspect.

TWI of the sites ranges between 2 to 5. Generally, the research site has wet soil conditions (Kiewiet et al., 2019). This is represented in the soil types and soil depths of the three main sites (Table 1). During fieldwork with Meret Vogler the soils at the three main sites were observed to be Gleysol with high clay content in the deeper soil depth (Vogler, 2025).

However, due to local topography the soil depth and type varies already at a small scale. At the lowest main site there is a small seasonal stream flowing next to it. The upper main site is steeper than the middle main site and the lower main site. Furthermore, the upper main site is characterized by more ground vegetation than the other main sites.

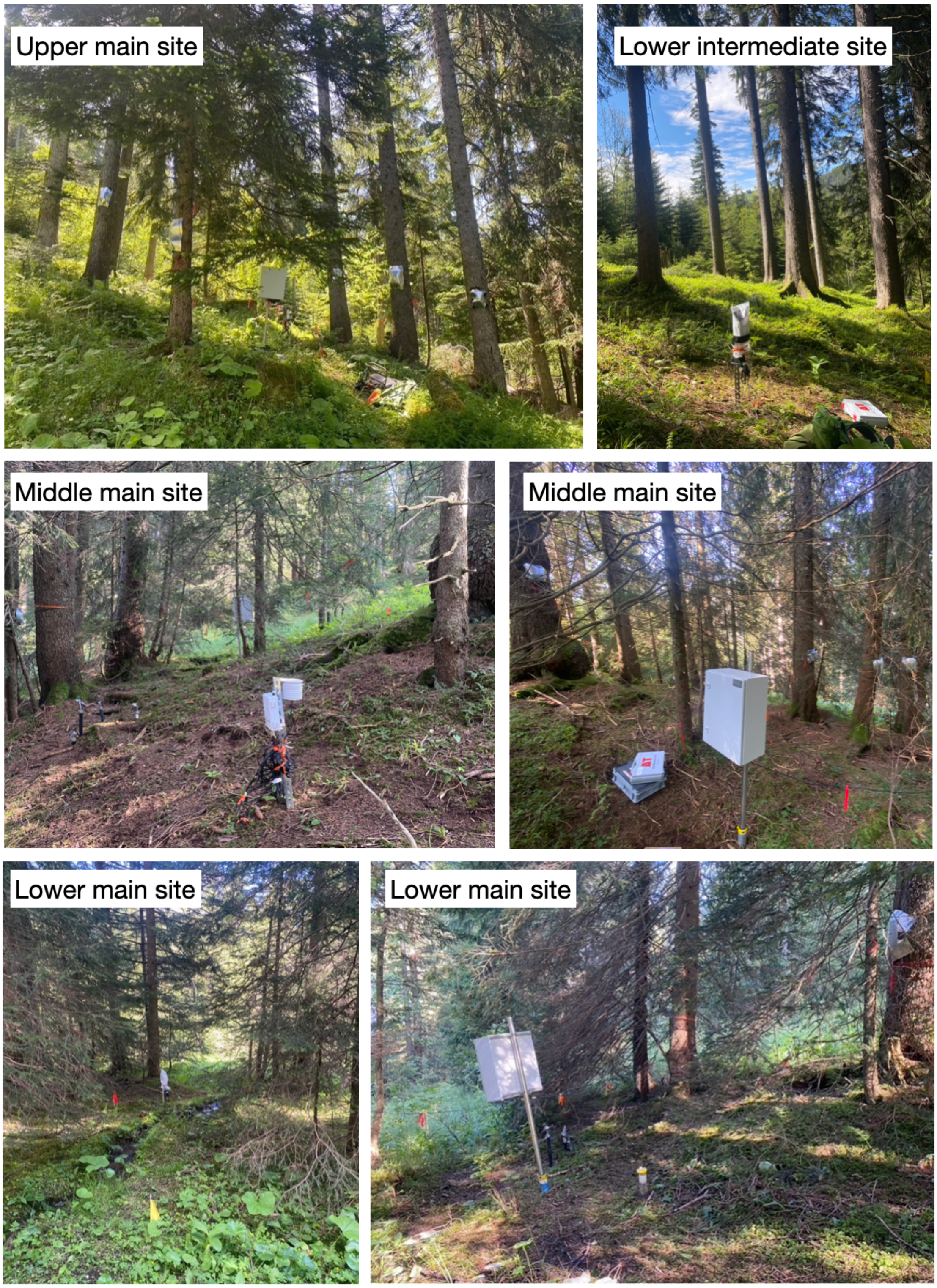

Figure 3. Photos of the measurement installation at multiple sites.

Table 1. Soil types and horizons at main sites , which is documented by (Vogler, 2025). during fieldwork.

Location	**Lower main site**	**Middle main site**	**Upper main site**
Organic horizon (L)	2-5 cm Needles, twigs	2-5 cm Needles, twigs	2-8 cm Needles, twigs, leaves
A_h	20-30 cm	20-30 cm	30-40 cm
G_r	>30 cm, very clayey and wet	>30 cm, very clayey and wet	>40 cm, less clayey, a bit drier and porous

Table 2. Characteristics of sites, M. = Main, Int.= Intermediate, SM = soil moisture: coordinate location, installed measurement instrument, manual measurements, slope, TWI and aspect (assessed with QGIS).

Site name	Location (CH1903/LV95 EPSG_2056) E/N		Manual -SM	Continuous-	Sap flow	Atmos 41	VP-3-sensor	Groundwater	Slope	TWI mean	TWI median	Aspect
Upper M. site	2697439.138	1210553.756	X	X	X	X	X		19.96°	2.65	2.79	261.7°
F0.5	2697437.713	1210556.73	X						23.55°	2.78	2.34	279.67°
F1	2697438.278	1210560.119	X						25.74°	2.76	2.05	265.29°
F2	2697435.916	1210563.918	X						24.04°	3.8	3.01	253.8°
F3	2697430.761	1210564.798	X						20.19°	5.36	5.29	237.18°
F4	2697428.728	1210571.62	X						17.8°	5.59	5.23	214.16°
Upper Int. Site	2697423.162	1210570.877	X	X					15.43°	3.69	3.78	227.08°
F4.5	2697419.225	1210572.099	X						15.27°	3.34	3.49	255.10°
F5	2697414.65	1210567.589	X						15.61°	2.5	2.41	244.07°
F6	2697405.013	1210568.382	X						17.27°	3.14	2.66	243.89°
F6.5	2697403.898	1210562.478	X						20.54°	2.24	2.17	251.21°
F7	2697394.387	1210564.924	X						15.99°	3.39	3.15	224.84°
Middle Int.Site	2697385.047	1210557.612	X	X	X		X	X	9.08°	2.53	1.99	205.36°
Middle M. site	2697244.801	1210553.482	X	X	X		X	X	17.94°	4.42	4.42	274.52°
F8	2697239.622	1210555.208	X						18.61°	4.62	4.14	266.19°
F8.5	2697238.118	1210552.479	X						21.7°	3.91	3.80	260.23°
F9	2697233.5	1210547.642	X						28.93°	3.69	3.72	256.05°
F10	2697229.46	1210546.766	X						26.87°	3.81	3.8	260.37°
F11	2697224.59	1210547.563	X						21.20°	4.46	4.4	262.11°
Lower Int. Site	2697221.328	1210547.332	X	X					18.67°	4.65	4.76	264.45°
F12	2697218.278	1210546.014	X						16.16°	4.44	4.95	271.85°
F13	2697211.715	1210543.791	X						14.77°	4.45	3.80	272.57°
F13.5	2697208.73	1210541.41	X						12.87°	4.28	4.93	273.65°
F14	2697204.147	1210540.072	X						12.63°	3.92	4.99	265.11°
F14.5	2697201.47	1210543.519	X						12.62°	4.57	4.25	260.53°
Lower M. site	2697197.016	1210540.59	X	X	X	X	X	X	16.22°	3.75	3.96	261.02°

4. Methods

4.1 Field measurements

The fieldwork took place from the 05.05.2024 until the 06.10.2024. The installation of the measurement instruments started in the beginning of May, while the data gathering went on until October to cover the growing season and therefore the temporal variation within. Different instruments were installed across the hillslope (Table 2) to measure soil moisture, sap flow, weather conditions and groundwater. Most instruments measure continuously. During field days batteries were exchanged, data downloaded, and instruments checked and repaired. Furthermore, on 21 days soil moisture was measured manually at all 26 locations. Fieldwork days were conducted once or twice every week (in total about 30 days), depending on the weather. As soil moisture measurements are more accurate when measured on days without rainfall. In the following the instruments are described in more detail.

4.1.1 Weather stations

At the upper main site, intermediate middle site and middle main site air temperature and relative humidity was measured every 10 min with VP-3 humidity and temperature sensors connected to the EM50 data loggers (Meter Group). The instruments measured from the 05.06.2024 until 05.10.2024.

Two ATMOS 41 weather stations connected to ZL6 data loggers (Meter Group) measured every 10 min air temperature, relative humidity, barometric pressure, vapor pressure, wind speed, wind direction, wind gust, solar radiation, precipitation, lightning strike count and distance. The locations chosen are close to the upper main site and lower main site, although more in an open space a few meters away from the trees. The weather station was installed 2 m above the ground. The measurement period was from the 13.06.2024 until the 05.10.2024.

Furthermore, existing meteorological data are available for the Alptal from the Erlenhohe long-term monitoring station of the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL, 2024a). It is the closest weather station to the Studibach catchment, only about 500 m away at 1210 m a.s.l. (WSL, 2024b).

4.1.2 Groundwater

The data of three already existing groundwater wells with water level loggers (Odyssey) were used. Two are located at the intermediate middle site and one close to the middle main site. At the lower main site, a new groundwater well was installed by Belle Holthuis and Ilja van Meerveld on the 13.06.2024 using the DCX-22 data logger barometer (Keller).

4.1.3 Soil moisture

At six locations along the transacts (three at each transact) soil moisture was measured continuously every 10 minutes with TERROS 12 Advanced Soil Moisture and Temperature sensor and GS3 sensors, connected to EM50 and ZL6 Advanced Cloud data logger (Meter Group). In cooperation with Belle Holthuis the soil moisture equipment was installed. At each location soil moisture sensors were installed in depth of 5 cm, 15 cm and 30 cm. While an additional sensor was included at the upper main site in the depth of 45 cm, as this location was the driest and the soil was deeper. Another sensor was added at the lowest main site in the depth of 5 cm to have a replicate, as the measurements seemed too low.

Furthermore, soil moisture was measured manually every week during the fieldwork period with the ML3 ThetaProbe Soil Moisture Sensor and HH2 Moisture Meter (Delta-T Devices). The measurements were conducted at 26 locations spread along the transacts (13 at each transact), to cover the spatial variation across the hillslope. The soil moisture was measured five times within a radius of 0.3m at each site and then the median was further used. The time of measurement was noted and was between 09:00 and 13:00 o'clock.

4.1.4 Sap Flow

To infer the transpiration of the Norway spruce trees the thermal dissipation probe method developed by Granier (1985) is applied. This method measures the xylem sap flow to estimate the transpiration of the tree (Granier, 1985). In detail, two cylindrical probes are inserted 2 cm into the sapwood (Granier, 1985). It is important that the two probes are inserted 10 cm apart and one above the other. The upper probe is heated constantly, while each probe contains a thermocouple which are connected in opposition (Granier, 1985). The temperature difference between the two probes is measured, which is influenced by the sap flow. As a general interpretation: increasing sap flow results in a decreasing temperature difference.

In practice, for the sap flow measurements SF-G sensors (Ecomatik) with an DL 300 datalogger (Umwelt-Geräte-Technik) were used. The sensors were installed at location the three main sites (lower, middle, upper) to cover wetter and drier sites and the spatial variation across the slope. To measure the sap flow similar sized Norway spruce trees were chosen (Table 3). Theoretically, six sensors in a 4 m radius from each of the three DL 300 datalogger could have been installed. However, due to technical issues and broken sensors the number of trees used for sap flow measurements changed throughout the measurement period and reaching a final count of 11 trees. However, in total there are three sensors at the upper main site, five sensors at the middle main site and three sensors at the lower main site. The sensors were installed at breast height on the north facing side of the tree to minimize sunshine exposure (Figure 4). As an additional measure the probes were covered with a generic type of aluminium-laminated insulation foil to avoid temperature fluctuations and protect from the rain. Sap flow was measured hourly from 09.06.2024 until 05.10.2024, although for every tree there is a different timespan and data gaps. Furthermore, the after the measurement period ended the sapwood area was measured with Meret Vogler together using an increment borer.

Figure 4. Installation of sap flow sensors into the tree

4.1.5 Catchment characteristics

The streamflow at the gauging station of the Erlenbach was measured by the WSL (WSL, 2024b). The data was provided in an interval of 10 min from the beginning of May until the beginning of October (WSL, 2024a). QGIS was used to calculate TWI, slope and aspect of the locations. The TWI was calculated using the DEM swissALTI3D (Swisstopo, 2024) with a resolution of 0.5m utilizing the r.watershed tool by GRASS on default settings in QGIS. Slope and Aspect are default operations provided by QGIS, the same DEM was used. Furthermore, the average aspect, slope and TWI of the sites was determined within an area with a radius of 5m around the sites (Table 2) utilizing the buffer and zonal statistic tool provided by QGIS.

4.2 Laboratory analysis

The Laboratory analysis was conducted together with Meret Vogler. To estimate the age of the studied trees cores were taken with an increment borer. At the WSL in Birmensdorf we were able to use the lab for forest dynamics and Dendrosciences. The tree cores were prepared and photographed with the Skippy system which allows digitizing tree rings. Further the CooRecorder software application was utilized to measure the tree-ring widths and count the age.

4.3 Data conversion

The data conversion was carried out in Excel, R and QGIS with the help of (Microsoft, 2024) and (Microsoft, 2025) to answer syntax and user interface questions.

4.3.1 Weather data

The temperature (T) and relative humidity (RH) data were used from the Erlenhöhe monitoring station from May to October. Utilizing the ASCE Standardized Reference Evapotranspiration Equation (Allen, et al., 2005), the saturation vapor pressure (SVP) can be calculated.

Equation 1. Calculation of saturation vapor pressure.

$$SVP = 0.6108 * e^{\frac{17.27*T}{T+237.3}}$$

T	=	Temperature
SVP	=	Saturation vapor pressure
e	=	Euler's number

Together with the RH the VPD is calculated.

Equation 2. Calculation of vapor pressure deficit by using the saturation vapor pressure and relative humidity.

$$VPD = SVP * \frac{1 - RH}{100}$$

VPD	=	Vapor pressure deficit
SVP	=	Saturation vapor pressure
RH	=	Relative humidity

For the mean daily values of transpiration only the daylight hours were used (Table 5).

4.3.2 Transpiration of forest patches

In the following section it will be explained in more detail how daily transpiration per square meter for the three main forest sites was inferred from heat probe measurements of single trees. First, it will be documented how the data from the heat probe measurements in temperature difference is converted into sap flow estimate. Secondly, the sap flow is converted into sap flux by using the sap wood area. At last, with diameter measurements of all trees within the forest patches of 15 by 15 meters, the transpiration flux of the three main sites can be estimated per square meter.

The signal of the thermal dissipation probes in millivolts is converted into temperature difference measurements (*ΔT*) based on the assumption that the thermoelectric voltage of 0.039 mV is equivalent to about 1°C (Ecomatik).

The VPD is calculated from the air temperature (in °C), relative humidity and atmospheric pressure (in kPa) utilizing the equation from the chapter 4.3.1. The data for calculating the VPD is used from Atmos41 at the lower main site and not from the Erlenhöhe weather station, as the data gaps were shorter and the measurement timespan sufficient.

The result of the two presiding steps (*ΔT* and VPD) were used to infer the sap flux density utilizing the R script "Thermal dissipation probe Review Assess Clean and Convert" (TRACC) provided by Ward et al. (2017). The following formula was used:

Equation 3. Calculation of sap flux density.

$$U = 0.714 \times (\frac{\Delta T_{max} - \Delta T}{\Delta T})^{1.231}$$

U	=	sap flux density (ml/cm^2/min)
ΔT	=	temperature difference between two probes
ΔT_{max}	=	max. value of ΔT every night

The data was assessed, cleaned, and converted in accordance with the provided instruction by Ward et al. (2017). The R script calculates the sap flow data in g/m^2/s for every hour of the day of the single trees.

To estimate the transpiration from the sap flow the sap wood area of the trees is needed. The diameter at breast height and sap wood width of all trees, where the thermal dissipation probes were installed, were measured during the fieldwork (Table 3). The sap wood width was also measured from a tree core. A linear relationship between the circumference and sap wood width was determined in order to estimate the sap wood area of those trees where no core was taken.

Equation 4. Calculation of sap wood width.

$$Sap\ wood\ width = 0.1833 * r + 2.3517$$

r = radius

Table 3. Trees for measurements and their characteristics.

Tree number	Site	DBH (cm)	Sap wood width (cm)	Sap wood area (m^2)	Min. age (yrs)
3.1	Upper site	75	4	0.025	1887
3.4	Upper site	111	3.9	0.039	-
3.5	Upper site	139	4	0.051	-
2.3	Middle site	193	6.8	0.117	1890
2.4	Middle site	187	8.7	0.139	1953
2.5	Middle site	130	9.3	0.094	1945
2.6	Middle site	83	4	0.028	1932
2.7	Middle site	69	6	0.03	-
1.0	Lower site	120	6.5	0.065	-
1.1	Lower site	100 (+41)	3	0.027	-
1.4	Lower site	87	5	0.036	1978

Thus, for all trees where no cores were taken at the three main sites in a grid of 15x15m, the sap wood area could be calculated by using the measured circumference (Equation 5). Thereafter, the total sap wood area of all trees within the 15x15m forest patch was inferred by using the radius of the trees:

Equation 5. Calculation of sap wood area from the radius of the tree and sap wood width.

$$sap\ wood\ area = (\pi * r^2 - \pi(r - sap\ wood\ width))^2$$

An average sap wood area per square meter for each 15x15m square meter was determined (Table 4).

Table 4. Sap wood area of the main sites.

Site	Total sap wood area [m^2] per forest patch (15x15m)	Sap wood area per m^2
Lower main site	0.3842	0.001707
Middle main site	1.0809	0.004804
Upper main site	0.6253	0.002779

The sap flow measurements of the single trees are assumed to be representative for the forest site, therefore the mean value of the measured trees was used for the calculations.
Next, from the sap flow (g/m^2/s) and the sap wood area the transpiration of the three main forest sites can be estimated. As the area times the velocity equals the transpiration in volume per area per time. The transpiration is divided by the forest patch area (15x15m) to get the transpiration per square meter. Multiplied by (60*60/1000) which is 36 to get l/d/m^2.

Equation 6. Calculating transpiration per square meter out of the sapwood area, sap flow and and forest area.

$$Transp. = \frac{sap\ wood\ area * sap\ flow * \frac{60 * 60}{1000}}{Forest\ area}$$

Transp. = Transpiration

To remove the values during the night where there is no transpiration only the data was used during the timespan of the day according to the daylight of the month (Table 5). Therefore, the daylight hours of the middle day of the month were looked up (SaS, 2025) and then rounded to a full hour and took this as an average of daylight hours for the month.

Table 5. Daylight hours per month (Sunrise-and-sunset, 2025).

Months	Sunrise	Sunset
May	06:00	21:00
June	05:00	21:00
July	06:00	21:00
August	06:00	21:00
September	07:00	20:00
October	08:00	19:00

4.4 Statistical Analysis

As confirmed by the shapiro-wilk normality test not all data was normally distributed. In Table 6 the p-values of a shapiro-wilk normality test are listed, with p-values greater than 0.05 suggesting a normally distributed data set.

Table 6. P-value Results from shapiro-wilk normality test.

Data set	p-value
Temperature	0.06367
Precipitation	1.2e-10
Radiation	0.01626
VPD	0.1412
Wind	0.0001004
Transpiration at three main sites (upper, middle, lower)	9.3e-05, 1.3e-06, 1.6e-06
Soil moisture	<1e-15

In the chosen pairings to correlate temperature, precipitation, radiation and VPD against each of the transpiration at the three main sites normality was not guaranteed, thus a spearman's rank correlation test was chosen for further analysis. The correlation between transpiration and soil moisture was assessed with a spearman's rank correlation test as the transpiration data set was not normally distributed.

For the difference between the three main sites in sap flow and transpiration, the Friedman-Test is used since the prerequisites for an analysis of variance are not met, and the sites are assumed to be connected as they experience the same weather conditions and are on the same slope. To test the difference between each site respectively a post hoc Bonferroni-Tests was used.

The correlation between TWI & soil moisture over the season was done using the Spearman's rank correlation test.

The R package relaimpo was used to calculate the relative importance of VPD, temperature, different soil moisture depths, precipitation, and wind to explain transpiration in the linear model (Groemping, 2006).

5. Results

5.1 Overview of weather recordings

Over the season from the 01.05.2024 to the 06.10.2024 weather was recorded at the Erlenhöhe station (Figure 5). Due to technical issues, there are three periods of data gaps over the measurement period. Temperature increased over the timespan from May to the highest temperatures in August. In the middle of September, the temperatures dropped, and it snowed. Measurements showed a mean temperature from 9.1°C in May, 13.2°C in June, 14.7°C in July, 16.9°C in August to 9.1°C in September. The summed recorded precipitation over the growing season was 1045.6 mm and the maximum time span without precipitation was five consecutive days. During periods of rain the temperatures decreased. The mean summed precipitation is 321.3 mm in May, 247.7 mm in June, 124.4 mm in July, 85.9 mm in August and 177.4 mm in September. On the 30. to 31. of May the precipitation reached up to 134 mm. Furthermore, on the 31. of July there was an intensive thunderstorm with about 50 mm precipitation with an intensity of 15-25mm/10min resulting in one of the highest discharge measurements of the Erlenbach in the past 55 years (WSL, 2025). Radiation varies greatly from day to day and was generally lower in September compared to the other months. VPD fluctuates in June and July, increases in August, and decreases in September.

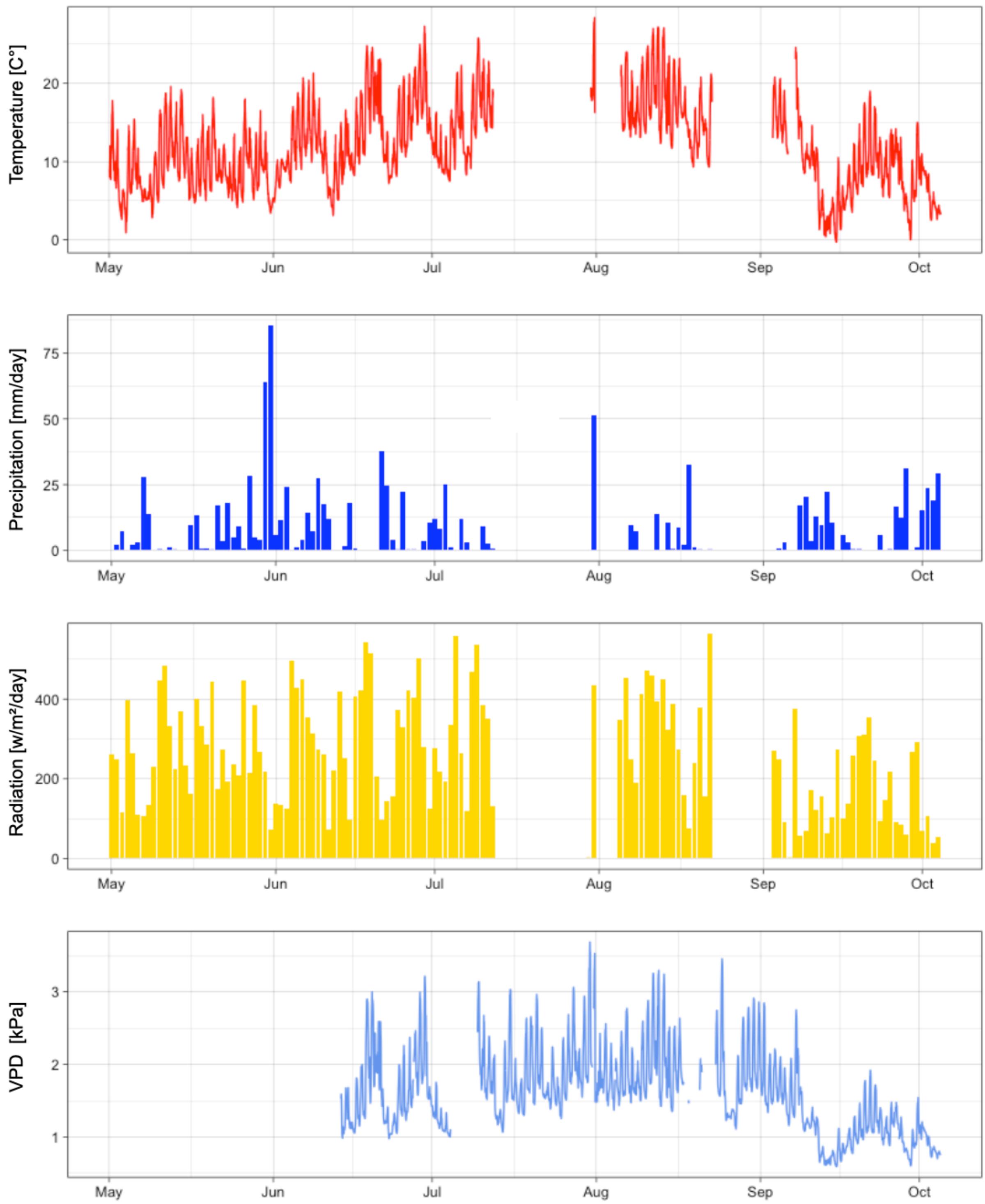

Figure 5. Weather recordings over the season at Erlenhöhe and Atmos41 at the lower main site.

5.2 Groundwater

At the middle intermediate site two groundwater wells are installed in a grassland, that showed high soil moisture level over the whole season, which is visible in the groundwater levels which reaches from around 50cm below ground, up until close to the surface (Figure 6). The two groundwater wells are installed only about 1 to 2 m apart and show the great variation in groundwater on a small scale within the Studibach catchment. The groundwater level at the lower main location is in the same range as the groundwater well is close to a seasonal stream. In comparison the groundwater level at the middle main site ranges from about 100 to 150cm below the surface that is located on a steep slope. Groundwater levels respond to the precipitation pattern, for example after the thunderstorm on the 31. of July there is a large increase of groundwater level at all locations.

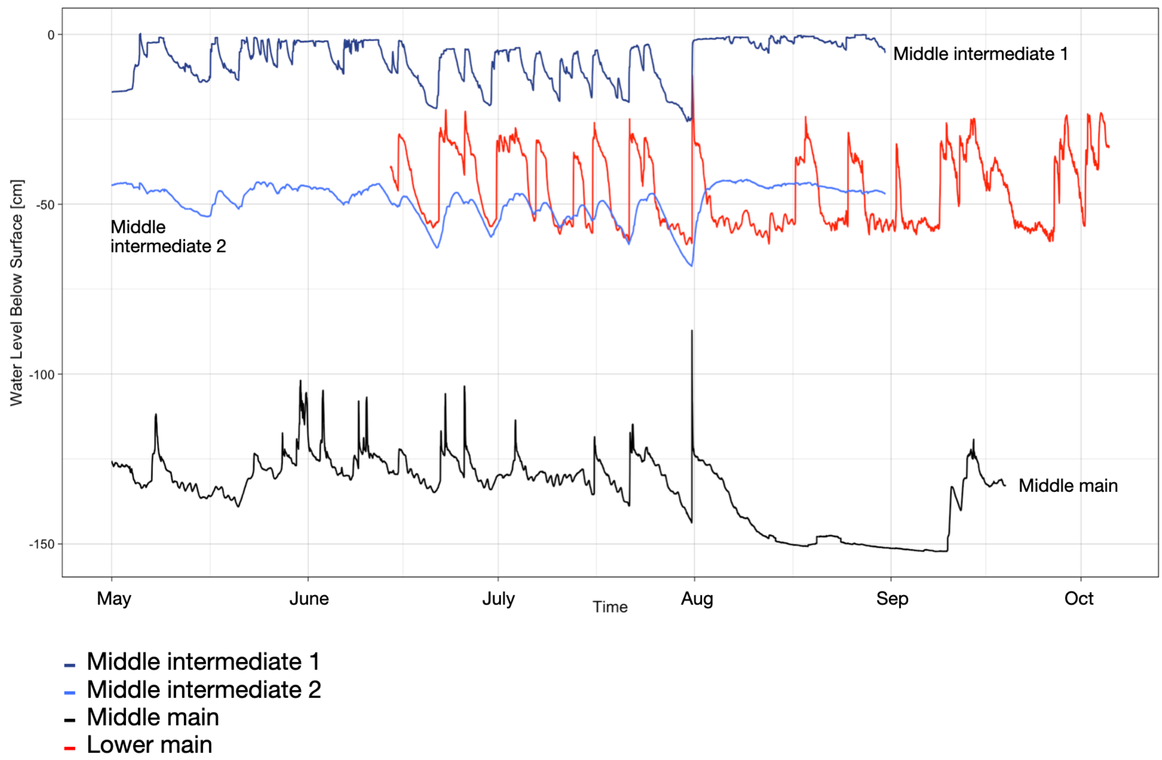

Figure 6. Groundwater level below the surface at the lower main site, middle main site and two wells at the middle intermediate site over the season.

5.3 Topographic wetness index

Results of the TWI are seen in the (Figure 2) representing the study area. The TWI of the three main sites is the lowest (2.65) at the upper main site. The middle main site has the highest TWI of 4.26 between the three main sites. While the lower main site lies in between with a TWI of 3.75. Of 26 all locations where soil moisture is measured the mean TWI ranges from the lowest of 2.24 at F6.5 and the highest two at F3 with 5.59 and F4 with 5.36 (Table 2).

5.4 Soil moisture

Over the whole measurement period the soil moisture is higher from May to July and lower in August, with an increase again in the middle of September. At most locations there is more fluctuation in soil moisture at 5 cm soil depth than 15 and 30 cm (Figure 7). Overall, the shallow soil depth shows lower soil moisture than the deeper soil. At the lower main site there is a great difference in soil moisture between the three soil depths, as the soil moisture in 30 cm depth is higher than in the shallow soil. In comparison at the lower intermediate site all three soil depths show similar soil moisture contents.

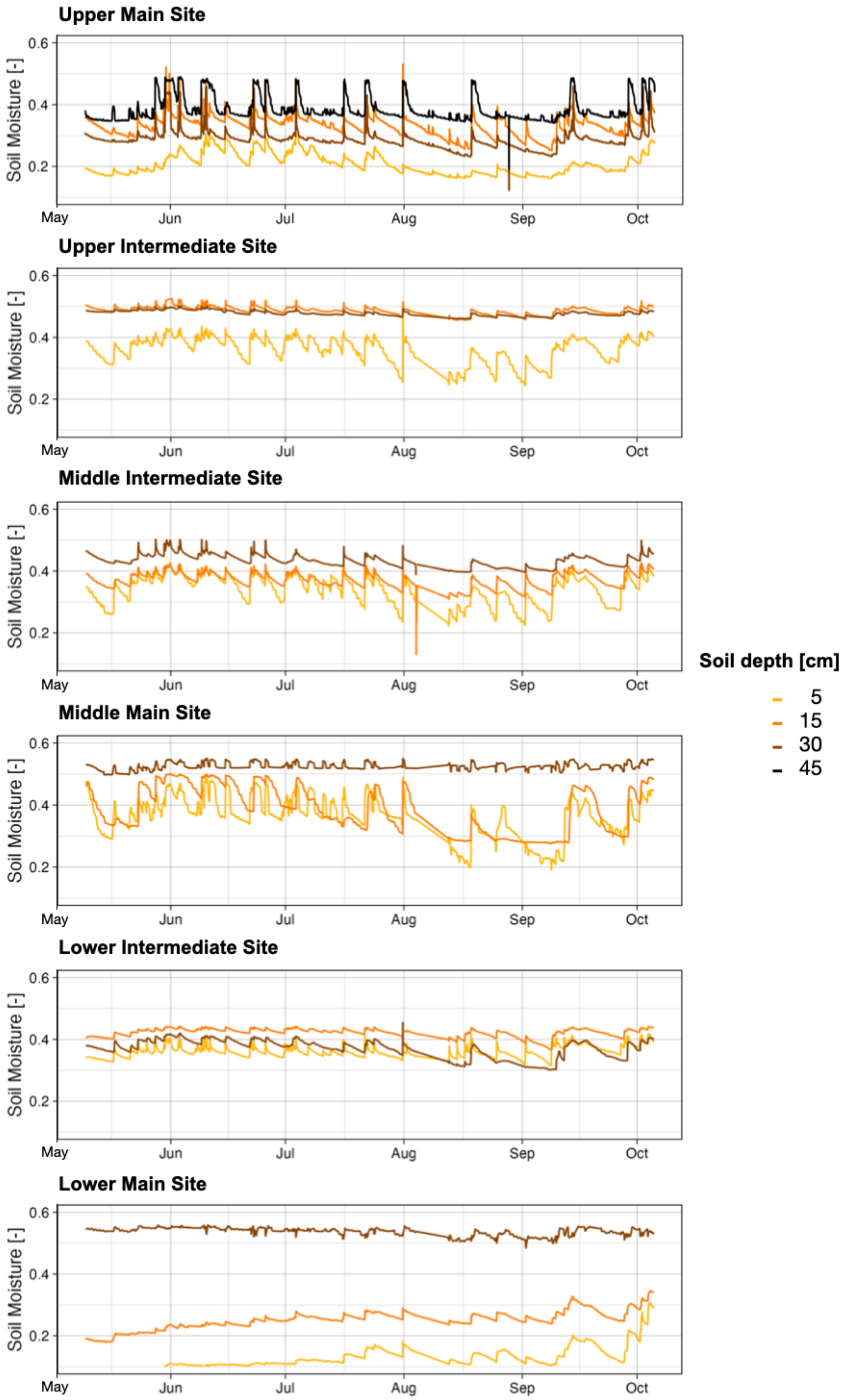

Figure 7. Continuous soil moisture recordings of every 10min over the season at six sites with soil depth of 5cm, 15cm, 30cm and 45 cm.

The temporal variation in soil moisture measured manually with instruments fit to the soil moisture pattern of the continuous measurements (upper most box, Figure 8). The lower and upper main site are the driest locations with a soil moisture content between 0.1 and 0.3. However, in 30 cm soil depth at the lower main site the moisture content increases to around 0.55 as the wettest measurement. In the shallow soil depth, the moisture content is similar between the sites (besides the upper and lower main sites), while there is more difference at greater depths.

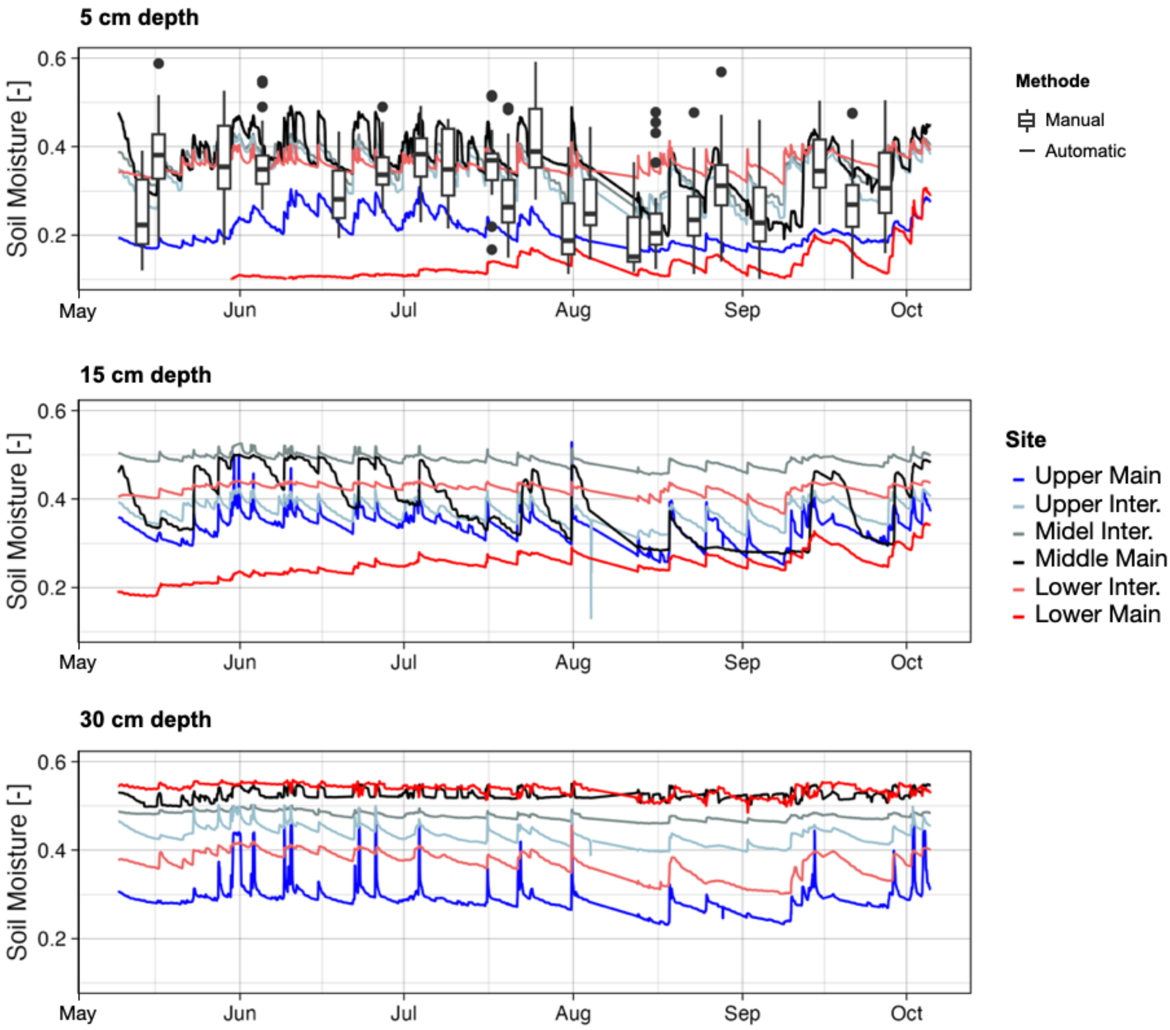

Figure 8. Soil moisture measurements by depth at six sites where soil moisture was measured continuously and at 26 flag locations with manual soil moisture measurements. Measurements are shown over the season according to the soil depth (5cm, 15 cm, 30 cm) and the 21 measurement days of the manual soil moisture.

The range of soil moisture measurements over all sites is high from about 12% to 87% which only displays the upper soil (Figure 9). Most of the measurements lie between 20% to 40%. The variation of soil moisture between the measurement days is the highest at the lower main site and Flag 14.5 as there was a seasonal stream which was nearly gone in August. Meanwhile Flag 4 and Flag 7 were wet locations throughout the whole summer.

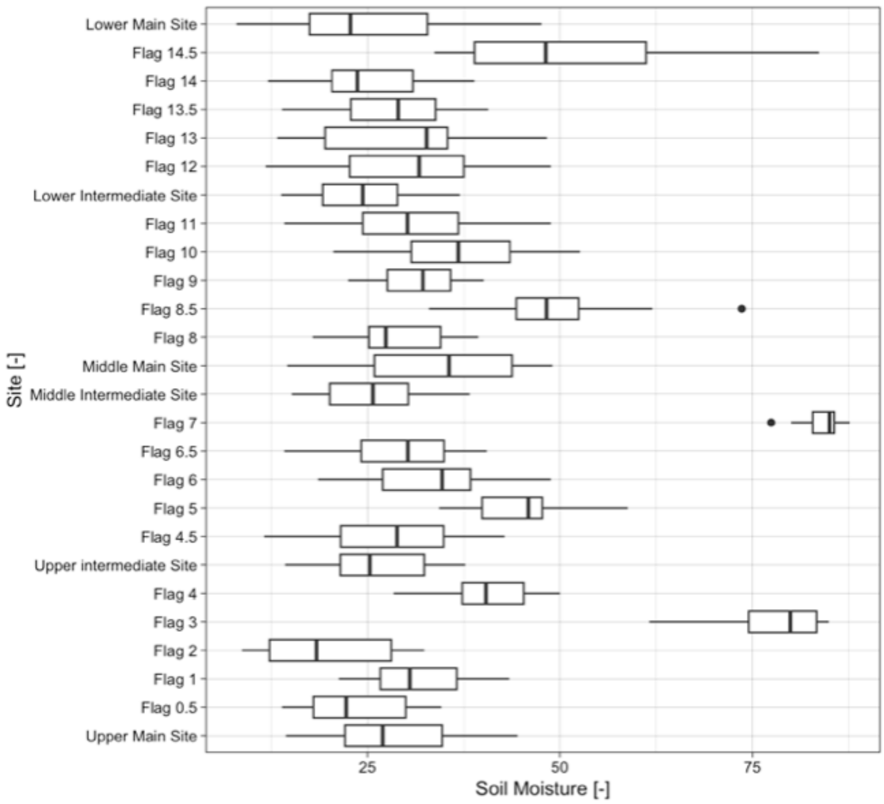

Figure 9. Manual soil moisture measurements on the 21 days arranged from the lower main site up the hillslope until the upper main site.

5.5 Sap flow at three main sites

In total there are 107 days where sap flow was measured from at least one tree (Figure 10). As sap flow calculation is dependent on VPD, sap flow data is only available if there is VPD data. The data recording at the lowest site started later than at the other two sites. From Mid-July until Mid-August there is only tree 1.2 recording sap flow at the lowest main site, which is then replaced by tree 1.1 and 1.4. At the main middle site there are five trees recording most of the season (2.3, 2.4, 2.5, 2.6 and 2,7). While the sap flow data at the upper main site consists between two to four trees (3.1, 3.4, 3.5 and 3.6).

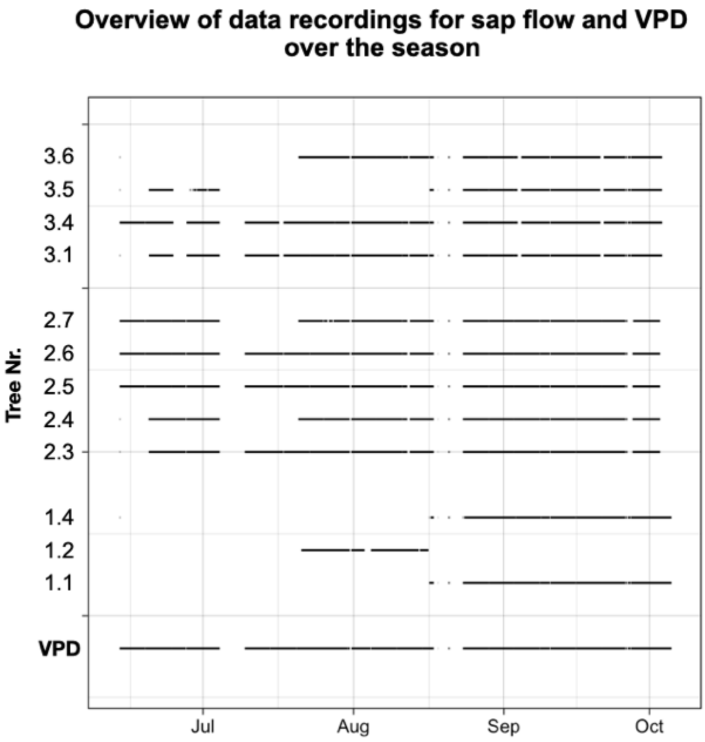

Figure 10. Data recordings and data gaps of the sap flow measurements of the single trees and the VPD over the season.

The daily average sap flow varies from 0 to 24 g/m^2/s. The daily sap flow pattern over the whole measurement period is similar at all three sites (Figure 11). In June the daily sap flow is variable, it increases in the middle of August and strongly decreases in the middle of September.

Resulting from the Friedman-test there is a significant difference between the sap flow of the three main sites in July (chi-squared 13.6, p-value 0.001) and even more so in August (chi-squared 17.4, p-value 0.0002). This trend dwindled in September (chi-squared lowered to 5 and the p-value climbed to 0.071), thus no longer indicating significance. A post hoc Bonferroni-tests indicates that it is the upper main site which differs the most from the other two main sites. In each month the upper main site was significantly higher from the middle main site, while in August and September there is a difference to the lower main site as well. The sap flow of the lower main site and middle main site were not significantly different during the summer month. In a weekly comparison (Appendix 2) the difference between the sites is less significant, but the pattern remains the same. The Bonferroni test in July (Appendix 2) showed that the difference between the middle main site and upper main site is also reflected by the analysis of the single trees. There is a significant difference for almost every single tree of the middle site when held against every single tree of the upper main site. Especially, tree 3.4 at the upper main site stands out with high daily average sap flow. The variance of the tree at the lower main site is large and it cannot be shown to be significantly different from any other tree. In August there are differences between the trees of different sites but also variances within the sites. The sap flow of tree 3.1 is closer to the sap flow shown by the trees of the middle main site.

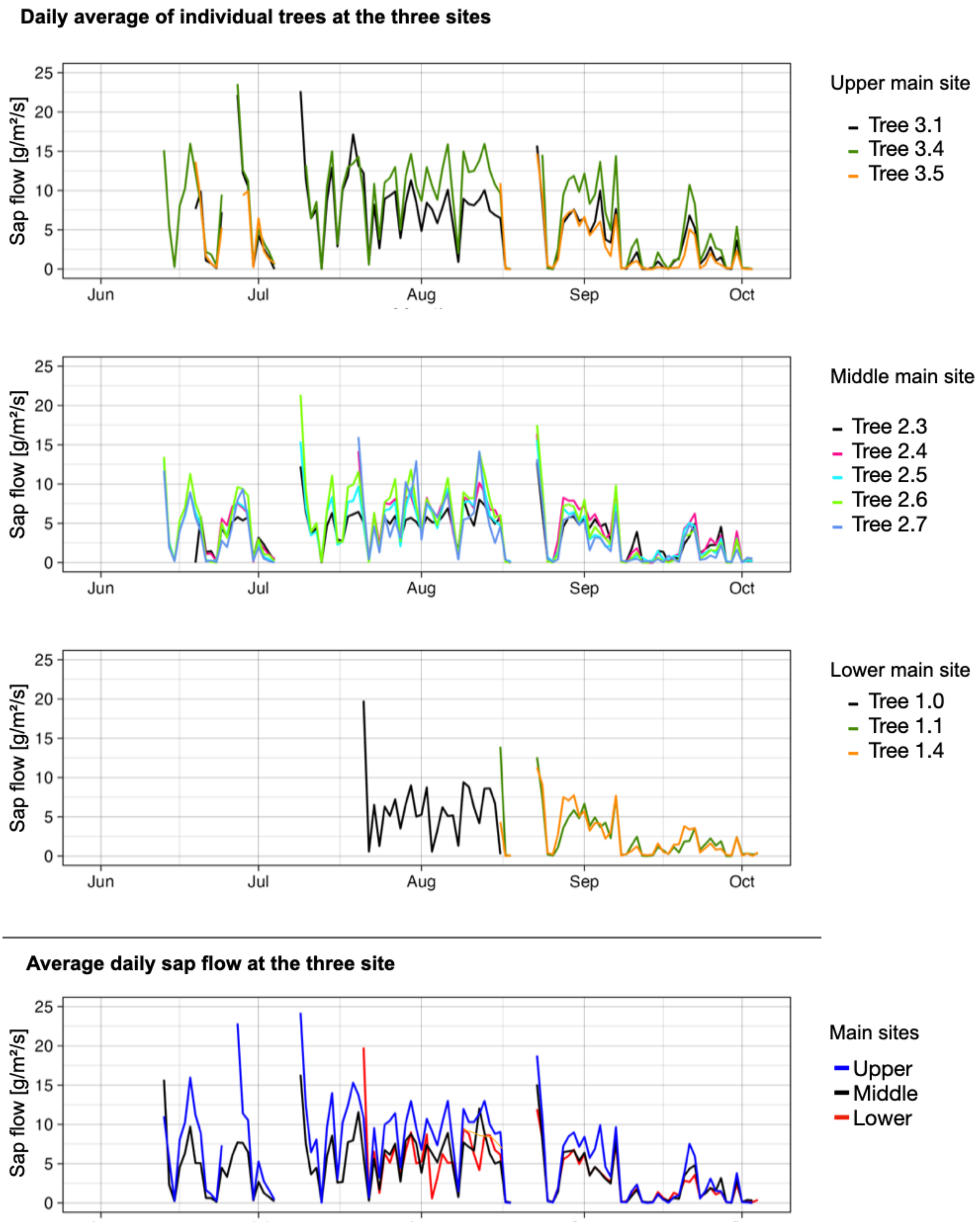

Figure 11. Daily average sap flow of the individual trees and the average of the three sites over the season.

5.6 Transpiration of three forest patches

Transpiration was calculated based on measured sap flow and required at least one tree to be monitored at each site. At the middle and upper site there were already measurement results during June and July while there were no measurements for the lower site for this period. Throughout the season there where some data gaps on the 25. and 26. of June for the upper site, from the 5. until the 8. of July for the middle and upper site and the 19., 21., 22. of August for all three sites at once as the data gap stems from a lack of VPD data.

Transpiration shows daily variability over the season across all sites from nearly no transpiration up to 4 mm per day (Figure 12). During weeks characterized by generally high transpiration, there are also days with low transpiration in between. The seasonal variation in transpiration is similar at all sites. Over the course of the season, variable transpiration levels are observed initially, followed by an increase during July and August, and a subsequent decline in September.

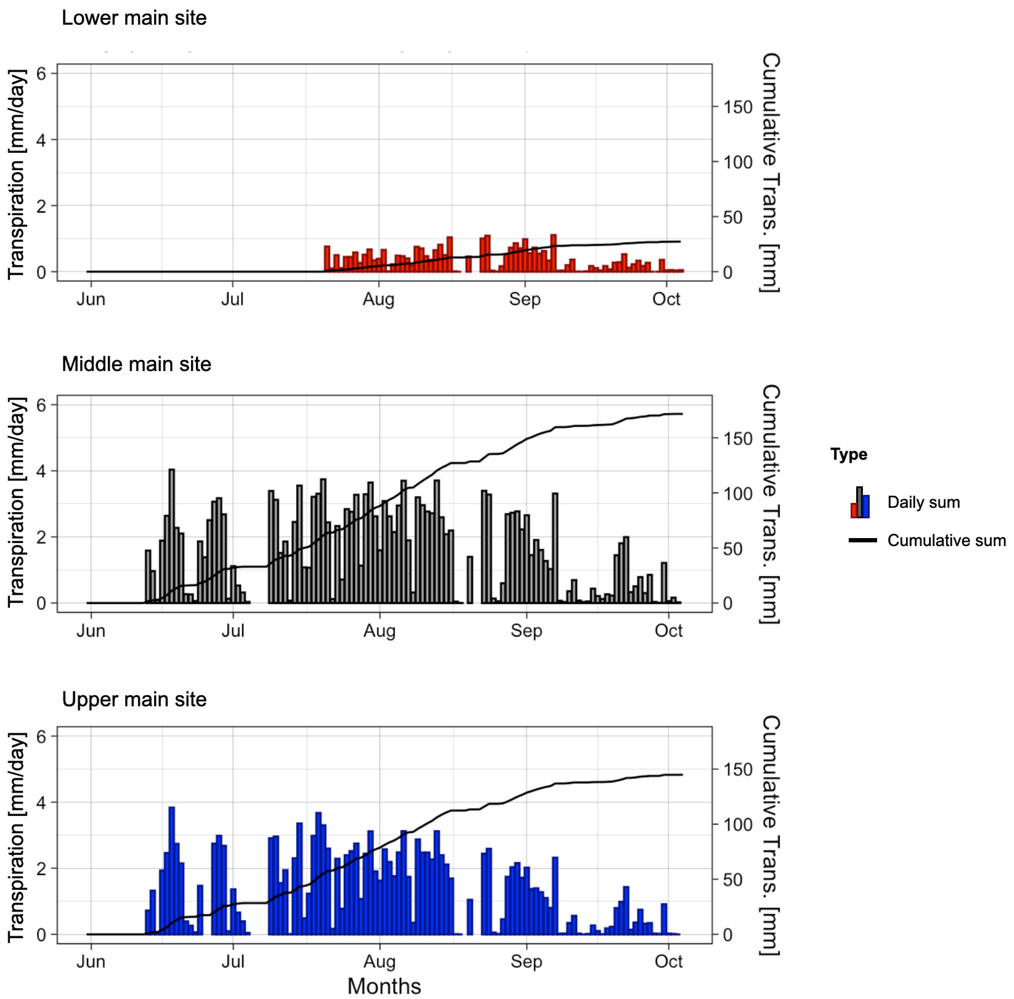

Figure 12. Daily summed and cumulative transpiration at the three sites over the season.

The cumulative transpiration over the whole season marks a pronounced increase in August, with a more gradual increase in September for all sites (Figure 13). Although the starting date is chosen the same of all three sites, the cumulative transpiration of the lower main site is significantly lower. Over the whole measurement period, the cumulative transpiration only reaches 27.3 mm at the lower site. In comparison the middle site reaches 171.7 mm transpiration, and the upper site reaches 144.8 mm.

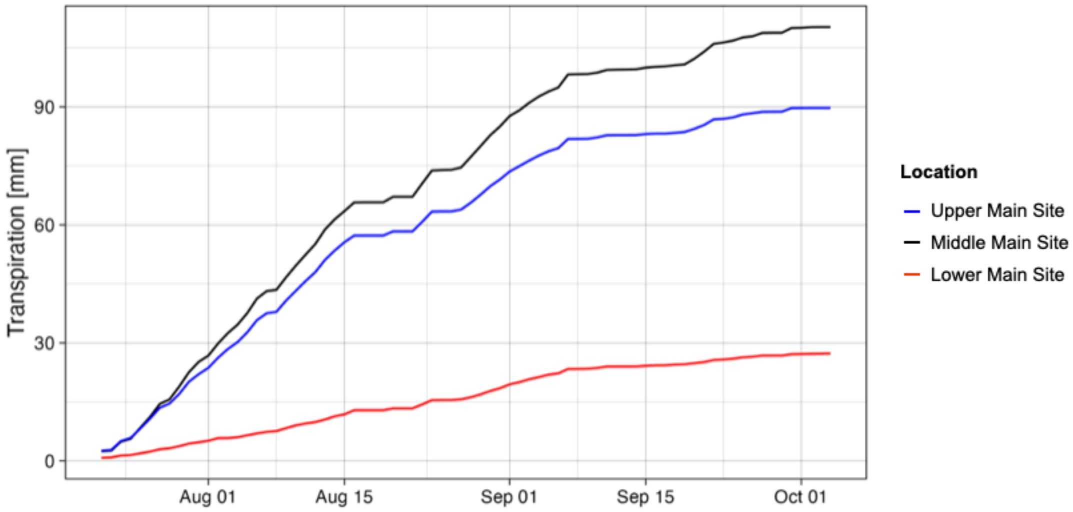

Figure 13. Cumulative transpiration of the three main sites from the starting date (mid-July) where all sites have data until the beginning of October.

The monthly comparison of sap flow data and transpiration data shows a different pattern between the sites (Figure 14). At monthly comparison of sap flow the upper main site is significantly higher to the other two sites. On contrary, the monthly transpiration is slightly higher at the middle main site. The analysis of the monthly data shows that the transpiration at the lower main site is significantly lower in July, August and September compared to the other two sites. Furthermore, the transpiration is significantly differing between all sites during August (chi-squared = 47.91, p-value = 3.949e-11). In September the transpiration is generally lower, however all main sites remain significantly different from each other (chi-squared = 42.975, p-value = 4.657e-10).

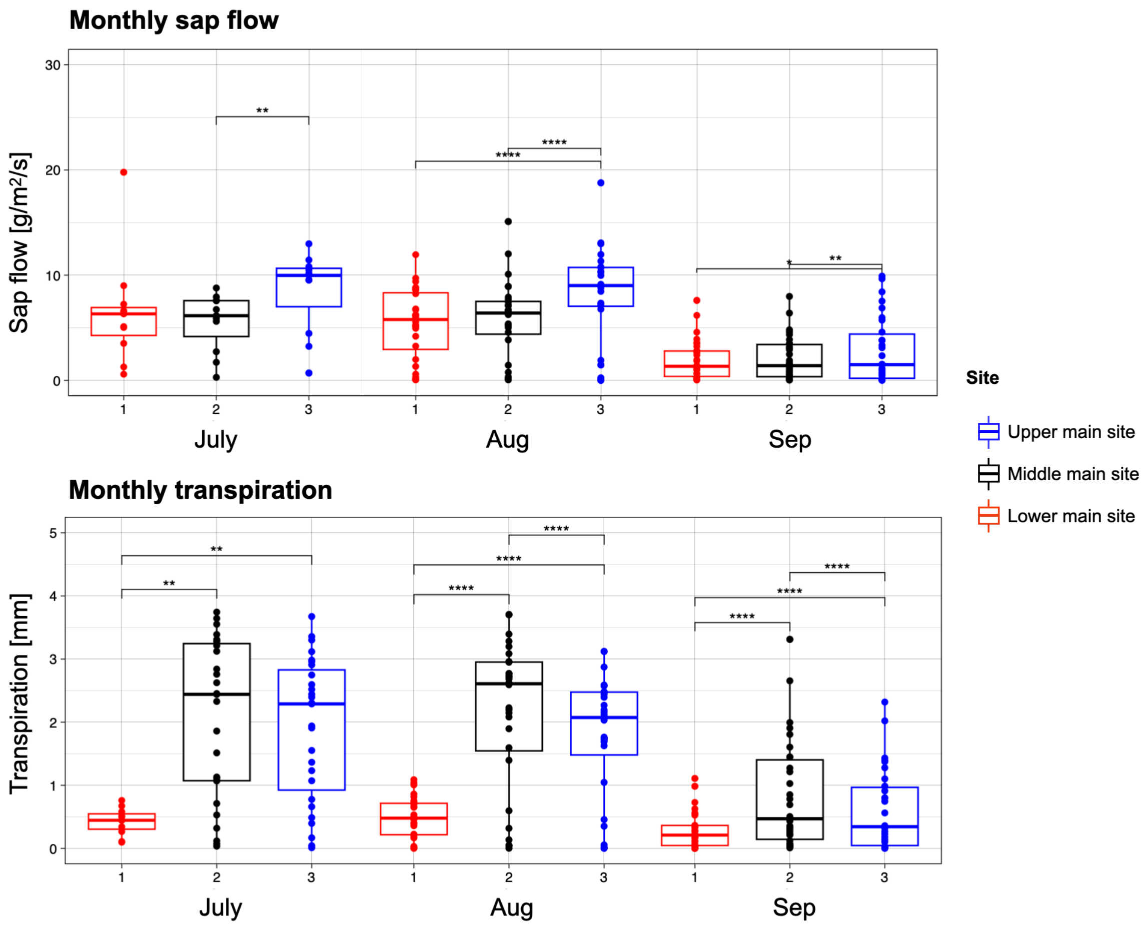

Figure 14. Monthly comparison between the sites of sap flow and transpiration. Using a Friedman test to confirm a difference between the three sites and a post hoc Bonferroni test to compare between the single sites.

When grouped by week, some weeks lack sufficient data for a Friedman test (Appendix 5). Weekly patterns align with the monthly analysis but highlight clearer site differences in certain weeks (31, 32, 35) with consistent daily transpiration across all sites. In contrast, weeks with high variability (33, 34) show less pronounced differences between sites.

5.7 Correlations

In the topsoil there is a weak positive correlation between the TWI of the location and the measured soil moisture over the whole season (Figure 15). For the manual measurements the correlation coefficient is 0.3183 (p-value 1.25e-5) and for the continuous measurements 0.1593 (p-value 0.0001). Although each site has a specific TWI associated, the variation in soil moisture over the season is large. In some cases, the TWI does not fit to the actual soil moisture content at all. The mean of the manual soil moisture measurements ranges between

0.14-0.3 (with a standard deviation of 0.016-0.064), while the mean of the continuous measurements lies between 0.2-0.84 (with a standard deviation of 0.025-0.143).

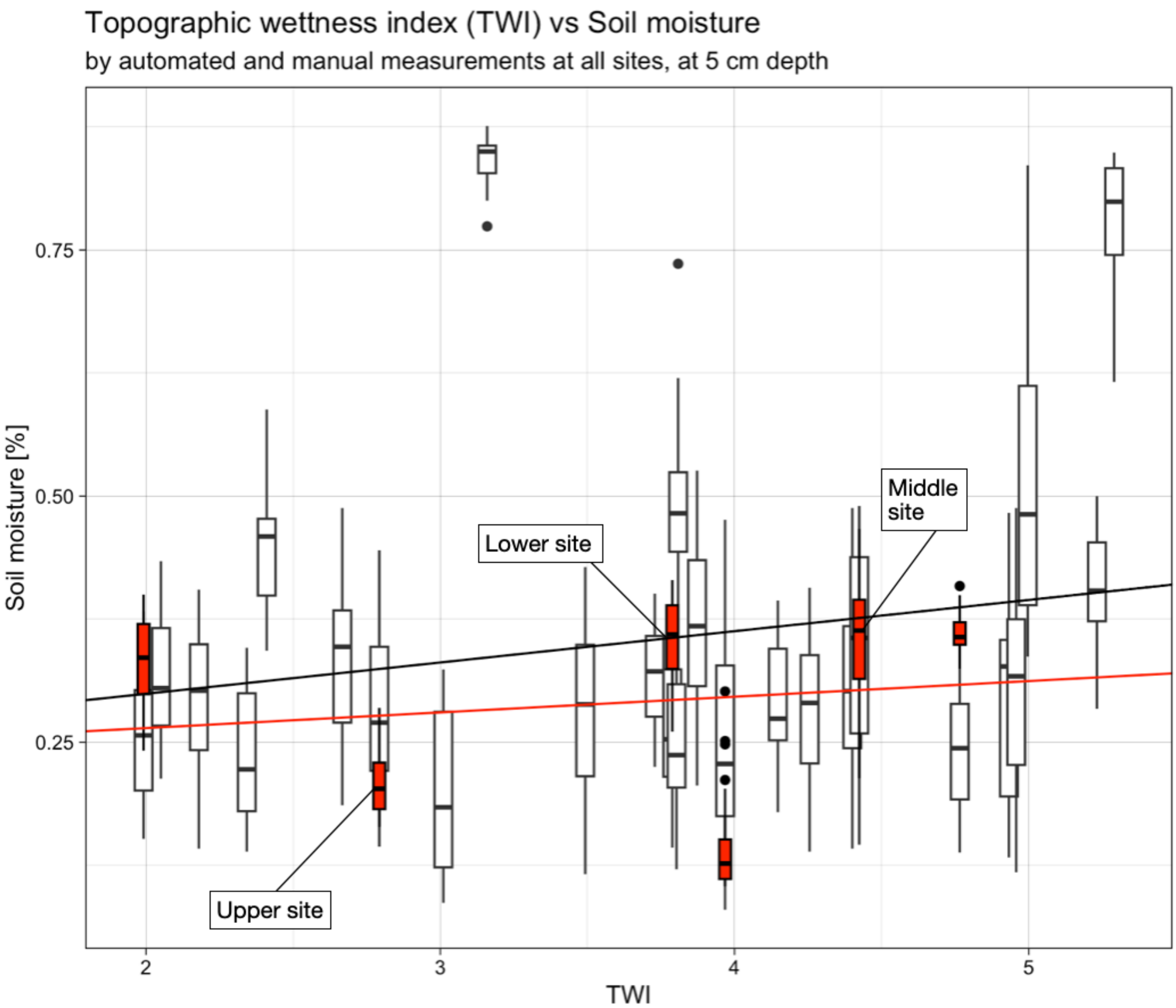

Figure 15. Boxplot of soil moisture at every location with the according TWI. In red are the continuous soil moisture sites with data over the whole season, while in white the manual soil moisture sites at soil depth 5cm are marked. The black line is the regression line of the manual soil moisture data with TWI and in red for the continuous soil moisture sites.

Trends in the relationship between TWI, soil moisture and transpiration over the seasons were shown. TWI and soil moisture showed a positive relationship of varying degree. TWI with sap flow/transpiration as well as soil moisture with sap flow/transpiration showed no correlation over the season (Figure 16).

Starting with TWI and soil moisture, the daily spearman's rank correlation between the average soil moisture of all six sites and TWI over the season shows values between 0.1 and 0.7 (Figure 16). Thich indicates a weak to moderate positive correlation. It must be considered that only six TWI values are used for the correlation. The p-value highlights that, the correlation is significant throughout the season, with the strongest significance in June and July. Generally, there is a stronger positive correlation when the mean soil moisture content is lower, for example in August. While the opposite occurs in June, when the mean soil moisture content is higher and the correlation weaker (this can also be seen in the upper most right plot). Moreover, peaks in correlation occur during drainage periods following rainfall events.

Throughout the season the daily Spearman's rank correlation value rho of the correlation between TWI and sap flow and TWI and transpiration are both within the range of -0.7 to 0.5 (Figure 16). A great variation in daily correlation is visible over the season, however mostly indicating no correlation. As sap flow was measured at three sites, the correlation could only be done using three TWI values, which must be considered. There is no clear pattern when correlation between TWI and both sap flow and transpiration peaks, suggesting no correlation between TWI and both sap flow and transpiration. The TWI correlated with sap flow shows overall lower correlation values than with transpiration.
On the right-hand side of the plot rho is plotted against soil moisture visualizing how the relationship between TWI and transpiration changes with soil moisture content. As no patter emerges there is no cause to suspect that soil moisture content influences the correlation of TWI and transpiration, on a daily scale.

The daily spearman's rank correlation value rho of soil moisture with transpiration/sap flow is within the range of -0.6 and 0.6, showing great fluctuations (Figure 16). Similar to the correlation between TWI and sap flow or transpiration, there is no distinct pattern in the correlation between soil moisture and sap flow transpiration throughout the season. The associated rho values did also not show a pattern with changing soil moisture content.

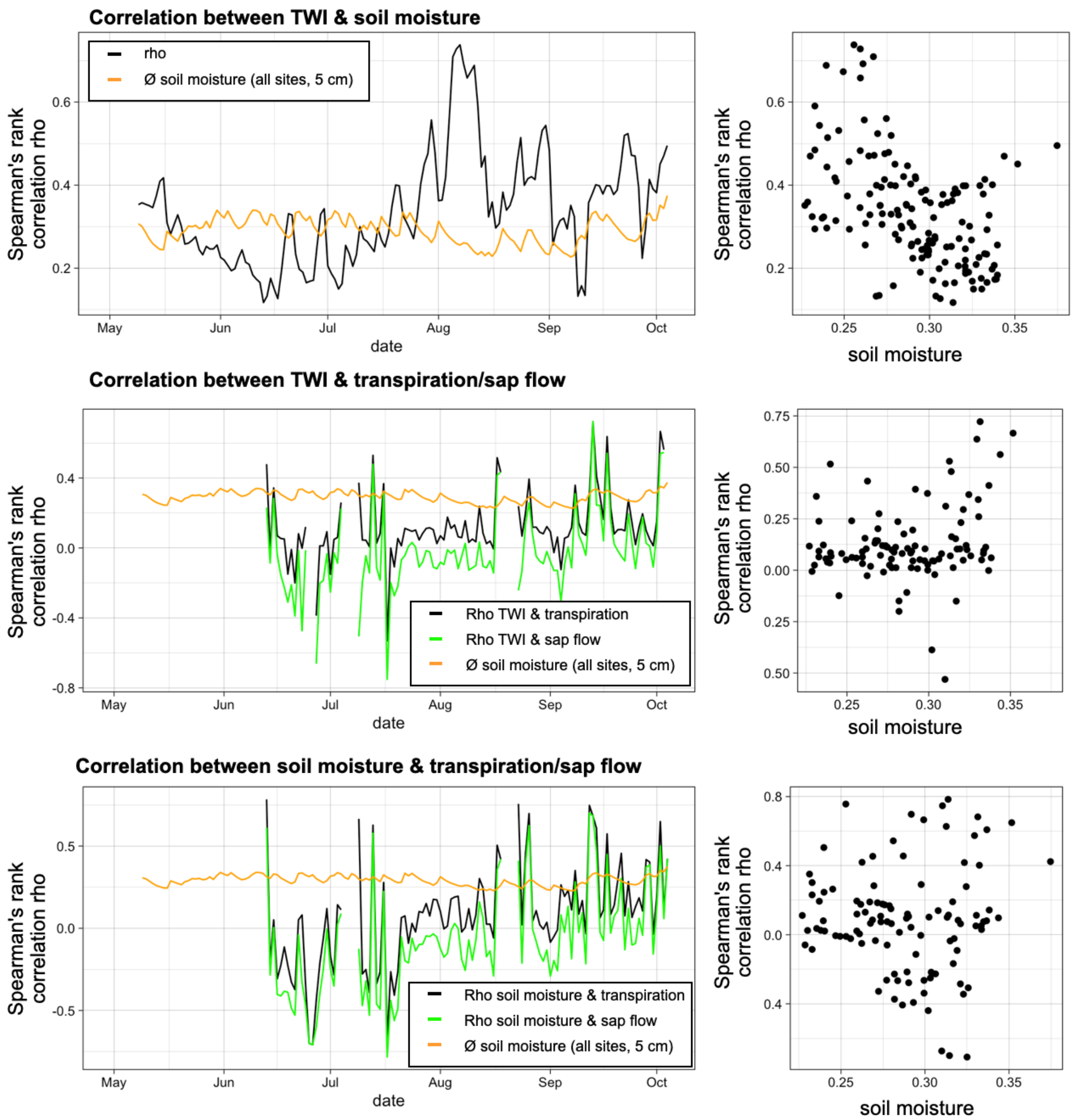

Figure 16. (On the left) The Spearman's rank correlation value rho of a daily analysis is plotted over the season. The mean soil moisture of all sites in a depth of 5 cm is plotted (orange) to compare the correlations to the soil moisture content. (On the right) the soil moisture is plotted against the rho values over the season – the same which are displayed on the left, to show that relationship between soil moisture and the respective rho values.

The Spearman's rank correlation hints at negative correlation in varying degrees, at single depths at different sites, when the soil moisture is correlated against the transpiration at the individual sites (Figure 17, Table 7). However, the range of soil moisture at each site is narrow, while the range in transpiration is high. If the data of all three main sites is united and tested for correlation, a positive correlation between soil moisture and transpiration is detected. This contrast to the negative correlation at each singular site, is known as Simpson's paradox. Thus, no clear correlation between soil moisture and transpiration can be shown in this data.

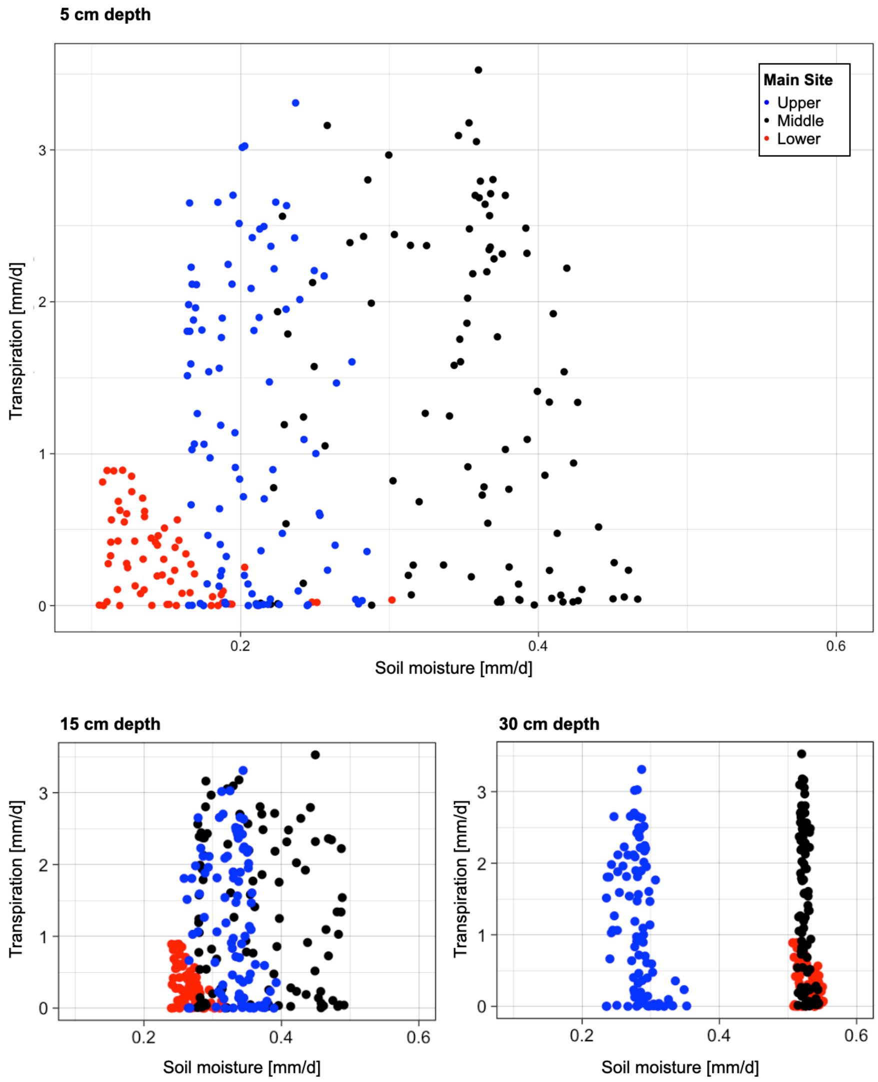

Figure 17. Daily spearman's rank correlation between transpiration and soil moisture at the three main sites according to the soil depths (5cm, 15cm, 30cm).

Table 7. Statistical values for soil moisture at three depths and transpiration at the three main sites (Daily Spearman's rank correlation rho and p-value). Accompanying Figure 17.

	Rho	**p-value**
5 cm		
Lower	-0.45	0.00015
Middle	-0.24	0.015
Upper	-0.094	0.36
15cm		
Lower	-0.55	2.055E-06
Middle	-0.09	0.37
Upper	-0.32	0.001
30 cm		
Lower	-0.28	0.02
Middle	-0.43	9.9E-06
Upper	-0.29	0.003

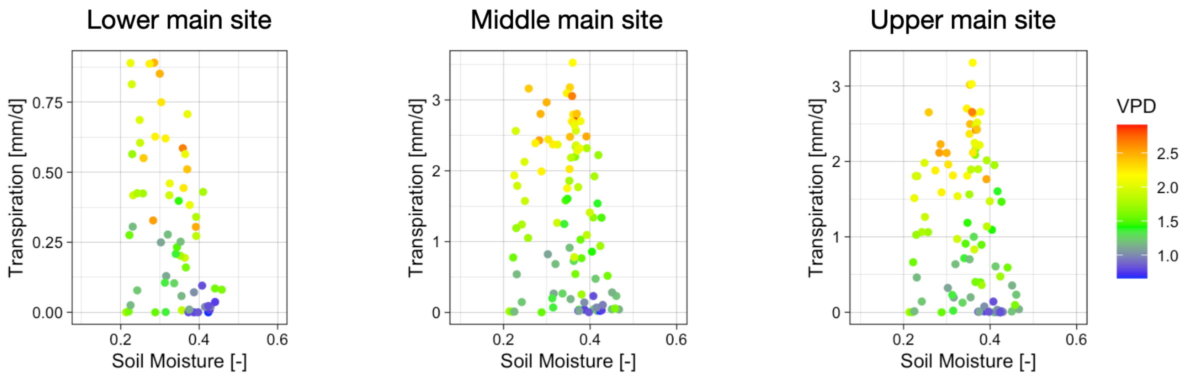

Figure 18. Daily average soil moisture against daily summed transpiration colored according of the VPD value on that day at three sites.

The data displayed in Figure (Figure 18) & Figure (Figure 19) as well as the multi linear regression model, show cohesively that VPD is the primary influence on transpiration.
Higher transpiration occurred when VPD was high and less when the VPD was low. The days with the lowest VPD fall together with the days where the soil moisture at all for sites was at 40% which was high for these sites. The fact that no data was gathered where VPD is high and soil moisture is high as well while transpiration was low, indicates that there is no soil moisture limitation on transpiration (Figure 18).

The spearman's rank correlation between transpiration with several possible drivers show that there is a significant positive correlation of transpiration with temperature, radiation and VPD at all three sites (Figure 19). The Spearman's rank correlation is stronger at the middle and upper site compared to the lower site. Nevertheless, no correlation of daily transpiration and precipitation is indicated.

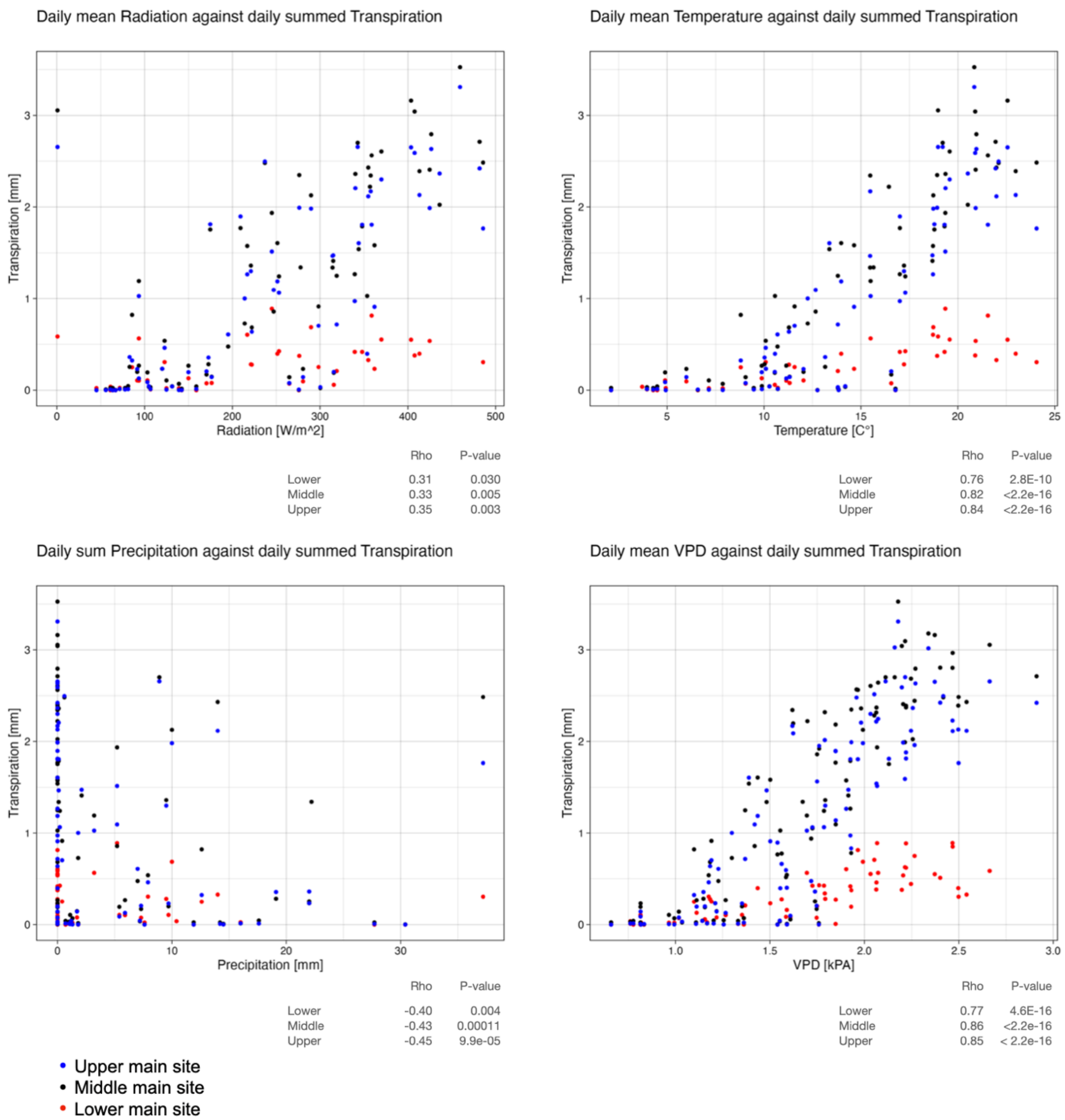

Figure 19. Daily spearman's rank correlation of the Climatic variables against transpiration colored according to the site. Additionally the rho and p-value of the spearman's rank test is listed.

In a multi linear regression model which explains transpiration with VPD and the soil moisture in 5cm depth, the proportion of variance explained by the model is 77.85%. The lmg metric by relaimpo (Groemping, 2006) indicates that the VPD explains 65.65% and soil moisture 12.2% of the transpiration data.

5.8 Water balance

There are multiple ways to rearrange the water balance Equation 7 based on certain assumptions to evaluate the measurements.

5.8.1 First approach

The first approach turned out to be not applicable in this study as it yields a lower ET than transpiration which cannot be possible as transpiration is part of ET and therefore must be lower. This indicates that the dry periods were probably too short to yield useful results with this approach.

Equation 7. Water balance.

$$dS = P - Q - ET$$

dS	=	Delta storage
P	=	Precipitation
Q	=	Discharge
ET		Evapotranspiration

In a dry period after a few days with no precipitation the discharge (Q) can assumed to be zero and of course the precipitation (P) is zero as well, which yields Equation 8:

Equation 8. In dry periods without precipitation and discharge, the delta storage is assumed to be equal to the evapotranspiration.

$$dS = ET$$

Thus, the change in storage (dS) was estimated from the soil moisture measurements (described in chapter, 4.1.3) according to Equation 9:

Equation 9. Water storage calculation of the summed volumetric soil moisture of the soil depths.

$$Water\ storage\ [l/m^2] = 100 * VSM_1 + 125 * VSM_2 + 75 * \ VSM_3$$

VSM	=	Volumetric Soil Moisture

The change in storage (dS) is calculated by subtracting the midnight value from the value of the preceding day.

The change in storage of the dry days 18.6.24-20.6.24 was selected, because these were the last four of five consecutive dry days (Table 8).

Table 8. Results of the estimate of theEvapotranspiration from the ground. ET of the ground storage (ET_{ground}) is set equal to the change in storage on the 18.06, 19.06 and 20.06 and the mean over this period. The T_{trees} is the measured mean transpiration of the three sites on that day. The unit of ET_{ground} and T_{trees} is mm.

Day	**18.06.24**	**19.06.24**	**20.06.24**	**mean**
ET_{ground}	2.29	2.75	2.20	2.41
T_{Trees}	3.93	2.5	2.12	2.85

The mean ET in these days was larger than the mean transpiration in these days, thus this approach was quit as discussed in the beginning of this section.

5.8.2 Second approach

In this method a time span is selected where the storage is the same in the beginning as in the end of the period. Therefore, the change in storage over this timespan can be set to zero, as shown in Equation 10.

Equation 10. Water balance assumed delta storage is zero.

$$P - Q = ET$$

Next, the sum of discharge of the Erlenbach and the summed precipitation over the chosen periods is calculated in Equation 11. There cannot be any data gaps in the timespan otherwise the ET would be overestimated or underestimated.

Equation 11. Water balance assuming delta storage is zero. Sum for a certain timespan.

$$\sum_{i \in v} P - \sum_{i \in v} Q = \sum ET$$

v = All the days within the selected timespan

In this Table 9 all possible identified time spans and the according calculated water balance are listed:

Table 9. Water balance for the different time spans. Marked in grey the longest estimate for each time period.

Time span			**Water balance variables [mm]**					
Start	End	Duration [d]	Q	P	ET	ET/d	T	T/ET
14.05.2024 15:00	17.05.2024 03:00	2.5	12.6	4.6	8	3.2	-	-
14.05.2024 15:00	20.05.2024 20:00	6.2	24	15.2	8.8	1.4	-	-
05.06.2024 15:50	08.06.2024 13:00	2.8	22.9	15.4	7.5	2.6	-	-
05.06.2024 15:50	13.06.2024 22:00	8.3	83	72.5	10.5	1.3	1.15	0.89
05.06.2024 15:50	17.06.2024 14:20	11.9	103.2	86.5	16.7	1.4	1.37	0.98
05.06.2024 15:50	22.06.2024 00:20	16.4	135.9	97.8	38.1	2.3	1.6	0.7
05.06.2024 15:50	27.06.2024 12:00	21.8	191.9	144.6	47.3	2.2	1.63	0.74
09.07.2024 14:00	11.07.2024 02:40	1.5	9.5	1.4	8.1	5.2	2.57	0.49

The resulting ratio of transpiration to ET is in a reasonable range compared to Schlesinger and Jasechko (2014) results who estimate that the transpiration to be on average 55% (±15%) of ET for temperate coniferous forests.

6. Discussion

6.1 Spatial and temporal pattern in soil moisture

The TWI is widely used as a quantitative tool to determine the theoretical distribution of soil moisture based on the topography (Jarecke, et al., 2021; Mohamedou, et al., 2019; Riihimäki, et al., 2021; Rinderer, et al., 2014; Sørensen, et al., 2006; Winzeler, et al., 2022). The TWI is especially useful as it not only considers the slope at a specific location but also includes the upslope catchment characteristics that influences the waterflow to the location (Beven & Kirkby, 1979). The generally low TWI results in this thesis (between 2-5) indicates rather low water accumulation in the Studibach catchment, which aligns with the steep slopes. However, even if there is low water accumulation at most locations, the study area is characterized by wet soil conditions due to the high precipitation. Some locations showed surprisingly dry or wet conditions for their attributed TWI. However, the main locations where sap flow was measured were close to the regression line and aligned with the expected pattern with high TWI locations being moist and low TWI locations being dryer (Figure 15).

It is well known that the TWI and soil moisture correlation yields mixed results (Winzeler, et al., 2022; Riihimäki, et al., 2021). Results of this study showed that there is a weak positive correlation of soil moisture and TWI. The research of Riihimäki et al. (2021) supports the finding that there is a weak positive correlation as the Spearman's correlation of measured soil moisture and TWI ranged from 0.12 to 0.48. Winzeler et al. (2022) also found a weak to moderate correlation between TWI values and volumetric water content, where the Pearson correlation coefficients varied from 0.18 to 0.64 over a measurement period of 5 years (Winzeler et al., 2022). This indicates that the TWI can spatially predict where soil moisture is accumulated, however studies have also reported that no correlation was found between TWI and soil moisture (Maduako et al., 2016; Liu et al., 2024).

In this study the DEM with 0.5 m resolution was available to calculate the TWI and the mean TWI in a 5 m radius around the sap flow measurement station was used. It is important to highlight that a mismatch in DEM resolution and the physical effects of soil moisture distribution can lead to a poor correlation between TWI and soil moisture (Riihimäki, et al., 2021) and that the correlation between TWI and soil moisture depends on the accuracy of the underlying DEM data (Maduako et al., 2016). While Sørensen et al. (2006) argued that there is no general calculation method that works best for all sites. Several authors (Maduako et al., 2016; Riihimäki et al., 2021; Winzeler et al. 2022) have found that adjusting the resolution of the DEM has an impact on the TWI values predictive capability for soil moisture. Thus, it is likely that exploring different flow routing algorithms and the resulting TWI could improve the correlation between TWI and soil moisture as explored by Riihimäki et al. (2021).

Further findings in this thesis show that the correlation with TWI is stronger using the manual soil moisture measurements (0.3183) than for the continuous measurements (0.1593). While the manual soil moisture measurements cover a greater spatial variation (26 locations of manual measurements, 6 locations of continuous measurements), the continuous measurements have a far greater temporal coverage (21 days for manual measurements, 10min interval data of five months of continuous measurements). The manual soil moisture measurements could have resulted in a higher correlation with TWI because the measurements took place on days without precipitation, as these dry days were often associated with a peak in correlation between TWI and soil moisture (Figure 15). Furthermore, there are outliers which could contribute to the strengthening of correlation in the manual data and the weakening of correlation in the continuous data. Especially since there were only six continuous soil moisture measurement stations which makes this analysis more vulnerable to outliers.

Over the season the Spearman's rank correlation between the continuous soil moisture and the TWI varies and a pattern with volumetric water content can be recognized (Figure 16). While there is a weaker correlation in June, when the mean soil moisture is higher, the relationship is stronger during the lower mean soil moisture in August. Winzeler et al. (2022) also connected the correlation between TWI and soil moisture to seasonal variation in soil moisture, in combination with the soil properties, vegetation type and environmental conditions. The soil moisture content is influenced by the balance between precipitation to evapotranspiration, which changes with the seasons (Western, et al., 2003) The research of Grayson et al. (1997) discusses that over the season there are different states (dry and wet state) which determine the spatial distribution of the soil moisture. Western et al. (1998) show that during wet periods the spatial pattern in soil moisture is driven by lateral redistribution. While in dry periods there is no topographically controlled spatial pattern rather soil properties and vegetation become more important factor (Western, et al., 1998). Further findings suggest that the spatial variation in soil moisture along the slope is the highest during intermediate soil moisture conditions, while dry states (close to wilting point) and wet state (close to saturation) show low variance (Western, et al., 2003). As the Studibach catchment is a very wet site it makes sense that the correlation is stronger between TWI and soil moisture in August when the soil wetness is intermediate and not high. The study of Liu et al. (2024) confirms the findings that there is a lack of relation between soil moisture and topography during the wet season. Furthermore, during short periods when soil moisture increases due to precipitation the correlation is weaker and after precipitation events during drainage periods the correlation shows a peak (Figure 16) due to wetter soils along drainage lines (Western et al., 1998). These short transition periods between wet and less dryer conditions where soil moisture is stronger correlated with TWI has been also observed in other studies (Liu et al., 2024; Tromp-van Meerveld & McDonnell, 2006; Western et al., 2003). Moreover, as the Studibach catchment has variable soil depths and vegetation density within a small scale (Tromp-van Meerveld & McDonnell, 2006; Vogler, 2025), this variance could also explain part of the spatial pattern of soil moisture rather than topography (Jarecke, et al., 2021).

6.2 Temporal pattern in transpiration

To discuss how transpiration changes over the season it is important to understand which factors influence transpiration. In theory as described by Dingman (2002) solar radiation, VPD, air temperature, and soil moisture are the main factors which affect the stomatal opening and thus the amount of transpiration. However, in natural ecosystems these factors and their interrelation get complicated as site specific conditions, environmental factors and vegetational characteristics also influence transpiration at different temporal and spatial scales (Jarvis, 1976). Thus, many studies try to quantify the influences of specific factors on transpiration in field studies (Calanca, 2007; Castelli, 2021; Ghimire, et al., 2022; Grossiord, et al., 2020; Liu, et al., 2019; Novák, 2012; Paul-Limoges, et al., 2020; Tromp-van Meerveld & McDonnell, 2006) or with models (Koehler, et al., 2023; Mastrotheodoros, et al., 2020).

Furthermore, radiation, VPD, temperature and soil moisture describe transpiration not in a multiple linear relation but can be described by different mathematical functions and are thus of different importance under particular environmental conditions (Dingman, 2002; Jarvis, 1976).

In this thesis a positive correlation between transpiration and radiation was found (Rho across the three sites: 0.31, 0.33, 0.35), which is well-established knowledge (Dingman, 2002). The radiation is dependent on the seasonal solar radiation pattern and the daily weather conditions. Moreover, tree stand structure and density influences the radiation input of an individual tree and the forest and therefore transpiration of a forest patch (Hassler, et al., 2018; Liu, et al., 2019). Liu et al. (2019) show that tree dominance, which is the position of a tree and its crown within a forest patch, affects transpiration. In this study this can be seen in the daily sap flow of the tree 3.4 (Figure 11) which has the highest over the whole season. The tree 3.4 has not the largest diameter among the trees within the upper main site, but its isolated position may have led to an increased exposure to incoming radiation and reduced competition with neighboring trees (Hassler, et al., 2018). Among other factors the tree structure leads to an overall high average sap flow rate at the upper main site over the season compared to the other two main sites.

The observed correlation between transpiration and VPD is strong (Rho across the three sites: 0.76, 0.82, 0.84). The correlation of transpiration with temperature and VPD (Rho of the three sites: 0.77, 0.86, .85) is very similar as VPD is dependent on the temperature. This is confirmed by the statistical test for relative importance where 65.65% of the variance in transpiration is explained by VPD.

While it is agreed upon that VPD affects transpiration (Dingman, 2002) characterizing the effect is still subject of discussion. Dingman (2002) states that there is a threshold in air temperature and VPD where the stress factor leads to a stabilization or reduction of sap flow. Ghimire et al. (2022) agree that VPD is the main driver of transpiration and that very high humidity can lead to a reduction in transpiration. Furthermore, high VPD, especially when combined with dry periods, can induce water stress in plants which can compromise their health (Grossiord et al., 2020).

In current studies a lot of interest is directed towards implication on the VPD, transpiration relation which are expected to become more important with climate change. Grossiord et al. (2020) expect VPD to rise with climate change, which could cause more droughts and tree mortality. Novick et al. (2016) agree that the relative importance of VPD will increase with higher temperatures and could limit transpiration. However, as there was no dry period during the growing season in 2024 in the Studibach catchment, there were no related impacts found. Therefore, studying the different effects on transpiration during a dry year in the Studibach catchment would be advised. It is especially important to research, as Masteodeothoros et al. (2020) state that in the Alps during the drought in 2003 the evapotranspiration increased due to the high VPD, which negatively impacts the water runoff in Switzerland and the surrounding countries. On the other hand, Norway spruce are found to be vulnerable to drought stress due to their shallow roots which in turn could reduce the transpiration rates with increasing droughts (Rabbel et al., 2018; Gebauer & Martinkova 2005).

In the Studibach catchment no threshold was identified where transpiration would be limited by high VPD. The threshold mentioned by Grossiord et al., (2020) is at a VPD of about 2 to 2.5 kPA. Within this span of VPD the transpiration in the Studibach catchment remains high and increases rather than stabilizes or decreases (Figure 19). Fabiani et al. (2022) specify that the threshold of VPD is species-specific, where for example beech trees were found to show decreased sap flow at 1.85 kPa when the sap flow of oak trees still remained stable.

While radiation, temperature and VPD are related to transpiration, no correlation is found between transpiration and precipitation (Figure 19). Nevertheless, the precipitation has an influence on the resulting soil moisture content, which is a part of the Jarvis model (Jarvis, 1976). VPD is usually a more important driver of transpiration than soil moisture (Bourbia, et al., 2025; Novick, et al., 2016). In this study soil moisture explained 12.2% of the transpiration at the Studibach catchment. Additionally, no clear temporal pattern is visible in the daily correlation between soil moisture and transpiration over the whole season. The impact of soil moisture observed in this thesis was low, likely because the influence of soil moisture on sap flow has been shown to be higher in dry periods (Bourbia, et al. 2025; Fabiani, et al., 2024) or in transition periods (Tromp-van Meerveld & McDonnell, 2006) which did not occur in the measurement period at the Studibach catchment. However, there also seem to be exceptions to that finding as Ghimire et al. (2022) found that the variance of daily sap flow was better explained with soil moisture during the wet season, than during the dry season in the tropical forest of Madagascar.

Furthermore, soil moisture is affecting transpiration on a different time scale (Koehler, et al., 2023). Novick et al. (2016) show that there is a seasonal and monthly correlation of soil moisture and VPD, while at shorter timescales VPD shows more variation than soil moisture.
While VPD seems to be the main temporal driver of transpiration in the encountered conditions the spatial influence of soil moisture has to be considered as well.

6.3 Spatial pattern in transpiration

Besides weather conditions, environmental factors of the site determine the transpiration rate (Ghimire, et al., 2022). While it was shown in section 6.1 that soil moisture is spatially distributed with topography (analyzed by the TWI), the question remains if this pattern could be shown to impact transpiration rates as soil moisture is the second main driver on transpiration (Koehler, et al. 2023) and the relative importance of soil moisture on transpiration was estimated to be 12.2%.

As transpiration is explained by multiple factors which can be described by different functions, some are more noticeable at certain conditions than others (Dingman, 2002). Transpiration and VPD are confirmed to be related (Jarvis, 1976; Grossiord, et al., 2020; Bourbia, et al., 2025). The focus of this thesis lies on the effects soil moisture has on the relationship between transpiration and VPD. It is currently presumed that at dry conditions this relationship between VPD and transpiration dwindle due to a limiting effect of soil moisture (Bourbia, et al, 2025; Fabiani, et al., 2022). Bourbia et al. (2025) estimate from their data that this limit is reached if the soil water potential (Ψsoil) gets more negative than -1 mPa, which can only be compared to soil moisture content if the water retention curve of the soil is known. Due to the generally high soil moisture levels recorded in this thesis, the impact of low soil moisture could not be shown. Especially since it has been found that the effect of soil moisture on transpiration and plant growth start to show after extended periods of low soil moisture (Koehler, 2023). The lack of a soil moisture limiting effect in this season in the Studibach catchment, fits the finding of Berg and Sheffield (2018). The findings of Berg and Sheffield (2018) show that globally in drier regions soil moisture is a limiting factor for ET. While in higher latitudes and wetter regions, there is no soil moisture limitation, instead the atmospheric conditions drive the variation in ET (Berg & Sheffield, 2018). The wet conditions encountered in this study showed that there is no correlation between soil moisture and transpiration, given the moderate to wet soil moisture conditions. This was also shown by Fabiani et al., (2024) where results show that high water availability did not necessarily result in more tree growth and transpiration, at a concave site. They attributed this to the characteristics of the observed tree species in their study. That the beech trees mainly use shallow soil water and thus are not tapping into the groundwater resources.

Soil moisture and transpiration showed generally no daily correlation over the season. To investigate the connected issue of topographic influence on transpiration, the transpiration and TWI were also analyzed for daily correlation. However, both of these daily correlations have to be considered carefully, as the main locations were selected in the field and also influenced by practical considerations, such as travers ability of the terrain and proximity to the road. Furthermore, the number of sites was limited to three locations. Thus, the correlation can only be done by plotting the transpiration values against three TWI or soil moisture values respectively. As a result of this limitation the daily correlation between TWI and transpiration/sap flow over the season fluctuates greatly. The low number of TWI values used for the correlation suggest that the fluctuation is due to random variation rather than an underlying relationship. Thus, more locations would increase the meaningfulness of these results. However, the data which was gathered suggests that there is no correlation between TWI and transpiration as it fluctuates around a rho value of 0. Although Balazy et al. (2019) have shown a 16% influence of TWI on spruce growth, other factors such as height above sea level (31%) or aspect (20%) seem to play a bigger role.

The lack of daily correlation between TWI and Sap flow/transpiration is not conclusive suggesting a lack of correlation, as different timescales have to be considered as well. The transpiration fluctuates on a daily timescale in response to VPD, while soil moisture varies over longer periods (Koehler, 2023). Novick et al. (2016) also found that the correlation of soil moisture and VPD has been observed on a seasonal or monthly scale but not on a daily or hourly scale. Bourbia et al. (2025) point out in their study that it was beneficial to have multiple years of data as is enables to properly account for the different timescales, a multitude of occurring weather conditions and differences between years.

Looking into the spatial pattern of sap flow on a weekly and monthly timescale, there is a difference between the sites. The upper main site with the lowest TWI (2.6) was in fact the driest site and showed the highest sap flow. While the middle site (TWI of 4.4) and the lower site (TWI of 3.7) were wetter and show generally lower sap flow over the weeks and months, compared to the upper site. This also fits the findings by Fabiani et al. (2022) where trees generally displayed higher sap velocity in upper locations than in downslope areas.
However, this spatial pattern changes after the upscaling from sap flow to transpiration of the forest patches. The highest transpiration rates over the months and weeks are found at the middle site. The upper site is also quite high, but the lower site shows significantly lower transpiration. Thus, the sites with high and low TWI show high transpiration while the site with the moderate TWI shows low transpiration, this pattern no longer suggests an influence of TWI on transpiration.

These changes in sap flow to transpiration pattern across sites, are due to the distribution of sapwood area which is the highest at the middle site and low at the lower site. The method of upscaling from sap flow to transpiration is common, but as pointed out by Liu et al. (2019) most appropriate for even-aged stands and plantations with a single canopy. Upscaling has been criticized as inaccurate for multi-layered and natural forests as they grow more complex regarding tree species, size, and age (Liu, et al., 2019). In this study the errors from this problem might be limited as only Norway spruce trees were analyzed, however size and age did still vary. Moreover, the daylight hour duration was only adjusted monthly in the transpiration calculation, which has introduced a certain inaccuracy.

Despite the limitations in the upscaling method, the upscaled data strongly suggests that the forest patch characteristics influence transpiration rates. The number of trees and their diameter at the lower site led to the much lower sapwood area and thus much lower transpiration compared to the other two sites. The middle and upper site display an interesting pattern where the middle site experiences less sap flow, but has more sapwood area, resulting in similar levels of transpiration at both sites (no significant difference).
These differences in transpiration could come down to several reasons. Tromp-van Meerveld and McDonnell (2006) showed that varying soil depth across the hillslope can lead to a spatial distribution of soil moisture and transpiration rates. At locations with deeper soils the

transpiration was less limited by soil moisture in comparison with sites that have shallow soils (Tromp-van Meerveld & McDonnell, 2006). However, as the soil depth and other environmental factors vary at a small spatial scale within the Studibach catchment, the comparison across the hillslope of the different factors on transpiration is challenging. Furthermore, it was observed during fieldwork that trees were merely at moderate soil moisture locations with steeper slopes, while in very wet and flatter sites grassland dominated (van Meerveld, et al., 2018). This observation is consistent with findings that vegetation cover tends to be shaped by topography through plant stressors such as water availability, nutritional condition, radiation input and soil characteristics (Silva, et al., 2023).

Fabiani et al. (2024) showed that topography results in varying sap flow responses to environmental conditions such as VPD but not consistently across hillslopes in different climatic locations (Weierbach catchment in Luxembourg and in the Lecciona catchment in Italy). This reflects the results in this thesis which also found a difference in sap flow and transpiration across the hillslope which however could also not be attributed to a clear driver yet.

7. Conclusion

This thesis studied the temporal and spatial pattern of soil moisture and transpiration of Norway spruce trees across a hillslope in the Studibach catchment in Switzerland, during the growing season in 2024. Findings showed that the soil moisture pattern could be aligned with the theoretical TWI through weak positive correlation. While the correlation is stronger with the manual soil moisture measurements compared to the continuous soil moisture data. The TWI values are generally low which suggests rather low water accumulation that fits the steep hillslope area. However, with the high precipitation rates the soil moisture only fluctuates between moderate and high values over the whole season. The daily correlation of soil moisture and TWI shows a pattern over the growing season where the correlation is weaker in June with higher soil moisture and stronger in August with lower soil moisture content. Thus, topography can predict the spatial soil moisture pattern across the slope to a certain degree in the Studibach catchment by using the TWI. However more precisely at moderate soil moisture content instead of high.

VPD and soil moisture are major contributing factors on transpiration, and the focus of this thesis lies on the effects of soil moisture in connection with topography on transpiration. It is currently assumed that at dry conditions soil moisture is in many settings limiting the relationship between VPD and transpiration. There was no opportunity to observe this in the Studibach catchment in 2024 due to high soil moisture levels over the whole growing season, thus the impact of low soil moisture could not be shown on a temporal scale. This becomes especially important since it has been found that the effects of soil moisture on transpiration and plant growth start to show after extended periods of low soil moisture.

Differences in sap flow at the three sites were shown on a weekly and monthly scale. The pattern of sap flow and transpiration between the three main sites was different which is due to the amount of sapwood area being different at the three sites. Which might be indicative of topographic influences on tree growth.

TWI or soil moisture both against sap flow and transpiration were not correlated when analyzed daily over the whole season, but this analysis must be considered carefully, as the number of sites was limited to three locations. As a result of this limitation the daily correlation between TWI and transpiration/sap flow over the season fluctuates greatly and no clear pattern is found.

The findings that sap flow was noticeably different between the three sites and that the amount of sap flow aligned with the TWI hints at an underlying process. Continuing the research in another growing period to compare the results and include dry periods to analyze the limitation of low soil moisture and the influence on transpiration would thus be recommended. Furthermore, including the soil water retention of the locations would be useful to estimate the threshold on water availability and limitation for the trees.

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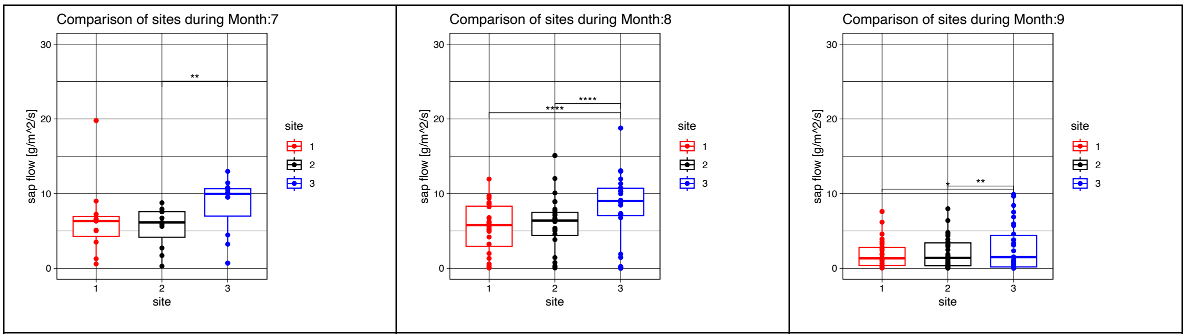
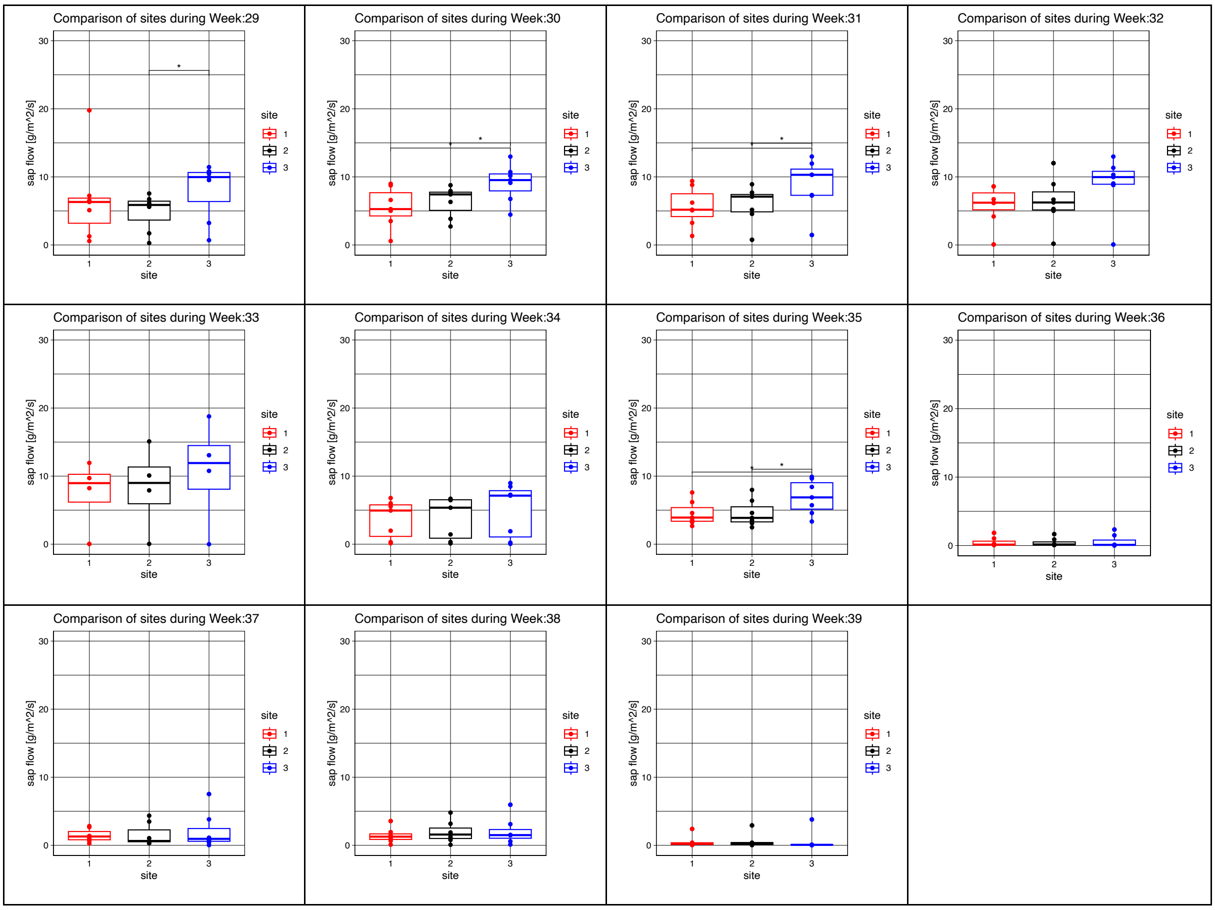
Appendix

Appendix 1. Monthly comparison of sap flow at the three sites, with chi-squared and p-value of the Friedman test (1= Lower main site, 2= Middle main Site, 3= Upper main site).

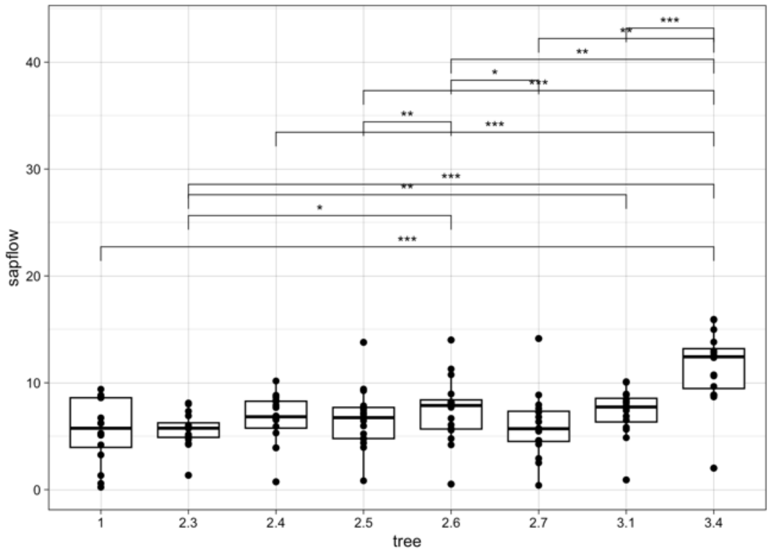


chi-squared = 13.636 p-value = 0.001094	chi-squared = 17.429 p-value = 0.0001642	chi-squared = 5.2667 p-value = 0.07184

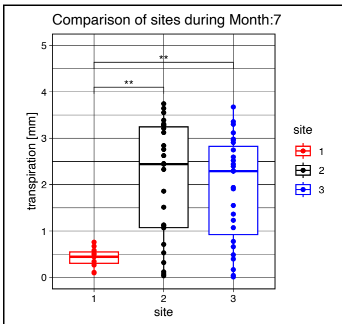
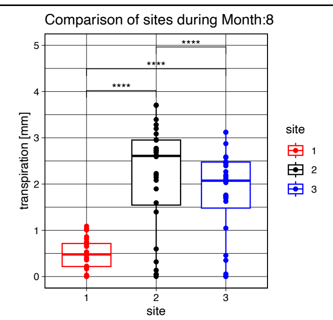
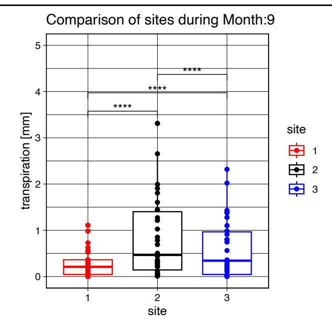
Appendix 2. Weekly comparison of sap flow at the three sites (1= Lower main site, 2= Middle main Site, 3= Upper main site).



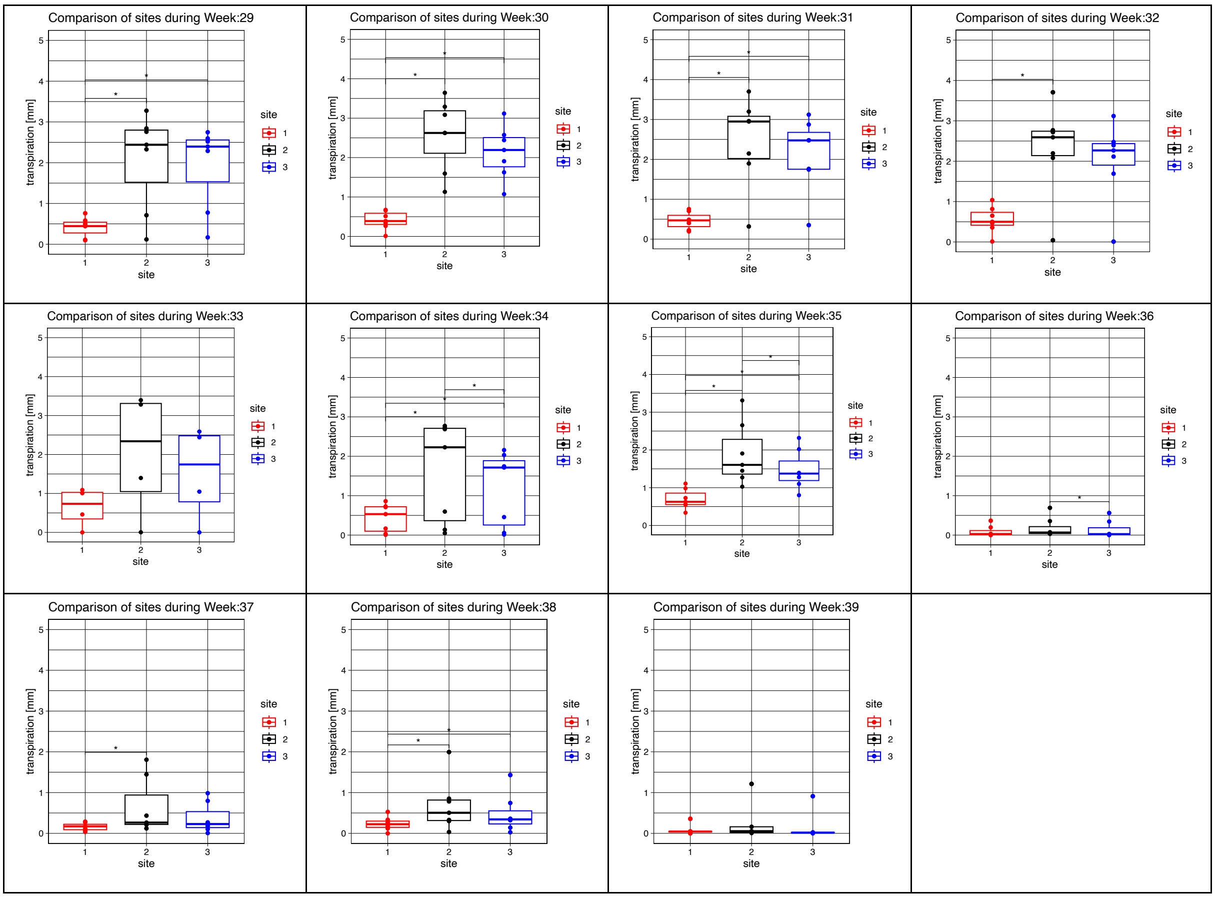
Appendix 3. Comparison between the sap flow of different Trees.



Appendix 4. Monthly comparison of transpiration between the sites, with the results of the Friedman and Bonferroni test.

		
chi-squared = 17.636, df = 2, p-value = 0.000148	chi-squared = 47.91, df = 2, p-value = 3.949e-11	chi-squared = 42.975, df = 2, p-value = 4.657e-10

Appendix 5. Weekly comparison of transpiration between the sites.



Appendix 6. Atmos41 weather station close to the lower main site.

Appendix 7. Upper intermediate site.

Appendix 8. Middle intermediate Site.

Appendix 9. Image representing the upper transect. View from the upper main site, looking towards the upper intermediate site.

Appendix 10. Image representing the lower slope. View from flag 13, towards lower intermediate site and middle main site (barely visible).

Personal declaration

Personal declaration: I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis. In this work AI was used as an “enhanced” search engine and the works found are declared as usual. AI was also used to answer questions regarding the syntax and user interface of the used programs.

Name: Charmaine Bassfeld **Date:** 25.04.2025

Signature:

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