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Evaluating Drought Impacts on Ecosystem Water Use Efficiency of Three Different Boreal Forest Sites

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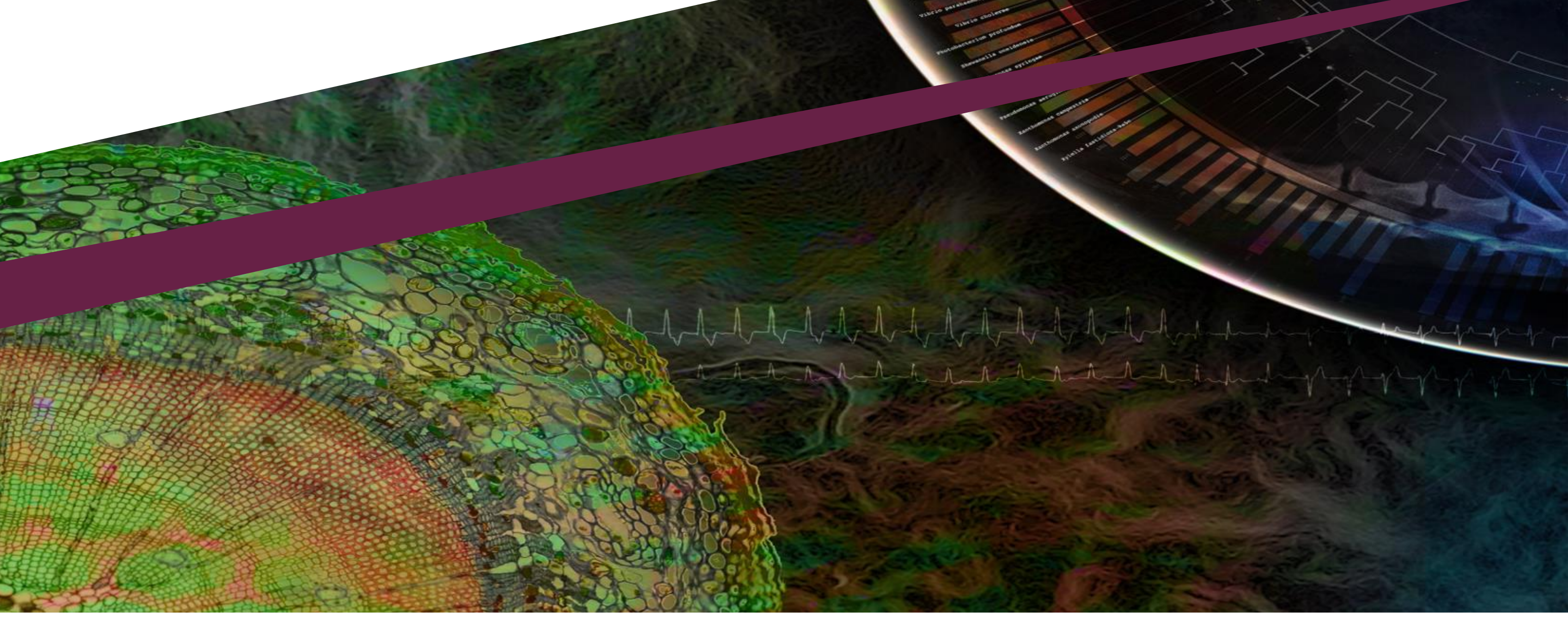

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Abstract

European boreal forests are the biomes most affected by climate change. For example, extreme weather events such as droughts are expected to become more frequent and severe. Especially in the summer months, droughts can drastically impact the carbon and water exchanges of boreal forests. This study aimed to identify the drought response of the water use efficiency (WUE) in three contrasting boreal forests. WUE, is the link between the carbon- and water cycle of forests and therefore a strong indicator of their ability to withstand droughts. To assess the drought response, the inter-annual variations and between-site differences in WUE, net ecosystem exchange (NEE), gross primary production (GPP), and ecosystem respiration of three forest sites were compared. The sites included one mixed stand, one pine stand, and one pine stand with regular nitrogen addition. Drought stress was quantified using various drought indices (SPI, SPEI, and SMI) as well as changes in temperature, precipitation, vapor pressure deficit, and the difference between potential- and actual evapotranspiration.

This study shows that GPP and NEE decreased in years with more drought stress. The results indicate that increased temperatures have the strongest negative correlation with WUE in all sites. It also found that under drought stress, the mixed stand had smaller losses of WUE compared to the two pine stands. Between the pine stands, WUE of the fertilized stand was more robust towards droughts. It was therefore concluded that nitrogen addition as well as mixing species can enhance forest resistance against droughts. These results provide information for practical management implications to make boreal forests more robust against droughts.

Keywords: flux data, carbon uptake, water deficit, Sweden, drought resistance, nitrogen, Eddy covariance

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Abbreviations

ΔET	Potential evapotranspiration – actual evapotranspiration
ET	Evapotranspiration
ETpot	Potential evapotranspiration
FC	Field capacity
GPP	Gross primary production
mSWC	Mean soil water content
NEE	Net ecosystem exchange
R_{eco}	Ecosystem respiration
rH	Relative humidity
Ros2	Rosinedal2
Ros3	Rosinedal3
SMI	Soil moisture index
SPEI	Standardized precipitation evaporation index
SPI	Standardized precipitation index
Svb	Svartberget
SWC	Soil water content
Tair	Air temperature
VPD	Vapor pressure deficit
WP	Wilting point
WUE	Water use efficiency

1. Introduction

1.1. Boreal forests in the global carbon and water cycles

The European boreal region is dominated by forests and wetlands. Typically, the boreal forests consist of Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), and species of birch (*Betula spp.*) and are characterized by intense human modification (Boonstra *et al.* 2016). Compared to boreal forests in Asia and North America, the climatic conditions in European boreal forests are milder and wetter. However, European boreal forests are still considered to be temperature- and light-limited (Ruiz-Pérez & Vico 2020). Despite their relatively low biodiversity, they are of great importance for global ecosystem services. This is mainly because Northern European forests store around 9.7 Gt C, which is the highest proportion of C storage of European forests (Thurner *et al.* 2014). Plus, by drawing up water from the soil and transpiring it into the atmosphere, forests regulate both soil and atmospheric moisture. They are therefore key regulators of the boreal water and energy balance (Hasper *et al.* 2015).

During the last years, climate change has drawn more and more attention and become a continuing threat to human health and the planet's ecosystems. However, climate change does not affect all global ecosystems equally. The boreal forests belong to the biomes most affected, with temperatures increasing twice as fast as elsewhere on the planet (IPCC 2015; Ruiz-Pérez & Vico 2020). Compared to drier ecosystems, negative effects of the warming climate are low so far and the rising temperatures might have even enhanced boreal forest productivity (Allen *et al.* 2010; Ruiz-Pérez & Vico 2020). The European boreal zone is expected to experience increasing temperatures as well as increasing precipitation. However, while precipitation is predicted to increase mainly during the winter, the summers are expected to get much warmer (Barber *et al.* 2000; Swedish Commission on Climate and Vulnerability 2007; Ruosteenoja *et al.* 2017). Especially the continental and southern parts of the boreal forests could therefore experience more drought stress (Dulamsuren & Hauck 2021) and Belyazid and Giuliana (2019) found that decreased summer precipitation can override the positive effects of increased temperatures. Hence, boreal forests appear to become increasingly vulnerable to water scarcity and droughts (Barber *et al.* 2000; EDO 2017).

1.2. Drought stress

Drought is considered to be one of the most complex natural hazards. Since the effects of droughts usually accumulate slowly and vary regionally, it is difficult to give one exact definition of drought. Hence, droughts have been grouped into the primary types: hydrological, socioeconomical, meteorological and agricultural (Wilhite 2000; EDO 2017). Signs of hydrological droughts are reduced streamflow or inflow to reservoirs, lakes, or ponds. Droughts are referred to as socioeconomical when social or economic water needs are affected. Meteorological droughts can be described as a precipitation deficit, whereas agricultural droughts represent the impacts of water scarcity to vegetation such as forests. Agricultural droughts can be described as a deficit of soil moisture and usually occur as a consequence of meteorological droughts (EDO 2017; Yihdego et al. 2019). Hence, in this study, the word drought refers to meteorological and agricultural drought.

Generally, forests experience drought stress when their evaporative demand exceeds the water available in the soil. Typically, this happens by either increased temperatures or decreased precipitation. Soil water scarcity is a major limitation for vegetational growth.

Relatively warm or dry conditions also increase the vapor pressure deficit (VPD). VPD is defined as the difference between the air's water vapor pressure at saturation and the actual water vapor pressure (Yuan et al. 2019). Since plants close their stomata when VPD is too high, increasing VPD leads to declining photosynthetic rates (Fletcher et al. 2007). A study by Konings et al. (2017) found that changes in VPD have stronger influence on vegetational growth than changes in precipitation.

The variety of causes of droughts as well as their impacts, make drought quantification challenging (Keyantash & Dracup 2002; Svoboda et al. 2016). Various drought indices have therefore been developed to help with the quantification and monitoring of drought. Typically, drought indices aim to give a numerical depiction of the drought severity. Usually, they get assessed using drought indicators, such as precipitation, temperature or soil moisture. Svoboda et al. (2016) grouped the drought indices into five classifications: meteorology, soil moisture, hydrology, remote sensing, and composite or modelled. Every index has their own advantages and disadvantages, hence choosing an appropriate index must be done for each study individually. To cover more aspects of droughts, and to make up for possible lacks in quality and quantity of recorded data it is reasonable to use multiple drought indices (Svoboda et al. 2016; Yihdego et al. 2019).

With droughts becoming common within the next decades (Toreti et al. 2019), the importance of water availability for the boreal forest carbon balance will increase. Plus, droughts do not only negatively affect forest productivity and vitality, but have a direct impact on the forests role in the carbon and water cycle (van der Molen et al. 2011). Enhanced drought stress due to a warmer climate has, therefore, the potential to further diminish the forests' ability to mitigate climate change.

1.3. Land-atmosphere exchange

To understand the importance of healthy forests in mitigating climate change, the basic concepts of the carbon and water cycle and how forests affect them needs to be understood. Both cycles are the key drivers for Earth's climate (Gentine et al. 2019). When looking at the water and carbon cycle, it is important to define the terms storage, flux, and process. In this study, storage is considered to be the total amount of carbon or water that a part of the system holds. The flow of either carbon or water between stores is considered to be a flux and the physical mechanisms that drive a flux are called processes.

1.3.1. Water cycle

On a global scale, the water cycle describes the circulation of water between the oceans, the land and the atmosphere (Holden 2005). Water gets stored in its three phases: liquid, ice, and atmospheric moisture. There are a number of key processes that cycle water between these stores. Evapotranspiration (ET) is the combination of water evaporation from open water or wet surfaces and transpiration. Transpiration is the process of plants taking up water through their root systems and releasing it as water vapor through their stomata. ET is mainly controlled by radiation, temperature, humidity, plant type and growth conditions (Allen et al. 1998). Potential evapotranspiration (ETpot) is the maximum amount that could be evaporated, if enough water was available (Thornwaite 1948). The difference between potential and actual evapotranspiration (ΔET) describes whether an ecosystem was experiencing a surplus or a lack of water supply. Atmospheric moisture enters the terrestrial system via precipitation and returns into the ocean either directly or indirectly through surface runoff or groundwater flow. Cryospheric processes include the accumulation of water through snowfall and the melting of ice. The water budget can be estimated on a global scale as well as on a local scale by measuring the key stores and fluxes.

1.3.2. Carbon cycle

Carbon pools exist in the Earth's mantle, crust, oceans, biosphere and atmosphere and the carbon cycle describes the processes that exchange carbon between them (Stern & Wieman 2021). The terrestrial part is dominated by the processes of plants which take up carbon via photosynthesis. The amount of fixed carbon by plants is referred to as Gross Primary Production (GPP) (Kirschbaum et al. 2001). However, through plants' internal metabolism they also lose carbon which is referred to as autotrophic respiration. Heterotrophic respiration is the loss of carbon by all other organisms. This study examines the so-called total Ecosystem Respiration (R_{eco}), which is the sum of both. The total amount of fixed carbon, thus the balance between GPP and R_{eco}, is called Net Ecosystem Exchange (NEE). This paper defines a negative NEE as carbon sink and positive NEE as carbon source.

Photosynthesis, respiration, and transpiration are the key processes for both the water and the carbon cycle. Plant stomata are major links between them. Changes in stomatal conductance due to drought stress have therefore influence on both cycles.

1.3.3. Eddy Covariance method

A direct way of measuring carbon dioxide and water exchange between the ecosystems and the atmosphere is the Eddy Covariance method. It uses the presumption that air flow is a horizontal flow containing numerous rotating eddies. Their size varies, and smaller eddies tend to be lower to the ground whereas bigger ones are usually further away. The basic idea behind the method is that each eddy carries an air parcel with its own characteristics such as gas concentration, temperature, and humidity. Usually installed on a tower, a sonic anemometer measures the vertical, horizontal, and lateral wind velocity (u, v and w), whereas a closed gas analyzer measures the concentration of water vapor and CO_2. For each of the fluxes, a covariance between the gas concentration and the vertical wind velocity can be calculated and the direction and magnitude of the flux can get estimated for each time step. If, for example, eddy A went up with three CO_2 molecules and afterwards eddy B went down with two CO_2 molecules, the calculated net flux was one molecule of CO_2 going upwards (NEE would be 1). Afterwards, GPP and R_{eco} can be calculated via various approaches (Reichstein *et al.* 2005). A conceptual presentation of an air flow including eddies is shown in Figure 1 and more in depth information about the Eddy Covariance Method can be found in Burba (2013).

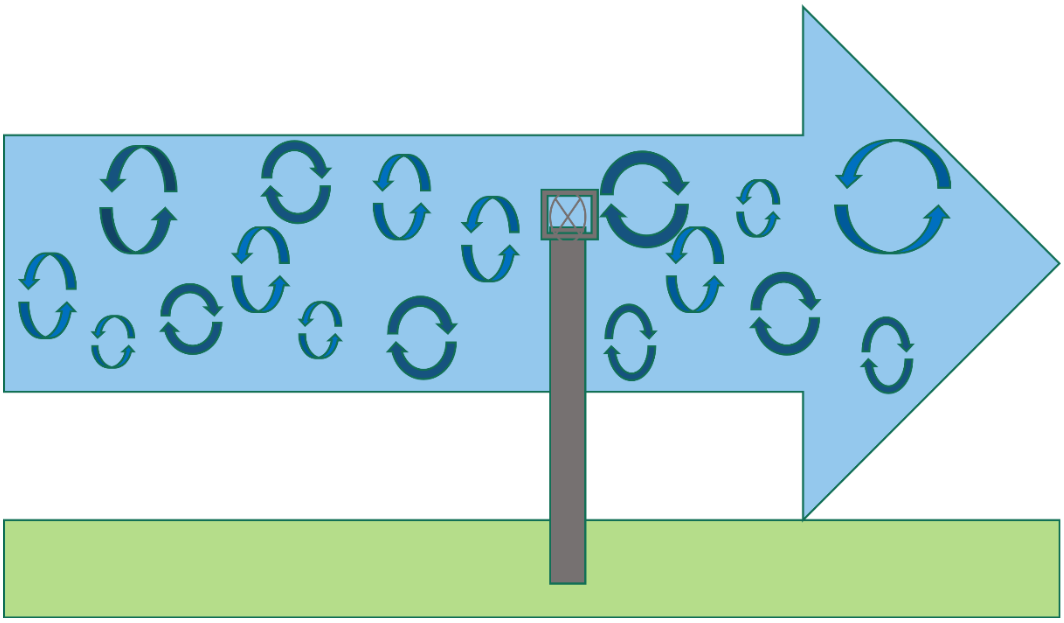

Figure 1: Conceptual presentation of a horizontal air flow (blue arrow) containing various eddies (dark blue circles). The Eddy Flux Tower (grey bar) measures the single eddies and calculates the net flux (Figure drawn by Tim Schacherl).

1.4. Water Use Efficiency

Water Use Efficiency (WUE) is a key indicator of the carbon-water coupling (Gentine *et al.* 2019). It is a commonly used metric to quantify the trade-off between carbon assimilation and water loss by plants (Farquhar *et al.* 1982). On a plant level, WUE is referred to as the ratio of net photosynthesis and transpiration (Knauer *et al.* 2018b). In this study however, WUE is assessed on an ecosystem level and defined to be the ratio of GPP to ET. Understanding WUE is crucial to predict how carbon and water budgets get affected by climate change (Hu *et al.* 2008).

1.4.1. WUE under drought conditions

Droughts do not only affect plants by reducing available soil water. Under conditions with high VPD, plants tend to close their stomata to protect themselves against high water loss (Gentine *et al.* 2019). Closed stomata tend to reduce GPP and ET with different intensities, so that their relative magnitudes change (Bhattacharya 2019). Droughts therefore highly influence plants' WUE. Assessing the changes of WUE under drought and non-drought conditions hence provides information about ecosystem resistance to droughts (Malone *et al.* 2016), with resistance being defined as the ability to withstand droughts while maintaining the same productivity. Multiple studies have shown that arid conditions increase WUE, and that WUE tends to be higher in water limited ecosystems (Roca *et al.* 2004; Reichstein *et al.* 2007; Ponce Campos *et al.* 2013). Malone (2017) therefore concludes that low WUE under normal conditions can be an indicator for low drought resilience. However, it appears that sporadic drought events have a different effect on WUE than constant water stress. Multiple studies found that WUE of most ecosystems could be reduced by droughts (Samanta *et al.* 2010; Gang *et al.* 2016). When analyzing the effects of the 2003 heatwave in Europe, Reichstein *et al.* (2007) also found that WUE tends to decrease under drought conditions. A general conclusion on how WUE reacts to drought conditions remains difficult, since it also depends on site conditions and vegetation. Kuglitsch *et al.* (2008) observed that the WUE of a boreal conifer site in Sweden peaked in the warmest examined years. That agrees with Hasper *et al.* (2015) who examined a boreal Norway spruce (*Picea abies)* forest in Sweden and did not find increased transpiration rates under elevated temperatures. Compared to other climatic zones, Kuglitsch *et al.* (2008) also found the largest interannual WUE fluctuations in boreal conifer stands.

The reaction of WUE to droughts might not only be influenced by plant species, but also by species composition. Complementary affects could help to maintain high WUE under drought conditions. Grossiord et al. (2013a) found that in drier soil conditions, mixed stands had much higher WUE than monocultures. Soil fertilization can also influence WUE. Nitrogen addition can lead to increased root growth which enables trees to utilize water from deeper soil layers (Bhattacharya 2019). Viets (1962) found that the use of fertilizer can increase yield significantly with only small increases of transpiration rates. Reviewing multiple studies of nitrogen addition to crops, Bhattacharya (2019) concluded that nitrogen addition leads to increases in WUE. Similar results could be expected for boreal forests since they are limited by available soluble nitrogen (Tian et al. 2021).

It is still not quite clear how different drivers of droughts such as high temperature or increased VPD affect WUE of boreal forest ecosystems and whether or not forest practices like species mixture or nitrogen addition can influence those effects.

1.5. Research aim

By comparing eddy covariance data of three different boreal forest sites in Sweden, this thesis aims to identify the drought response of the carbon and water exchanges in three contrasting boreal forests. In particular, it focuses on the questions: (i) how does drought stress during the vegetation period affect the weekly and monthly mean WUE of forests, and (ii) how does species composition and nitrogen availability influence WUE? For this purpose, the inter-annual variations, and site-differences in WUE, NEE, GPP, and R_{eco} of three boreal forest sites were compared. Drought stress was quantified using various drought indices (SPI, SPEI, and SMI) as well as changes in air temperature (Tair), precipitation, VPD, and the difference between ETpot and ET. It is hypothesized that with increasing drought conditions WUE of all sites decreases. The decrease of WUE in the mixed stand is expected to be less compared to the monocultures. Within the two pine stands, WUE of the fertilized stand is predicted to be more robust against droughts than the one without nitrogen addition.

2. Methodology

2.1. Site description

Data for this study was obtained at the three sites Svartberget (Svb), Rosinedal2 (Ros2), and Rosinedal3 (Ros3). Since 2011, Svb is part of the ICOS Sweden infrastructure, and hence follows their standardized protocols for data acquisition. The Rosinedal sites are used for experimental nitrogen addition studies since 2006 and are also equipped with eddy covariance towers. The sites are located in North-West Sweden near Umeå. They fall into the boreal vegetation zone which is dominated by coniferous forests. Their mean annual Tair and precipitation sum are 2.4 °C and 624 mm, respectively (Laudon et al. 2021; SITES n.d.).

Svartberget (64°15′N, 19°46′E, 267 m asl) is part of the well investigated Krycklan catchment, located about 9 km north of Vindeln. Detailed information about the Krycklan catchment can be found in Laudon *et al.* (2021). According to Zanchi *et al.* (2016) the gneiss bedrock is overlaid by glacial till and the field capacity (FC) and wilting point (WP) were estimated to be 0.326 and 0.059 m^3/m^3, respectively. The site is an about 110 years old mixed forest containing 64% *Pinus sylvestris*, 35% *Picea abies*, and 1% *Betula spp*. (Laudon *et al*. 2013). It has an average canopy height of about 23.5 m and an approximate basal area of 30.3 m^2/ha (ICOS 2020).

Both, Ros2 and Ros3 (64°10'N, 19°45'E, 145 m asl) belong to an experimental forest area located in Rosinedalsheden east of Vindeln. The dominating soil texture is fine sand. FC and WP of Ros2 are 0.298 and 0.059 m^3/m^3, respectively. Ros3 has a FC of 0.202 and a WP of 0.059 m^3/m^3 (Duursma *et al.* 2008; Tian *et al.* 2021). The sites are naturally regenerated pine forests (*Pinus sylvestris*) around 100 years old. Both stands have an approximate basal area of 27.4m^2/ha (Chi *et al.* 2021; Tian *et al.* 2021). The tree heights of both stands are shown in Table 1. Since 2006, Ros2 is annually treated with nitrogen, using the Skog-Can fertilizer (Yara, Sweden). The fertilizer contains NH_4 (13.5%), NO_3 (13.5%), Ca (5%), Mg (2.4%), and B (0.2%) (Lim *et al.* 2015). The applied amount of fertilizer between 2015 and 2019 can also be found in Table 1.

Table 1: Tree height of the sites Rosinedal3 and Rosinedal2 and the amount of applied fertilizer at Rosinedal2 for the years 2015 until 2019.

Year	**Tree height (m) Ros3**	**Tree height (m) Ros2**	**Fertilizer application (gN/m^2) Ros2**
2015	18.3	17.3	6.36
2016	18.5	17.9	6.36
2017	18.7	18.1	6
2018	18.9	18.3	6
2019	19.1	18.4	6

2.2. Data acquisition

The used data were obtained from measurements using the eddy covariance technique and additional ecosystem and meteorological measurements were carried out at all sites. For Svb, data were available from 2015 to 2020, excluding the year 2017. Both sites in Rosinedal provided data from 2015 to 2020.

In Svb, the LI-7200 enclosed-path gas analyzer (LI-COR Biosciences, USA) was used for CO_2 and H_2O concentration measurements. Prior to the 28th of June 2017, the measurement of wind components (u, v, and w) was carried out using the uSonic-3 Class-A ultrasonic anemometer (Metek Meteorologische Messtechnik GmbH, Germany) and after the Gill HS-50 (Gill Instruments Ltd, Lymington, UK). The measurement heights were adjusted during the data recording and are displayed in Table 2.

Tair and relative air humidity (rH) were recorded at 40 m above ground until the 13th of October 2019, when it was set to 32.5 m. Radiation was measured at a height of 50 m, precipitation at 2.5 m and air pressure at 2 m.

In four profiles, soil water content (SWC) and soil heat flux (G) were measured at different depths. SWC at the depths of 10 and 30 cm and G was measured at 5 cm below ground level.

In Ros2 and Ros3, the LI-7200 enclosed-path gas analyzer (LI-COR Biosciences, USA) was used for CO_2 and H_2O concentration measurements. The measurement of wind components (u, v, and w) was carried out using the ultrasonic anemometer Gill R3-100 (Gill Instruments Ltd, Lymington, UK). The measurement heights were adjusted various times during the data recording and are displayed in Table 2.

Table 2: Measurement heights of gas analyzer and ultrasonic anemometer at the sites Svartberget (Svb), Rosinedal2 (Ros2) and Rosinedal3 (Ros3).

Date	**Measurement height (m)**
Ros2	
07.07.2014 – 31.07.2017	20.5
31.07.2017 – 13.06.2019	21.5
13.06.2019 – 31.12.2020	23
Ros3	
07.07.2014 – 03.08.2017	20.5
03.08.2017 – 19.06.2019	21.5
19.06.2019 – 31.12.2020	23.5
Svb	
01.01.2014 – 22.05.2018	32.5
22.05.2018 – 31.12.2020	34.5

The meteorological data was recorded on top of the measurement mast and was therefore a bit higher than the eddy covariance measurements. However, the accurate measurement height was not recorded. In both sites, SWC was measured at one profile at the depths of 15 and 50 cm. In Ros2, G was measured at two profiles, which together recorded at 5, 10, and 15 cm below ground level. In Ros3, G was recorded by sensors at 5 and 15 cm below ground level.

The data provided for this study (eddy covariance flux, meteorological and ecosystem data) were quality checked prior to use, processed in local time without daylight saving time, and given in half-hourly time steps. Changing measurement heights were considered and, if necessary, the data were processed individually. If measurements were taken by multiple sensors, the analysis was proceeded with averaged values. All processing of the data was done using R, version 4.0.3 (R Core Team 2020).

2.3. Defining reference data

To compare meteorological anomalies and for computing drought indices, daily temperature, and precipitation data from 1991 to 2020 from the Hygget climate station (64°14’N, 19°46’E, 225 m asl) were used. The data were provided by the reference climate monitoring program at Swedish University of Agricultural Science (SLU) experimental forests and SITES Svartberget (SITES n.d.). Temperature data were based on minute measurements using a thermistor (Campbell Sci. Model T107) with a ventilated radiation shield. The thermistor was installed 1.7 m above ground within a forest clearing area. Daily accumulated precipitation was measured with a standard SMHI gauge and a wind shield. The gauge was installed 1.5 m above ground. For the year 2020, precipitation values were only available for the vegetation period. Hence, the precipitation values for 2020 were taken from Krycklan data portal (2021). In this study, the series of all years is referred to as reference data, whereas the average of all 30 years is defined as reference year.

2.4. Data preparation

The difference in data coverage and measurement quality of the meteorological data and the usage of different measurement devices led to systematic errors when comparing the sites. Contrasting to that, calculated regression models between the variables of all sites showed a minimum R^2 of 0.64, excluding precipitation. The correlation of the precipitation was lower, with a minimum R^2 of 0.14 between Ros2 and Svb. However, when daily precipitation was tested it was 0.40. Additionally, Rosinedal was missing precipitation measurements in winter. It was therefore decided that the meteorological measurements (Tair, precipitation, air pressure, rH) of Svb were to be used for all sites. They were gap filled in two steps. First, short gaps were filled using linear interpolation. The maximum length of gaps to be filled that way was set to 2 hours, except for SWC, for which it was set to 7 days because it does not fluctuate as quickly. To fill remaining gaps, a reduced major axis regression (RMA) between Svb and each Ros site was calculated, using the R package lmodel2, version 1.7-3 (Legendre 2018). RMA was chosen because it is an appropriate approach when both variables show measurement uncertainties (Harper 2014). Using the regression, Svb data was first filled with Ros3 and afterwards with Ros2 data.

Following Allen *et al.* (1998), the saturation vapor pressure (esat) and VPD were calculated in hPa using Equation 1 and 2, respectively using Tair (°C) and rH (%).

Equation 1: $esat = (610.8 * \exp\left(\frac{17.27 * Tair}{237.3 + Tair}\right))/100$

Equation 2: $VPD = esat - \frac{rH}{100} * esat$

Short gaps in the flux data were filled using linear interpolation. The maximum length of gaps to be filled was set to 2 hours. To prevent measurement errors due to storage fluxes, sensible heat (H), latent heat (LE), and NEE were corrected with the storage terms. Storage terms were estimated based on the concentration measurements at the eddy covariance system level. This correction is needed because eddy flux towers only measure fluxes at their specific measurement height. Especially during calm periods, gas and energy can build up below that height and can be transported away sideways by wind gusts. These storage terms can therefore remain at least partially undetected. The calculated storage terms account for that error and were added to the measured fluxes (Burba 2013).

After the manual gap filling and correcting of fluxes, the data were processed using the REddyProc Tool for R, version 1.2.2 from the Department of Biogeochemical Integration at the Max Planck Institute for Biogeochemistry located in Thuringia, Germany (Wutzler *et al.* 2020). REddyProc processes data in three steps. First it determines and filters periods with low turbulent mixing (u* filtering). Second, it fills gaps using a combination of three methods (Falge *et al.* 2001; Reichstein *et al.* 2005) depending on the availability of data. If only the data to be gap filled are missing, a lookup table is used to estimate an averaged value from times with similar conditions. If some meteorological data are missing, the shortwave incoming radiation is used to find an averaged value in similar conditions. If all data are missing, it gets replaced by the mean of that time of day based on adjacent days.

In the third step, REddyProc separates NEE into its major components GPP and R_{eco}. This source partitioning can be done either based on nighttime or daytime flux measurements. For this study, the nighttime partitioning method after Reichstein *et al.* (2005) was chosen. This method works with the assumption that during nighttime no GPP occurs and hence, NEE can only contain R_{eco} fluxes. Exponential relationships between these nighttime fluxes and Tair were derived for short time windows. By extrapolating these relationships to daytime conditions, GPP can be computed as the difference between NEE and R_{eco} (Reichstein *et al.* 2012).

Since the data were already quality checked for time periods with low turbulent mixing, no u* filtering was conducted. A more detailed description of REddyProc can be found in Wutzler *et al.* (2018).

After the final gap filling and source partitioning with REddyProc, ET was estimated using the R package ‘Bigleaf’, version 0.7.1 (Knauer *et al.* 2018a). The function computes ET using Equation 3 in which LE is measured latent heat flux (W/m^2) and λ is the latent heat of vaporization (J/kg). The calculation of λ was done according to Stull (1988) and is displayed in Equation 4.

Equation 3: $ET = LE/\,\lambda$

Equation 4: $\lambda = (2.501 - 0.00237 * Tair) * 10^6$

Site specific ETpot was calculated using the R package ‘Bigleaf’, version 0.7.1 (Knauer *et al.* 2018a). It calculates ETpot using the Penman-Monteith equation (Equation 5) according to Allen *et al.* (1998). The equation uses the slope of the saturation vapor pressure curve (Δ in kPa/K), net radiation (Rn in W/m^2), G (W/m^2), the sum of all energy storage fluxes (S in W/m²), air density (ρ in kg/m³), Tair (degC), VPD (kPa), aerodynamic conductance to water vapor (Ga in m/s), the psychrometric constant (γ in kPa/K) and the potential surface conductance (Gs_{pot} in mol/m²/s). Gs_{pot} was defined to be the 90th percentile of the surface conductance Gs. Ga and Gs were also calculated using the R package 'Bigleaf', version 0.7.1 (Knauer *et al.* 2018a). Since Ros3 had a gap of soil heat flux data in the first half of 2015 that was too large to be filled properly, G was assumed to be zero.

Equation 5: $ETpot = \frac{(\Delta*(Rn-G-S)+ \rho*Tair*VPD*Ga)}{\Delta+\gamma*(1+\frac{Ga}{Gs_{pot}})}$

In this study, GPP was defined to be negative when CO_2 was assimilated by the ecosystem and WUE was computed as shown in Equation 6, so that higher WUE values represent a more efficient uptake of carbon.

Equation 6: $WUE = \frac{GPP}{ET} * (-1)$

2.5. Drought Indices

To represent various aspects of droughts, three different indices were used to quantify the level of water stress. The Soil Moisture Index (SMI) was chosen to display soil moisture dynamics, whereas the Standardized Precipitation Index (SPI) only displays changes in precipitation. The Standardized Precipitation-Evapotranspiration Index (SPEI) was chosen to capture the influence of temperature differences, because it considers, in addition to precipitation, the potential evapotranspiration. The indices were calculated as follows.

2.5.1. SMI

Equation 7 was used to calculate SMI. The calculation was presented in Gao et al. (2017), where mSWC is the weighted mean soil water content in m³H2O/m3. Since the measured SWC values of Ros2 and Ros3 were unreasonably low, following Tian et al. (2021) a corrected mSWC was calculated using Equation 8. The time series of mSWC is displayed in Figure 11 (Appendix). The variables s and r were site specific correction parameters, with s = 1.21 and 1.35, and r = 0.826 and 0.945 for Ros2 and Ros3, respectively. Information about the estimations of the parameters can be found in Tian et al. (2021). SWC15 and SWC50 were the measured SWC in 15 and 50 cm depth, respectively.

FC is a threshold, after which gravitational drainage is too strong for soil moisture to be retained, whereas the soil specific WP represents a threshold at which the moisture is held by the soil matrix and therefore cannot be used by plants (Gao *et* *al.* 2017). SMI was calculated with weekly data over the vegetation period and for each site individually with FC and WP values as described in Chapter 2.1. Weeks with negative WUE, or WUE bigger than 20 g/kg were excluded from the SMI presentation.

Equation 7: $SMI = \frac{mSWC - WP}{FC - WP}$

Equation 8: $mSWC = s * (r * SWC15 + (1 - r) * SWC50)$

The values of this index can be classified into five groups representing the soil moisture level (Table 3).

Table 3: Soil Moisture Intex intervals according to Gao et al. (2017) representing the soil moisture dynamics from very dry to very wet.

Interval	**Drought severity**
0.00 - 0.20	Very dry
0.21 - 0.40	Moderate dry
0.41 - 0.60	Mid-range
0.61 - 0.80	Moderate wet
0.81 - 1.00	Very wet

2.5.2. SPI

SPI was calculated using the R package 'SPEI', version 1.7 (Beguería & Vicente-Serrano 2017). It standardizes a monthly series of precipitation values using a Gamma distribution function. The output is monthly values that can be interpreted as the number of standard deviations by which the measured value differs from the long-term mean. The values are both positive and negative and indicate droughts in various groups as presented by Sönmez *et al.* (2005) and shown in Table 4. SPI was calculated using the precipitation values from the reference data. Hence, all sites have the same SPI values.

2.5.3. SPEI

SPEI was calculated with the R package 'SPEI', version 1.7 (Beguería & Vicente-Serrano 2017). The basic calculation is similar as for SPI, but the SPEI uses the difference between precipitation and ETpot as input, which represents a simple climatic water balance. Since SPEI used the reference data, ETpot could not be used as calculated in Equation 5. Thus, for SPEI it was calculated using the R package ClimClass, version 2.1.0 (Eccel *et al.* 2016). The function computes ETpot according to Thornwaite (1948), using a monthly series of Tair as input. The SPEI function then standardizes the input values using a log-logistic function. The output values can be interpreted the same way as the SPI values (Table 4). SPEI was calculated for the reference data and hence, applies to all three sites.

Table 4: Drought groups for SPI and SPEI as presented by Sönmez et al. (2005).

SPI and SPEI values	**Drought group**
>0	No Drought
0 to -0.99	Mild Drought
-1.00 to -1.49	Moderate Drought
-1.50 to -1.99	Severe Drought
≤ -2.00	Extreme Drought

3. Results

The results of this study give information about the meteorological conditions on the examined sites, the water and carbon fluxes of each site and the dependencies between WUE and various variables.

3.1. Meteorological conditions

3.1.1. Thermopluviogram

The Thermopluviogram (Figure 2) shows the temperature and precipitation anomalies from a 30-years average from 2015-2020 (excluding 2017). Except for 2019, the months during the vegetation period were mostly warmer than the 30 years average. Plus, except for 2015 at least half of the months during the vegetation period were too dry. In 2018, May and July were the warmest months with an anomaly of 4.4 °C and 3.7 °C, respectively. In 2020, June and August were especially dry months with 44.1 % and 66.7 % less precipitation, respectively. The annual average of all years was either warmer or dryer than the average (green square). Only 2019 was colder than the average (-0.1 °C) and only 2015 and 2020 had more precipitation than the average (+3.6 % and +13.2 %, respectively).

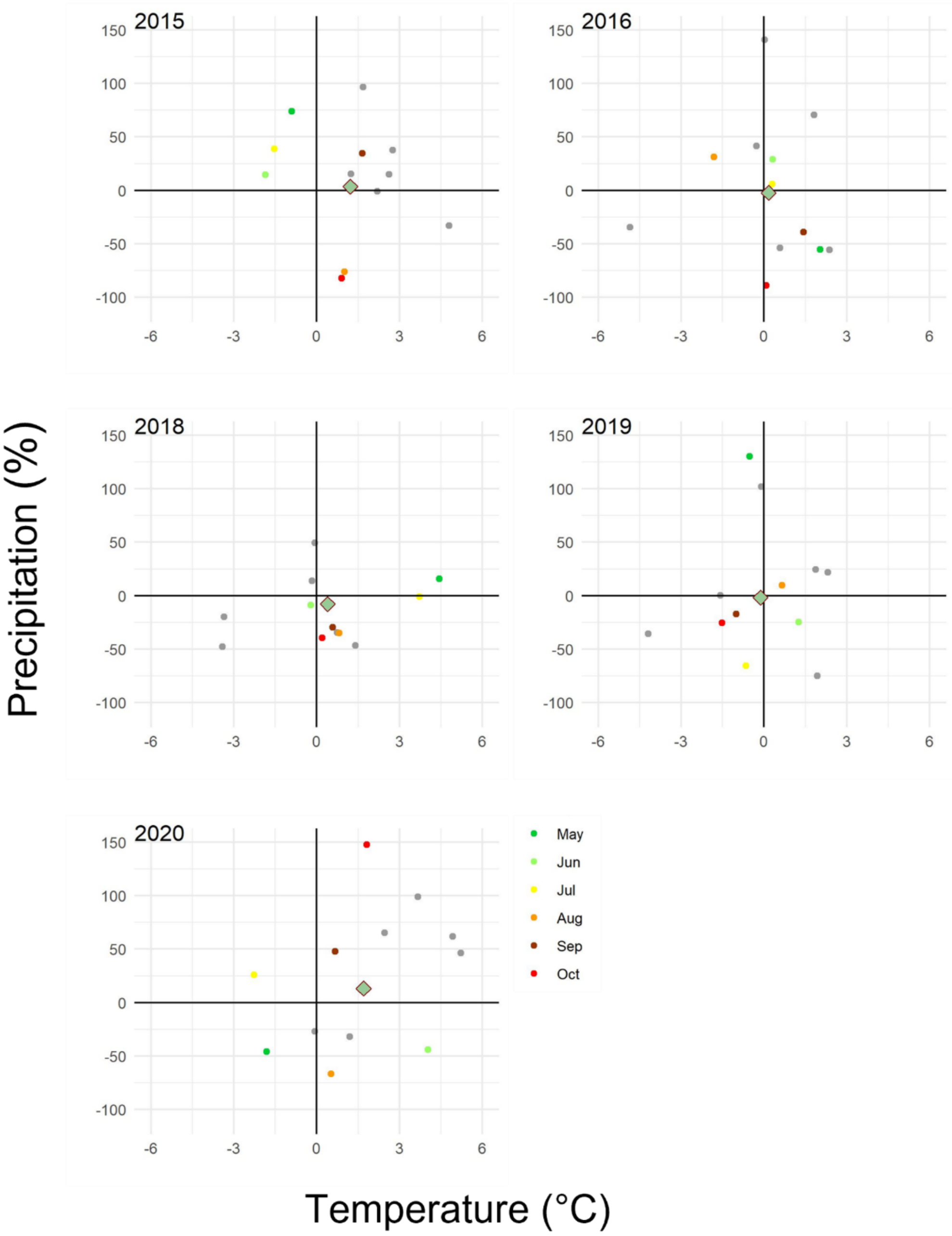

Figure 2: Monthly and annual precipitation (%) and temperature (°C) anomaly from a 30-years monthly average. The grey dots show months outside the vegetation period and the green squares show the annual mean.

3.1.2. VPD

All years showed two maxima with a first one being either in May or June and a second one in July or August (Figure 3). The year 2018 had the highest average VPD (0.31 kPa) and the highest maxima (May: 0.77 kPa and July: 0.96 kPa). In 2020, the first maximum was one of the two most extreme maxima (June: 0.96 kPa).

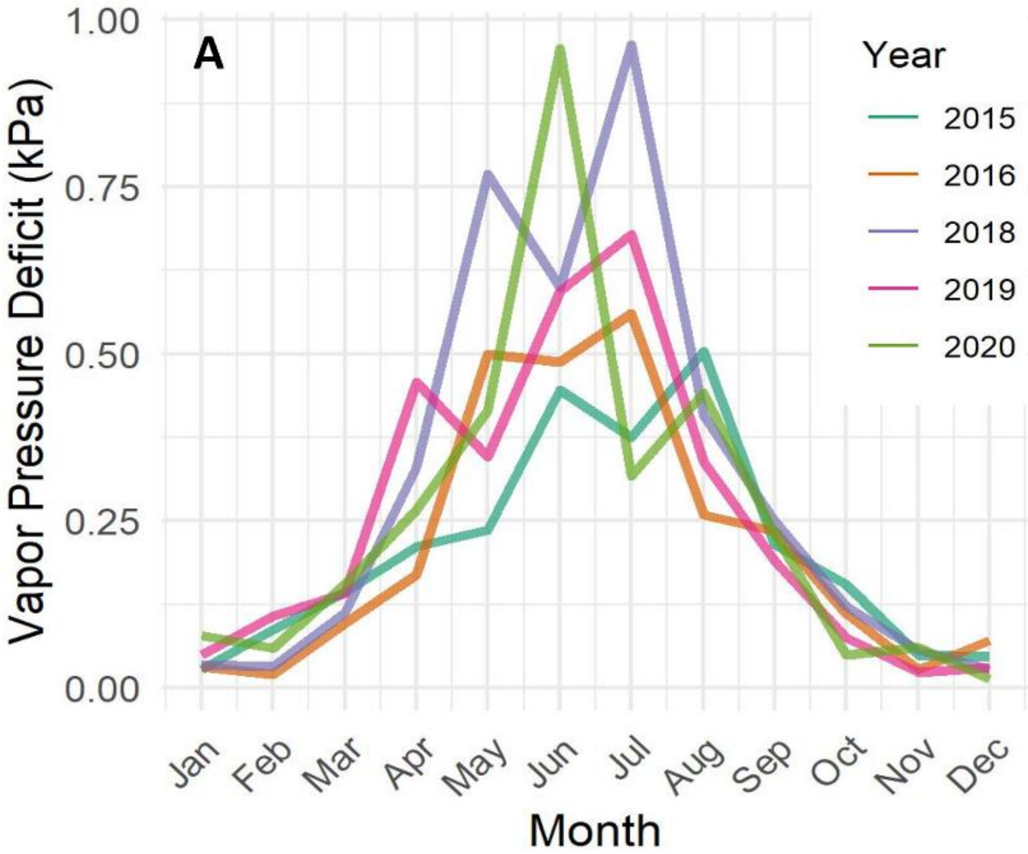

Figure 3: Monthly Vapor Pressure Deficit for the three sites Rosinedal2, Rosinedal3 and Svartberget.

3.1.3. ΔET

In Svb, the two years with the highest mean ΔET (ETpot - ET) were 2018 (44.81 mm) and 2020 (35.28 mm). For Ros2 and Ros3, the two years with highest mean ΔET were 2018 (35.99 mm and 31.93 mm, respectively) and 2019 (28.75 mm and 28.31 mm, respectively).

Each year, Svb had the highest mean ΔET and Ros2 second highest. Monthly ΔET values for all sites are displayed in Figure 4.

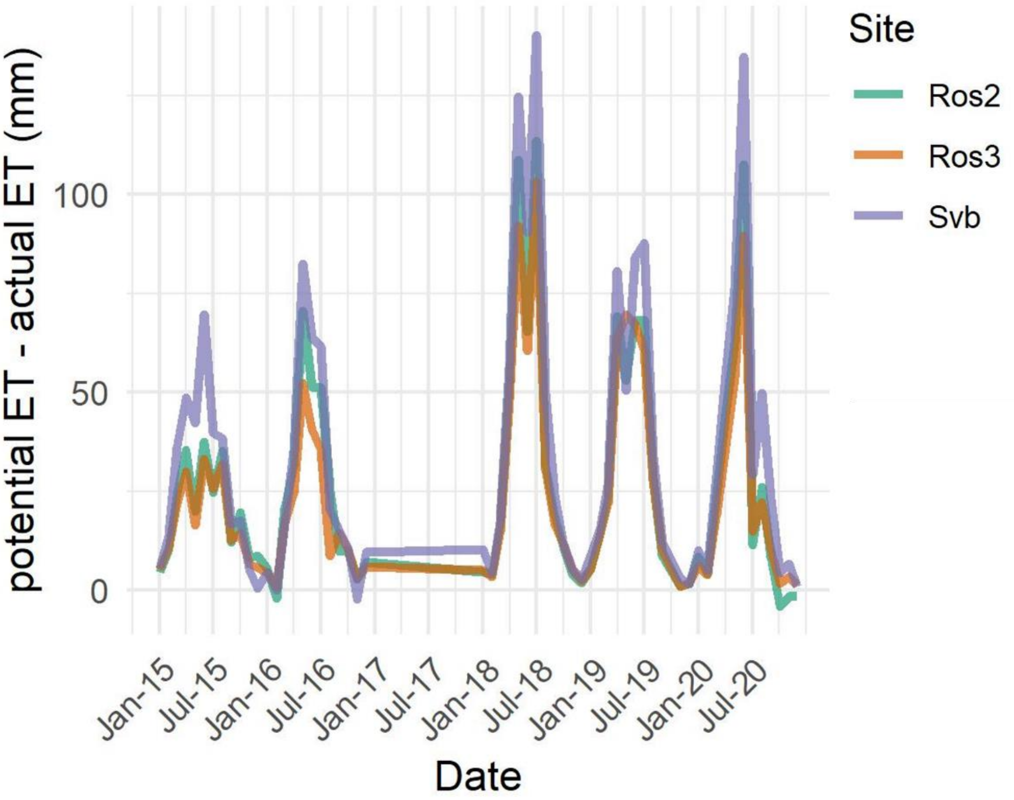

Figure 4: Time series (excluding 2017) of the difference between potential Evapotranspiration and actual Evapotranspiration.

3.2. Comparison of water and carbon fluxes between the sites

3.2.1. GPP

In Svb, the cumulated magnitude of GPP was largest in 2015 with -1097.4 gC/m^2 (negative numbers indicate ecosystem carbon uptake). The lowest uptake was in 2018 with -841.1 gC/m^2. In Ros2, the cumulated magnitude of GPP was largest in 2015 with -1116.7 gC/m^2. The least uptake was in 2020 with -931.8 gC/m^2. In Ros3, cumulated GPP was largest in 2016 with -960.6 gC/m^2. The least uptake was in 2020 with -790.1 gC/m^2. The five-year average of GPP was largest in Ros2 (-1001.4 gC/m^2), followed by Svb (-935.4 gC/m^2) and Ros3 (- 882.4 gC/m^2). The cumulative GPP of all sites are displayed in Figure 5A.

3.2.2. ET

Svb had the highest cumulative ET in 2016 (363.5 mm) and the lowest in 2018 (289.8 mm). Ros2 and Ros3 had the highest ET in 2020 (281.8 mm and 235.0 mm, respectively) and the lowest in 2019 (220.6 mm and 179.7 mm, respectively). The averaged cumulated ET was highest in Svb (309.4 mm), followed by Ros2 (251.3 mm) and Ros3 (214.5 mm). The annually cumulated ET values are displayed in Figure 5B.

3.2.3. Reco

Svb had the highest cumulative R_{eco} in 2015 (788.2 gC/m²) and the lowest in 2019 (650.9 gC/m²). Ros2 had the highest R_{eco} in 2020 (689.2 gC/m²) and the lowest in 2016 (542.1 gC/m²). Highest R_{eco} in Ros3 was in 2018 (584.0 gC/m²) and the lowest was in 2019 (494.5 g C/m²). The five-year averaged R_{eco} was highest in Svb, second in Ros2, and lowest in Ros3 (721.6 gC/m², 628.91 gC/m², and 544.2 gC/m², respectively). The annually cumulated R_{eco} values are displayed in Figure 5C.

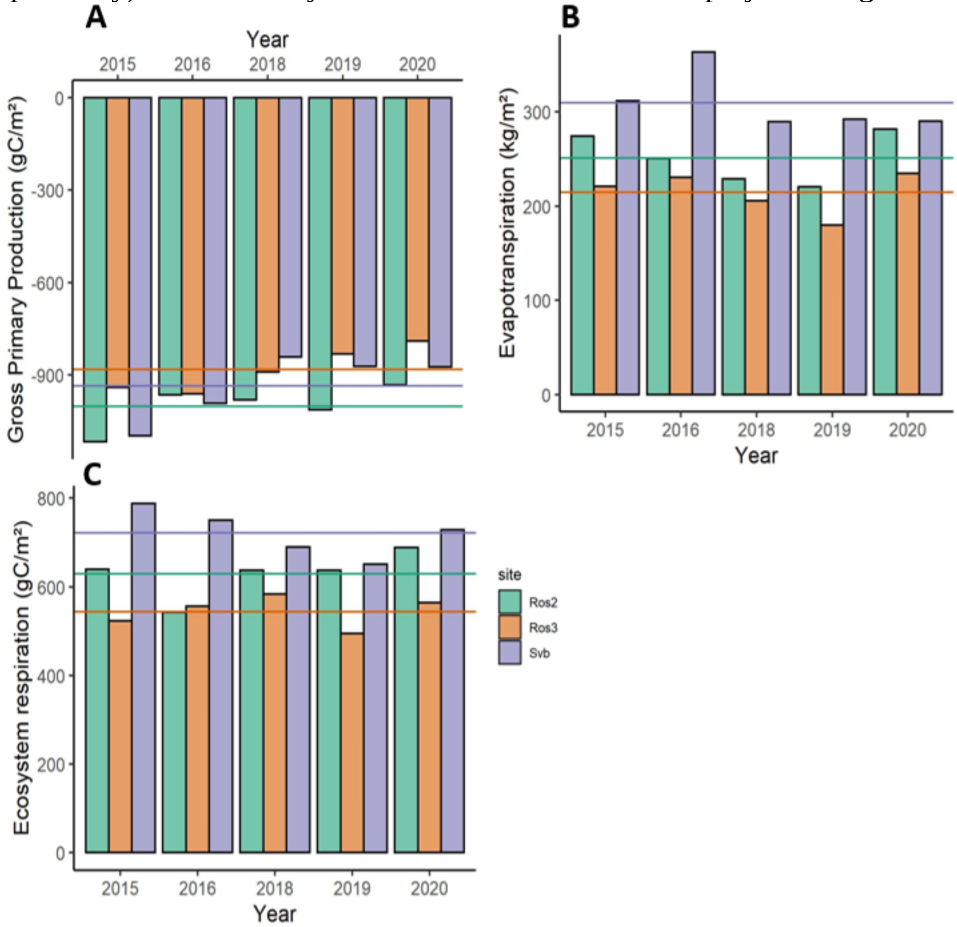

*Figure 5: Annual sum of **A**: Gross primary production, **B**: Evapotranspiration, and **C**: Ecosystem respiration for all three sites in the years 2015 to 2020 excluding the year 2017. The lines indicate the site specific 5-year average.*

3.2.4. NEE

Throughout all years, Svb's cumulative NEE was the last one to become negative (net CO_2 uptake). Ros2 and Ros3 turned negative similarly except for in 2018 and 2020, when Ros2 turned negative one month later than Ros3. Svb was also the site with the highest CO_2 losses during the winter months, with Ros3 being second and Ros2 having the smallest. Over the five years, the total carbon uptake of Svb was lowest (-1069.1 gC/m²), followed by Ros3 (-1691.0 gC/m²) and Ros2 (-1862.3 gC/m²). For all sites, 2018 and 2020 were the years with the least and 2015 the year with the highest CO_2 uptake. The monthly cumulative NEE throughout the years can be seen in Figure 6.

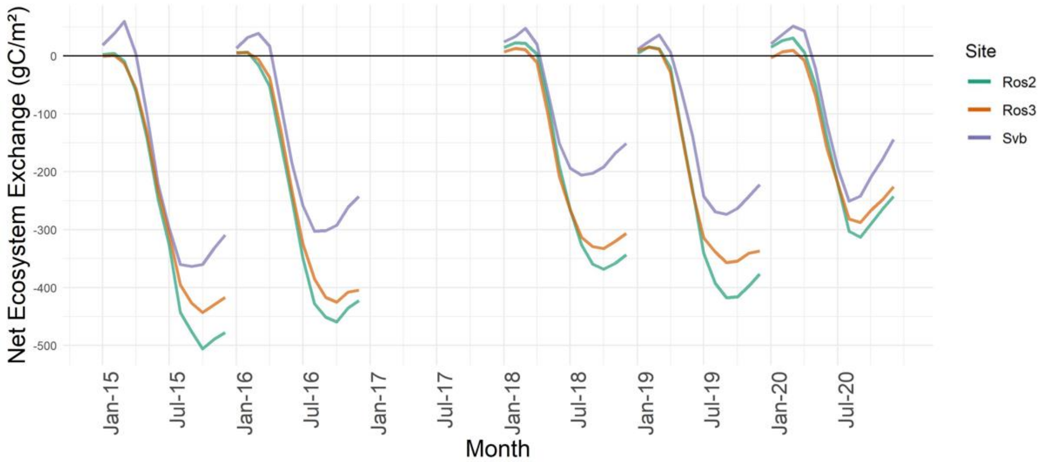

Figure 6: Cumulative annual Net Ecosystem Exchange for the sites Svartberget (Svb), Rosinedal2 (Ros2) and Rosinedal3 (Ros3).

3.3. Dependencies of WUE

The meteorological indicators Tair, precipitation, VPD, and ΔET as well as the drought indices were tested for significant correlation with WUE using the Pearson correlation test. Here, only weeks during the vegetation periods were considered (May - October). The correlation coefficients were grouped into 'little, if any' (0 – 0.3), 'low' (0.31 – 0.5), 'moderate' (0.51 – 0.7), and 'high' correlation (> 0.7). During the considered 5 years, average WUE during the vegetation period in Ros2 was 4.24, in Ros3 it was 4.68 and Svb had lowest WUE with 3.39 (Figure 12, Appendix). A Tuckey's HSD test showed a significant difference between WUE of Svb and the two Ros sites (p-value < 0.05). The difference between Ros2 and Ros3 was not significant (p-value > 0.05)

3.3.1. Meteorological Indicators

WUE of all sites decreased with higher temperatures (Figure 7). Only in Ros3, WUE increased again when temperature was above 20 °C (n = 1). Throughout all temperature groups, WUE was highest in Ros3 and lowest in Svb. Most weeks had temperatures between 10 and 15 °C (n = 60). Only 14 weeks had temperatures above 15 °C. The decrease of WUE between temperatures < 5 °C and 15-20 °C was biggest in Ros3 (-2.76) and smallest in Svb (-1.36). WUE of Ros2 decreased by 2.56. The distribution of WUE between the temperature groups is displayed in Figure 7. A Pearson correlation test between temperature and WUE had p-values < 0.05 for all three sites with correlation coefficients of -0.55, -0.57, and -0.66 for Svb, Ros2, and Ros3, respectively. According to the correlation coefficients the correlations in all sites can be considered to be moderate. To examine whether the change in WUE depending on temperature was based on changes in ET or GPP, a quadratic function was calculated between the variables (Figure 8). The models indicate that WUE decreases due to stronger increases in ET than in GPP.

Correlation tests between VPD of all years and WUE showed significant correlations for all three sites (p-value < 0.05) with correlation coefficients of -0.44, -0.37, and -0.39 for Svb, Ros2, and Ros3, respectively. This can be interpreted as a low correlation. Precipitation only showed a significant correlation with WUE in Ros2 (p-value < 0.05). The correlation coefficients were below 0.3 for all sites and thus indicated little, if any correlation. The correlation between ΔET and WUE was significant for Svb and Ros2 (p-value < 0.05), but the correlation coefficients of all sites were between 0 and 0.3 indicating little, if any correlation.

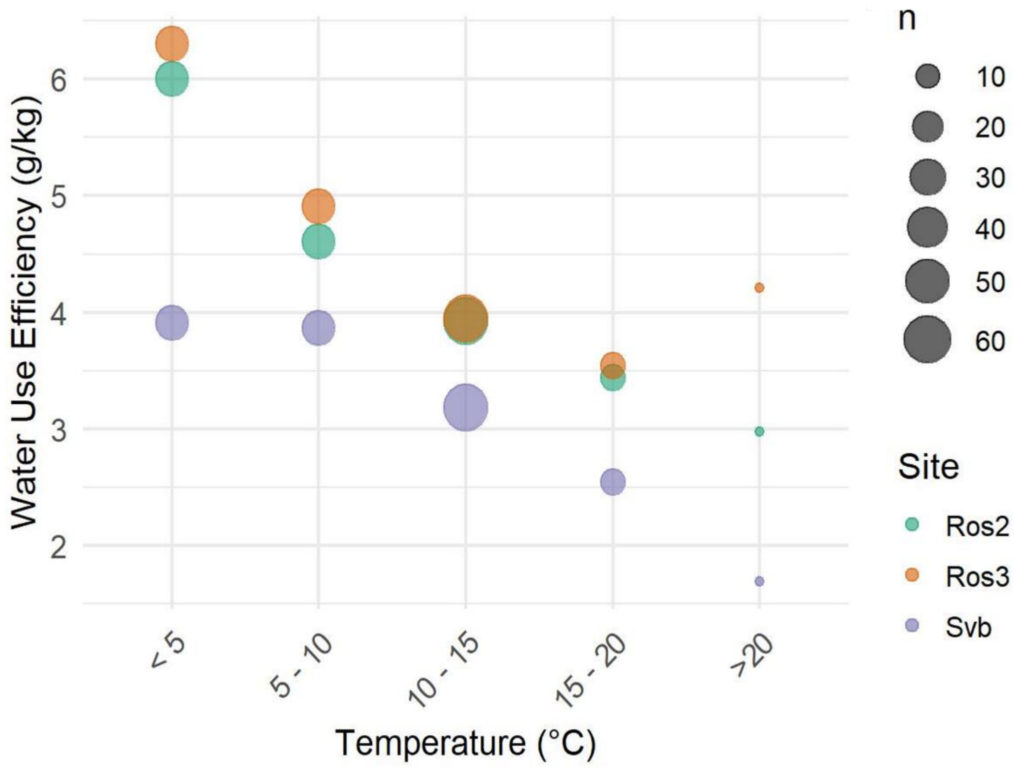

Figure 7: Grouped air temperature against water use efficiency using weekly data from the vegetation period (May – October) for all five years. n is the number of weeks in a group.

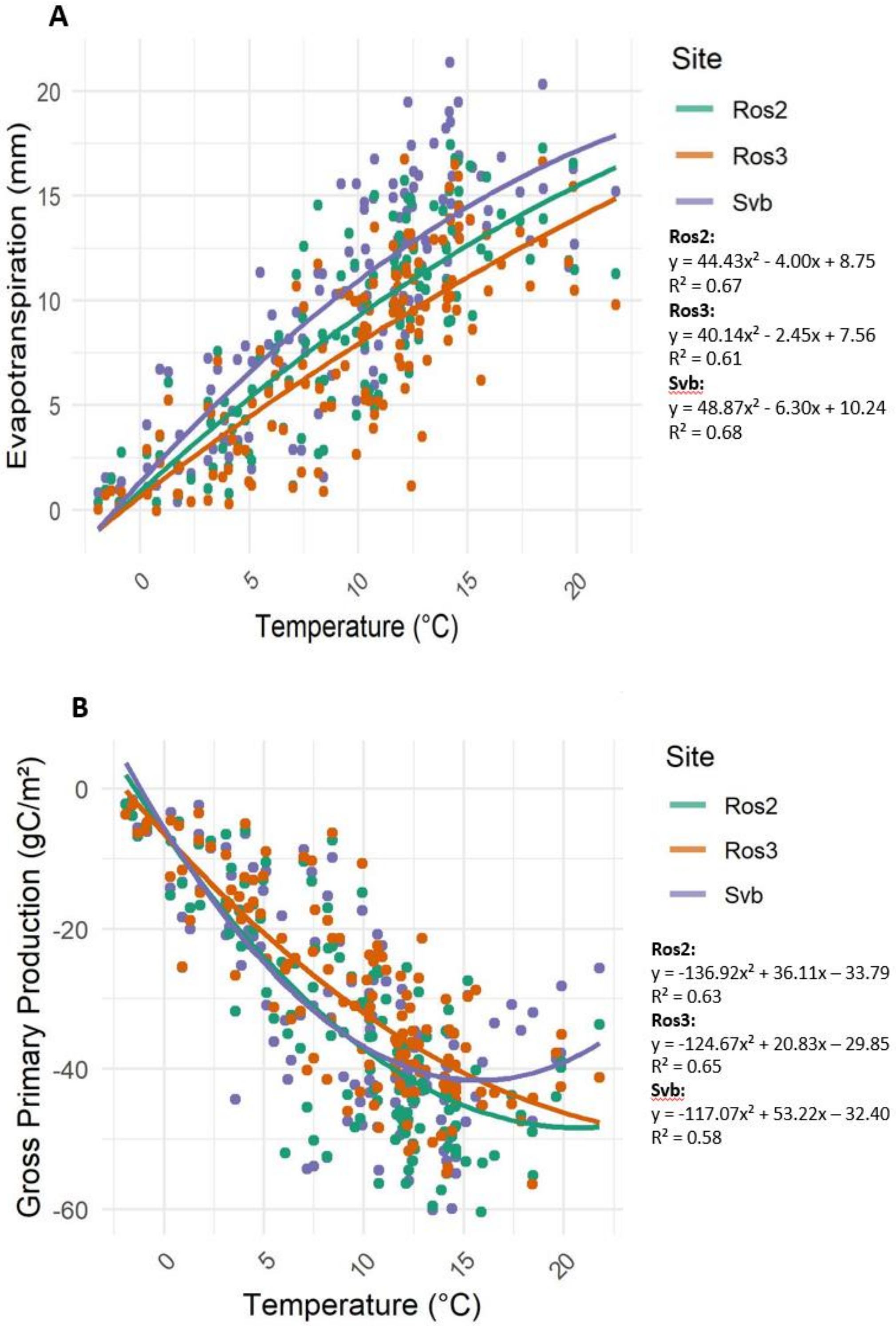

*Figure 8: Scatterplot for air temperature against evapotranspiration (**A**) and air temperature against gross primary production (**B**) of all sites from weekly data (May - October).*

3.3.2. SMI

SMI indicated that most weeks in Svb were 'Moderate Wet' or 'Mid-Range' (n = 59 and 49, respectively). The drought group with highest WUE (5.78) was 'Very Dry' (n = 1). Between 'Mid-Range' and 'Very Dry' conditions, Svb's WUE increased continuously. In Ros2, most weeks were 'Very Dry' and 'Moderate Dry' (n = 52 and 33, respectively). WUE increased between 'Moderate Wet' and 'Moderate Dry' conditions with the highest WUE (4.90) under 'Moderate Dry' conditions. In Ros3, most weeks were 'Moderate Wet' and 'Mid-Range' (n = 45 and 29, respectively). The drought group with highest WUE (5.71) was 'Mid-Range'. WUE of Ros3 increased steadily between 'Very Wet' and 'Mid-Range' conditions and dropped down under 'Moderate Dry' conditions. The WUE distribution for the drought groups indicated by SMI are displayed in Figure 9. The correlation test indicated no significant correlation between SMI and WUE. The correlation coefficients were all below 0.3, indicating little, if any correlation.

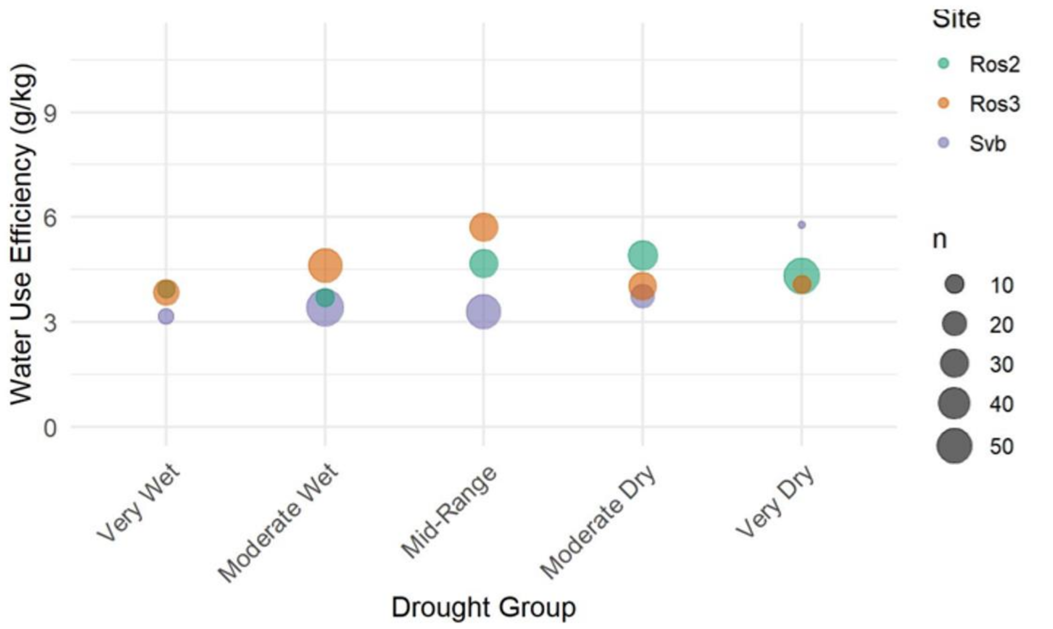

Figure 9: Grouped Soil Moisture Index against water use efficiency using weekly data from the vegetation period (May – October). n is the number of weeks in a group.

3.3.3. SPI and SPEI

SPI indicated that most months were 'No' or 'Mild' droughts (n = 14 and 9, respectively). Svb had a decreasing WUE between 'No' and 'Severe' droughts, with a maximum at 'Extreme' droughts (WUE = 4.17, n = 2). Ros2 and Ros3 had a similar pattern in WUE distribution. Both had their maximum under 'Extreme' drought conditions (WUE = 5.80 and 10.07, respectively, n = 2) and a second maximum under 'Mild' drought conditions (WUE = 4.71 and 5.02, respectively).

The WUE distribution for the drought groups indicated by SPI are displayed in Figure 10A. Pearson correlation tests found no significant correlation between SPI and WUE and the correlation coefficients were below 0.3, indicating little, if any correlation.

SPEI indicated that most months had ’No’ or ’Mild’ droughts (n = 13 and 9, respectively). Unlike SPI, SPEI did not indicate any ’Extreme’ droughts. In Svb, the decrease of WUE between ’No’ and ’Moderate’ drought conditions was slightly stronger than with SPI. However, under ’Severe’ droughts, WUE increased again. For Ros2 and Ros3, the WUE distribution was similar to their distribution with SPI, with the maximum being during ’Severe’ droughts (WUE = 4.61 and 6.81, respectively, n = 4). Their second maximum was during ’Mild’ droughts (WUE = 4.60 and 4.88, respectively, n = 4). The WUE distribution for the drought groups indicate by SPEI are displayed in Figure 10B. A Pearson correlation test for SPEI and WUE only indicated a low correlation for Svb (p-value < 0.05, correlation coefficient: 0.42). Contrasting to that, the correlation coefficients for Ros2 and Ros3 were negative (-0.04 and -0.02, for Ros2 and Ros3, respectively) but not significant.

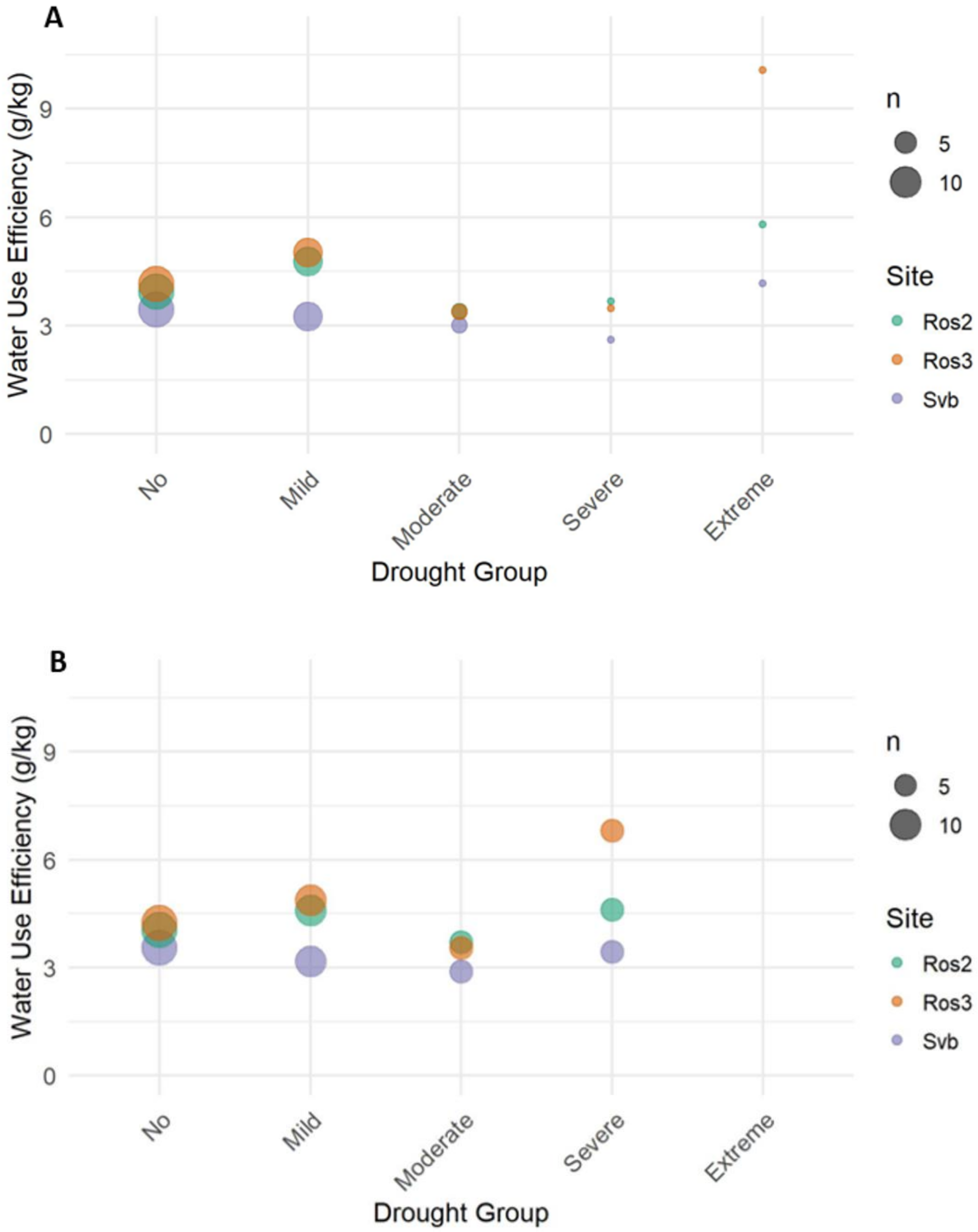

*Figure 10: Grouped SPI (**A**) and SPEI (**B**) against water use efficiency using monthly data during the vegetation period (May - October). n is the number of weeks in that drought group*

4. Discussion

The Thermopluviograms show that except for 2019 all the examined years were warmer than the 30-years average. Even though 2019 was colder and rather wet, the average VPD was still one of the highest. The constant high ΔET during 2019, which is a sign for water deficit, indicates that this could be a long-term effect of the dry year 2018.

During all years, Svb showed the highest values of ΔET while also having the highest ET during all years. This indicates that ETpot must have been proportionally higher in Svb compared to the other sites. Since the meteorological measurements were the same for all sites, the differences probably result from different soil heat fluxes, and aerodynamic and surface conductance. Svb had the highest canopy height and due to the mixture of species, presumably an overall rougher canopy. Both are assumed to strongly influence aerodynamic conductance (Peng et al. 2019). ΔET differs between the sites; however, it confirms for all sites that most drought stress occurred during the years 2018, 2019, and 2020. The differences in actual ET likely result from differences in soil moisture. The results confirm a direct relationship between soil moisture (indicated by SMI) and ET (Miller 1977). Lower magnitudes of NEE in all sites mainly resulted from less carbon uptake, as indicated by GPP. The magnitude of GPP increased with temperature. However, with very high temperatures, the magnitude decreased again, which could explain the tendency of lower GPP between 2018 and 2020 compared to 2015 and 2016 (Ciais et al. 2005; Gao et al. 2017).

Even though the pattern of GPP agrees with the Thermopluviograms, VPD and ΔET, it is not certain whether decreases in GPP occurred because of decrease of growth or because of increased tree mortality. Ma et al. (2012) found that in Canadian boreal forests, lower GPP after droughts was mainly induced by higher tree mortality. Plus, droughts can affect photosynthesis long after the drought event (von Buttlar et al. 2018). It must therefore be noted that this study did not differentiate between immediate and delayed effects of droughts.

The differences in NEE were not only caused by GPP but also affected by Reco. Svb had by far the largest Reco which is responsible for its low magnitude of NEE. This could be either due to more respiration by the trees during photosynthesis or due to higher heterotrophic respiration. A study in boreal forests of Canada found that Reco was mainly influenced by soil temperature and dissolved oxygen levels (Bhanja & Wang 2021). Plus, in this context, the site's ground vegetation might also be of interest since the vegetation type is found to highly influence Reco (Parker et al. 2015). Ros3 has the least GPP, but also the smallest Reco, which indicates generally lower photosynthetic activity compared to the other sites. While both GPP and Reco were lower between 2018 and 2020, the reduction of GPP was stronger than of Reco. This goes in line with other studies who found that GPP was more sensitive to drought stress than Reco (Ciais et al. 2005; von Buttlar et al. 2018).

The results of this study indicate that WUE decreases with increasing drought conditions which generally agrees with studies of other authors (Reichstein et al. 2007; Malone 2017). On the other hand, they stand in contrast with the findings of Kuglitsch et al. (2008) who found highest values of WUE in boreal forests during droughts. However, they also found the strongest fluctuations of WUE in boreal conifer stands which makes it difficult to detect clear trends. The same problem occurred in this study. Since WUE is a ratio, when overall values of GPP or ET get small, even small measurement errors can lead to large outliers. Plus, it is important to stress that GPP itself is derived from estimations instead of direct measurements (Reichstein et al. 2012). Due to the strong fluctuation, peaks of WUE might not be suitable to describe the general behavior of WUE. Thus, no temporal pattern of WUE was included.

This study found the highest correlation between rising temperature and decreasing WUE. According to the correlation coefficient it can be classified as 'moderate' in all three sites. The correlation between precipitation and WUE on the other hand was only classified as 'little, if any'. This was rather surprising, since in a pan-European study of the summer drought 2003, Reichstein et al. (2007) found a stronger correlation between precipitation and WUE than temperature and WUE. Plus, northern European boreal forest are considered to be temperature limited (Ruiz-Pérez & Vico 2020), hence, one would expect increasing temperatures to enhance GPP and therefore increase WUE. This study however, found that above 15 °C the carbon uptake was not enhanced any further but started to decrease in all sites. This effect might result from the site's latitude (around 64 °N). Various authors found 65 °N to be a threshold below which increasing temperatures usually lead to negative correlations between temperature and GPP (Babst et al. 2012; Hellmann et al. 2016; Ruiz-Pérez & Vico 2020). They argue that below that threshold, temperatures are already high enough so further increases might not be any more beneficial to boreal forests. The examined sites in this study were relatively close to that threshold which could explain the enhanced GPP at lower temperatures and the negative effects of higher ones.

The indicator with the second strongest correlation with WUE was VPD. The strong effects of VPD were to be expected since stomatal closure is the most dominant plant response to increasing VPD to regulate their gas exchange. VPD therefore has direct effects on plant photosynthesis. However, multiple studies found the relationship between VPD and intrinsic (i.e., plant level) WUE to be positive (Frank et al. 2015; Wang et al. 2018). That stands in contrast with the negative effects of increasing VPD on ecosystem WUE found in this study. Stomatal sensitivity to changes in VPD is known to differ between ecosystems and species (Creese et al. 2014; Gao et al. 2015) Hence, this discrepancy might indicate that boreal forests' stomatal sensitivity is quite low meaning that they react either very late or very little with stomatal closure.

Soil moisture is known to regulate stomatal closure and can therefore directly affect the plant gas exchange (Konings et al. 2017). Plus, SMI was approved to be an appropriate tool to determine drought conditions (Sridhar et al. 2008; Gao et al. 2016). Hence, the low correlation between SMI and WUE was unexpected. Only Ros3 showed a trend of increasing WUE between the drought groups 'Very Wet' and 'Mid-Range'. Ros2 was the site with the most weeks being 'Very Dry' (n = 52) and showed lower WUE compared to the two drought groups before. The strong increase of WUE in Svb under 'Very Dry' conditions might not be representative since n was only 1. Generally, these results agree with Gao et al. (2017) who found only a strong correlation between WUE and SMI < 0.2 and more scattered results for wetter soil conditions. Another reason why SMI did not show strong correlations with WUE might be that it is based on SWC measurements. Whereas in Svb SWC was measured in four profiles, in Ros2 and Ros3 the values derived from only one profile each. It is therefore likely that the measured values are not representative for the whole site. That might also be why the measurements in Ros3 were unreasonably low and had to be corrected afterwards. With more accurate SWC measurements, the correlation between SMI and WUE might be stronger than in this study.

SPI indicated a clear downwards trend of WUE in Svb, since the maximum at 'Extreme' drought conditions can be ignored due to low number of months (n = 2). Ros2 and Ros3 behaved similar to each other but did not show a clear trend. SPI did not show any significant correlation with WUE which goes in line with other results of this study since SPI is a purely precipitation-based index. Examining multiple years with SPI might be problematic since it ignores changing water demands due to increasing temperatures or radiation. The effects of climate change might therefore get overlooked. Thus, it was not expected that SPI would indicate more 'Extreme' droughts than SPEI. This might be because we only used 30-years of precipitation data which is the minimum time series that should be used

(Svoboda et al. 2016). A longer series of reference data might have led to a more robust index.

SPEI showed a similar pattern as SPI but did not indicate any ‘Extreme’ drought conditions. The correlation between SPEI and WUE was significant for Svb; however, even though SPEI includes a water balance the correlations for Ros2 and Ros3 were not significant. One problem might have been that because of lacking long-term data, ETpot used for SPEI was not calculated using the Penman-Monteith equation but according to Thornwaite (1948). Hence, VPD was not considered, which has a strong influence on ETpot (Grossiord et al. 2020).

This study used three different drought indices in order to display different aspects of drought stress. It was expected that they would help to identify whether anomalies in soil moisture, precipitation, or precipitation and ETpot are the main drivers for changes in WUE. However, as discussed above, none of the indices showed significant correlations with WUE. Additionally, all three indices showed similar patterns. This goes in line with the results of the examined indicators, since only temperature was shown to have a significant correlation with WUE. For further studies, I would therefore recommend using drought indices that have a stronger emphasis on temperature, such as the self-calibrated Palmer Drought Severity Index (sc-PDSI) or the SPEI using the Penman-Monteith equation as discussed above.

Generally, it is assumed that WUE is a site or vegetation characteristic that adapts to drier environments (Kuglitsch et al. 2008). When Malone (2017) studied WUE in Californian forests, he found that arid regions tend to have higher values. That goes in line with other authors that found adaptation to dry conditions to be more important for WUE than species composition or site fertilization (Roca et al. 2004; Reichstein et al. 2007; Ponce Campos et al. 2013). Direct comparison between the two pine stands in this study shows slightly higher WUE values in Ros3, the site with the lower soil water content. However, the difference in mean WUE between Ros2 and Ros3 was not significant. Additionally, in ‘Moderate-Dry’ and ‘Very Dry’ soil conditions (as indicated by SMI) WUE of Ros2 was much higher than of Ros3. Plus, the decrease of WUE with increasing temperature was lower in Ros2 compared to Ros3. These results indicate that nitrogen addition might not increase overall WUE but it can make it more robust to droughts. This might result from enhanced root development and increased carbon uptake (i.e., growth) as described by Bhattacharya (2019) and Viets (1962). Indeed, Ros2 had the highest average carbon uptake, which confirms the effects of nitrogen addition found by Lim et al. (2015). Since European boreal forests tend to be nitrogen limited, constant addition might surpass the effects of dry soil conditions on WUE (Tian et al. 2021). That might be the reason why Ros2 had smaller losses of GPP in temperatures > 15 °C.

In their literature review, Forrester (2014) state that various factors influence whether or not species compositions will show complementary effects (i.e. increased WUE) and that it remains unclear what exactly those factors are. Hence, they concluded that it cannot be confidently answered if mixing species will increase WUE. However, multiple studies from various climatic zones have found higher WUE in mixed stands compared to monocultures (Forrester et al. 2010; Kunert et al. 2012). Plus, Grossiord et al. (2013a) found that under drought conditions, stands with higher biodiversity showed the greatest increase in WUE. Contrasting to that, a study in a boreal forest did not find any facilitation mechanisms for WUE in mixed stands (Grossiord et al. 2013b). They explained the absence of facilitation mechanisms with the absence of soil water or nutrient stress. According to the 'stress-gradient hypothesis' a more stressful environment (drought conditions) can enhance complementary effects between species (Malkinson & Tielbörger 2010). Thus, WUE in mixed stands could be more robust against drought stress. This agrees with the findings of our study. Although the results did not show any increase in WUE, the mixed stand did have the smallest decline of WUE under warmer conditions. Svb also had the smallest variation in WUE when compared to SPI and SPEI. Since there was only one week with 'Very Dry' soil conditions (as indicated by SMI), the occurring peak of WUE is no reliable result and could be ignored. If done so, the variation of WUE compared to SMI is also smaller than of the other sites. The reason why WUE did not increase as described by Grossiord et al. (2013a) might be that the main species in Svb, Picea abies and Pinus sylvestris, are considered to have low complementary effects due to a similar development of their root system. A higher number of Betula spp. could therefore enhance WUE stability.

5. Conclusion

This study aimed to identify the drought response of the carbon and water exchanges in contrasting boreal forests. It focused on the effects of drought stress on WUE and whether species composition and site fertilization could influence them. Using the Eddy Covariance data this study found that all sites had lower NEE in years with high VPD and ΔET. The results of this study indicate that precipitation had only little influence on WUE whereas temperature and VPD showed a significant correlation with changes in WUE. Especially temperature was the key driver and influenced WUE mainly by decreasing the magnitude of the sites' GPP. Changes in soil moisture did not show a significant correlation. The indices SPI and SPEI showed similar patterns in regard to their effect on WUE, but SPEI tended to indicate less drought stress. Both did not have strong influence on WUE. It can therefore be concluded that in boreal forests, temperature induced drought stress leads to a decrease in WUE.

The mixed stand (Svb) had the lowest magnitude of NEE throughout all examined years. Plus, the point in time when Svb became a carbon sink was always later than in Ros2 and Ros3. The results indicate that mixed stands might have smaller decreases in WUE when temperatures increase. The fertilized site Ros2, was overall the larger carbon sink and had higher ET than Ros3. This indicates more photosynthetic activity compared to the non-fertilized pine stand (Ros3). Average WUE was higher in Ros2 than in Ros3; plus, the losses of WUE under drought conditions were smaller in Ros2 compared to Ros3. That indicates that nitrogen can reduce losses of WUE under drought conditions. It appears that species mixture does not generally lead to higher WUE compared to monocultures. However, WUE in the mixed stand was more robust against temperature induced drought stress. Nitrogen addition on the other hand seems to both enhance overall WUE as well as make it more robust against droughts.

The influence of droughts on WUE is still not fully understood and extensions of this study are necessary. Yet, this study gave first insights to how species composition and site fertilization influence WUE. A drought robust WUE can improve forest's drought resistance and reduce drought related damages. Hence, the present study provides evidence that mixing species and adding nitrogen are practical climate adaptation actions in forest management. However, further studies with more precise meteorological data over a longer period are necessary to understand how droughts affect WUE and different management regimes.

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Tim Schacherl
August 2021, Alnarp

Appendix

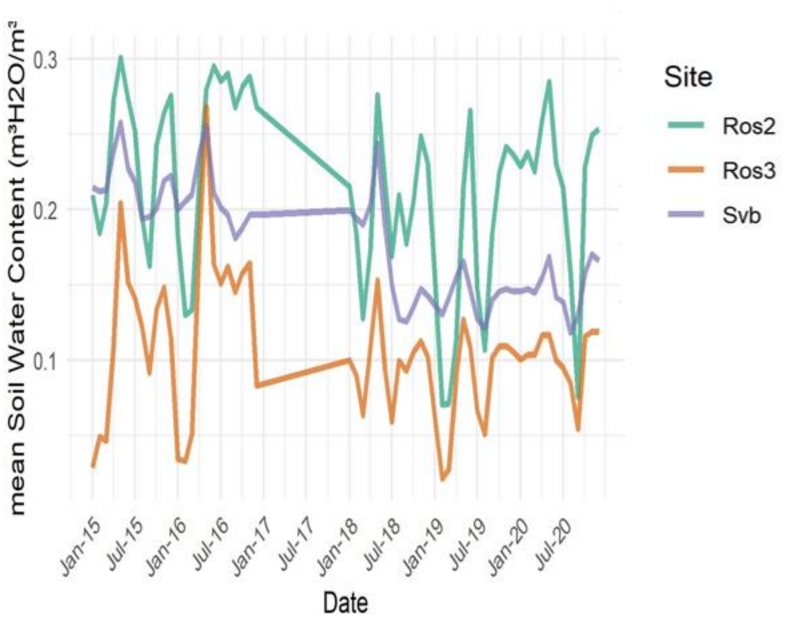

Figure 11: Corrected mean soil water content for Rosinedal2 (Ros2), Rosinedal3 (Ros3), and Svartberget (Svb).

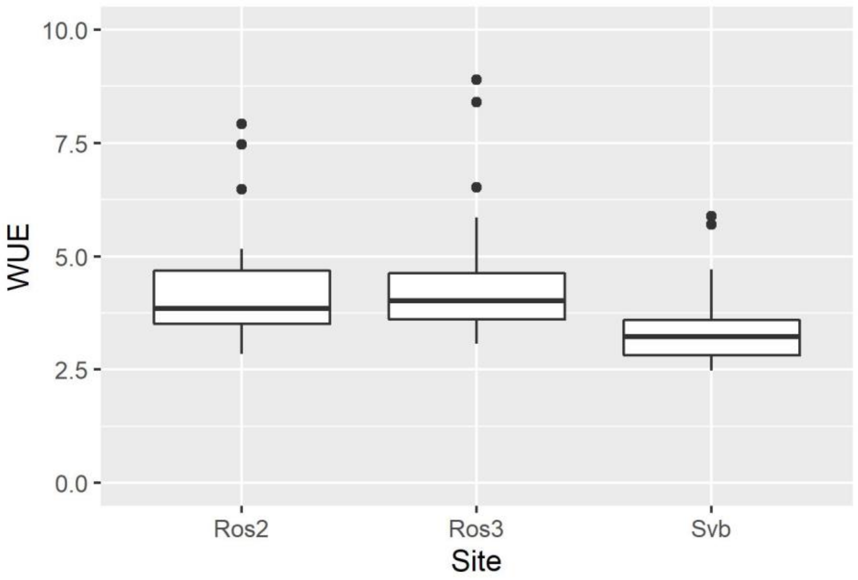

Figure 12: Distribution of the water use efficiency of Rosinedal2 (Ros3), Rosinedal3(Ros3), and Svartberget (Svb).

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