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Forest Reaction to the 2018 Drought: Comparing the Hyltemossa and Rumperöd Forests

Emily Delin

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Department of

Physical Geography and Ecosystem Science

Lund University

Sölvegatan 12

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Emily Delin

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Supervisor Thomas Holst

Department of Physical Geography and Ecosystem Science, Lund University

Exam committee:

Harry Lankreijer

Fredrik Lagergren

Department of Physical Geography and Ecosystem Science, Lund University

Abstract

This paper analyzes the reactions of two forests, located in the same region, to drought conditions that occurred in 2018. Both locations experienced similar conditions including higher temperature and less precipitation than the previous four years. Both experienced drought that would be categorized as moderate according to standard precipitation index calculations and soil moisture values were very similar. It was found that both forests reacted very differently despite these similarities, with the Hyltemossa location experiencing a more severe decrease in net ecosystem exchange and variations in ecosystem respiration and gross primary production. Possible reasons put forward for this difference include crowding, diversity, and canopy protection attributed to the different management techniques used in each forest (clear-cutting in Hyltemossa and continuous cover forestry in Rumperöd). Due to the complexity of interactions within the ecosystem, it is not possible to definitively state a leading cause for this difference in response. Other variables such as vapor pressure deficit, evapotranspiration, water retention curves, and topography of the sites should be evaluated in the future in order to get a broader understanding of the reaction to drought and similarities or differences between sites.

Key Words: forest, drought, forest management, ecosystem flux

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Introduction

The summer of 2018 was an uncharacteristically hot and dry one for the majority of Europe (Liberto 2018). Drought can result from lack of precipitation or disproportionately high evapotranspiration due to high temperatures that make precipitation levels insufficient. There are three primary types of drought: meteorological, hydrological, and socioeconomical. In this study, the word drought refers to meteorological drought which focuses on soil moisture deficits and the impacts on crops and natural vegetation such as forests (EDO 2018).

The consequences of drought have long been studied and discussed (English-Loeb 1990, Smith 1931). Sweden experienced many of these consequences in 2018, such as forest fires and crop yield reduction. In order to mitigate the effects of the drought of 2018, the Swedish government provided aid to many farmers and the country received increased aid from the European Union (Government Offices of Sweden 2018). The southern-most county of Sweden, known as Skåne, contains both cropland and forests that suffered from the drought conditions. This region experienced especially arduous conditions throughout the 2018 drought with exceptionally low ground water levels (Belyazid and Guiliana 2019). Although concerns and aid received for preventing stunted growth and crop reduction were focused on food agriculture, it has been determined before that drought can also greatly impact forests in these ways.

Forests experience consequences related to drought when water availability in the soil becomes too little to maintain the functions necessary for growth. The dry and/or warm conditions that cause drought can impede on forests ability to grow, cause more tree mortality, and negatively impact overall productivity (Wu et al. 2018, Hartl et al. 2014, Pan et al. 2011, McDowell et al. 2008, Ciais et al. 2005). Multiple studies have shown that forests in southern Sweden have already been and continue to be limited by water even during times without drought conditions, whereas the northern area is more limited by nutrients (Belyazid and Guiliana 2019, Bergh et al. 2005, Van Leeuwen et al. 2000, Bergh et al. 1999). This already existing stress can lead to higher vulnerability and more severe reaction to water stress in the future (Seidl et al. 2017, Ciais et al 2005,). Some signs of suffering from drought in forests are visible such as tree discoloration, the falling or change in appearance of leaves and needles, cracks in trunks, and death of the tree from the top down (Rosner et al. 2018, Guada et al. 2016). However, these visible symptoms are not the only consequences of drought that forests experience.

Forests contribute to the health of the planet in ways that cannot be seen with the naked eye. Through primary production and respiration, forests can sequester and release carbon, affecting the carbon balance of our atmosphere. In a time when climate change is an urgent issue and greenhouse gases must stop being released to the atmosphere and ideally removed (Allen et al. 2018), forests play a very important role in reducing the amount of the main greenhouse gas, CO_2, in the atmosphere. Pan et al. (2011) found that the majority of carbon stored in forests all over the planet is stored in boreal and temperate forests, the forest types that are found in Sweden. This ability to sequester carbon is quantified in the net ecosystem exchange (NEE) of a forest. NEE is the net release of carbon to the atmosphere by a terrestrial ecosystem and is made up of uptake from gross primary production (GPP) and release from ecosystem respiration (Reco). This means that negative NEE values signify net uptake of carbon from the atmosphere by the forest and positive values are net releases from the ecosystem to the atmosphere. Changes in the activity of either of these functions could result in a drastic difference in how much carbon a forest can sequester (Lindroth et al. 2008). Drought, for example, can alter primary production and respiration and in consequence decrease forest uptake of carbon (Anderegg et al. 2018b, McDowell et al. 2008, Irvine et al. 1997). A positive relationship between temperature and soil respiration has been consistently found (Carey et al. 2016, Lloyd and Taylor 1994, Gupta and Singh 1981), meaning the higher temperatures that can occur during drought and future climate conditions could increase the amount of CO_2 released by the forest ecosystem (Liberto 2018).

The forests that contribute to this global sequestration of carbon can be managed in different ways. A study done by Eggers (2017) found that forest owners in Sweden are transitioning to more environmentally responsible management practices rather than production-oriented methods. These newer methods are usually based on small-scale clear cutting and thinning. Clear cutting is the practice of harvesting all the trees in an area at the same time (EPA 1992). This is considered the most cost-efficient method of tree harvesting and is used heavily throughout Sweden (Sahlin 2011, Keenan and Kimmins 1993). Clear cutting can result in higher temperatures due to increased direct shortwave radiation that reaches the surface compared to areas covered by a forest canopy. If these temperatures reach a level above the threshold for the tree species, photosynthesis of new seedlings will decrease, and growth can be affected. A decrease in protection from tree cover can also result in higher wind speeds near the surface and consequentially decreased soil moisture in the upper levels where the majority of microbial respiration takes place and soil carbon is present (Fang and Moncrieff 2005, Keenan and Kimmins 1993).

Continuous cover forestry (CCF) is another forest management method that is becoming more popular for forest owners. CCF maintains the forest canopy by avoiding clear cutting and instead harvesting individually selected trees. This method of management increases tree species and age diversity in the stand (Pommerening and Murphy 2004). It has been found that more diversity in an ecosystem can greatly enhance a forests ability to function in and recover from drought conditions as well as other environmental stressors (Anderegg et al. 2018a, Van Ruijven and Berendse 2010). Selective cutting CCF and thinning can be beneficial to forest drought resilience as decreased density and competition between trees through thinning has been found to strengthen forests against drought (Lechuga et al. 2017, Falge et al 2001).

Despite forests' ability to sequester carbon released into the atmosphere, they should not be relied on for this purpose because their ability to sequester can be reversed by both human activity and natural occurrences, making them sources instead (Pan et al. 2011). Soil moisture has been predicted to decrease all over Europe in the future due to climate change (Ruosteenoja et al. 2018). Droughts are also expected to increase in frequency and severity along with other disturbances and resulting nutrient losses that negatively impact forest health (He et al. 2018, Houle et al. 2016). On a small scale, this recent drought and other potential future drought occurrences will negatively impact the ecosystem and future measurements through increased susceptibility to pests. On a continental scale, decreased water availability and increased temperatures can affect the long-term carbon balance (Ciais et al. 2005). Southern Sweden is expected to have drier growing season months and already existing moisture limitations will only be made worse by this increasing lack of summer precipitation. The lack of moisture in the growing season is one of the main factors that will decrease forests' ability to grow and uptake carbon (Belyazid and Guiliana 2019).

Fu et al. (2017) found that forests take longer to recover than some ecosystems such as grasslands but recover more quickly from drought than from other disturbances such as fires, harvest, and deforestation. They also found that carbon fluxes were the fastest of all ecosystem functions to reach maximum value when the ecosystem recovered back to stability. If the extremity of predicted climate change can be decreased with preventative measures, there could be benefits rather than the consequences currently expected from extreme changes. For example, Ciais et al. (2005) found that southern Sweden experienced an increase in NPP with moderate warming without water-related stress. For these reasons, it is imperative that we continue to learn about forests' reactions to drought conditions as future climate scenarios predict higher temperatures and less precipitation during the growing season which could have long-lasting effects on forest health and carbon sink capacity.

Little research has been done on the effect of high temperatures and decreased precipitation on southern Sweden forest productivity and carbon exchange (Belyazid and Guiliana 2019). The focus of this paper is the effect on carbon sink capacity of the 2018 drought on two forests located in southern Sweden: Rumperöd and Hyltemossa. The aim of this study is to determine how two differently managed forests growing in the same region reacted to the water deficit and high temperatures associated with the meteorological drought of 2018. In order to analyze this, overall NEE values as well as GPP and ecosystem respiration (R_{eco}) were compared between years and sites. Comparisons were also done for variables such as precipitation, temperature, soil moisture, and light and temperature responses in order to analyze environmental conditions and inputs and examine how they differed (or did not differ) between sites. Due to differences in stand characteristics and management techniques between the two forests, it is hypothesized that Hyltemossa will have reacted more strongly to the change in conditions compared to previous years.

Method

Site and Stand Description

Both forests in this study are located in northern Skåne, Sweden with Rumperöd (56.332911°, 14.114581°) being about 50km north-east of Hyltemossa (56.100000°, 13.416667°). Despite their proximity, however, there are differences between the forests.

Hyltemossa is a young Norway spruce forest managed with clear cutting methods. Sections are clear cut every 50 years with an estimated growth of around 34 meters in 100 years. There is little diversity of tree species, with small amounts of pine and birch present. The forest floor is covered with mosses and very little shrub life grows in the forest understory. The forest stand height is 19m and contains a timber volume of 190 m^3 $hectare^{-1}$ (ICOS Sweden 2018).

Rumperöd, on the other hand, is an older mixed forest consisting of mostly Norway spruce with frequent appearances of birch, beech, and some oak. Tree age varies from 0-100 years as the selective cutting technique consists of removing trees with a dimeter of 50-60cm at breast height and all others determined to be profitable in the future are left. This means that older, yet smaller trees may be left behind and allowed to further age. There is around 120 hectares of forest and about half of this is managed using selective cutting techniques. Ideally, volume is kept above 100 m^3 $hectare^{-1}$ (Westin 2015).

Both locations have eddy covariance systems to measure fluxes as well as other auxiliary ecosystem and meteorological data such as soil moisture, precipitation, temperature, etc. The soil at the Rumperöd site is sandy moraine and at Hyltemossa there is a mix of sandy moraine, glaciofluvial sediment, and a small occurrence of peat (SGU 2019).

Data Sources

The data used in this study were obtained from eddy covariance measurements done at both sites as well as auxiliary ecosystem and meteorological data. This eddy covariance data is collected using flux towers and is the most common method for measuring ecosystem fluxes (Dubois et al. 2018).

Data for the years 2015 and 2016 at Hyltemossa were acquired from the ICOS RI Carbon Portal online (Carbon Portal 2019). Data for the years 2017 and 2018 at this location were acquired directly from the staff working at the site since it had not yet been uploaded. The majority of this data was already quality sorted and gap filled according to ICOS protocol (ICOS 2019).

Precipitation data for both sites were taken from nearby SMHI stations as Hyltemossa had problems with the gauge in two of the four years and the location and conditions of the precipitation gauge at the Rumperöd location is not ideal and therefore leads to high levels of uncertainty in the values. The stations chosen to represent Hyltemossa and Rumperöd were Klippan and Havsteda Mo, respectively. These stations were chosen due to their proximity to the forests (~12 km) and the time span over which data were available. Temperature data were also taken from the Havsteda Mo SMHI station for Rumperöd when on-site measurements were missing (SMHI 2019a, 2019b).

Soil moisture and temperature data were available at both forest locations. At Hyltemossa, soil moisture and temperature are measured at five different depths within four plots around the eddy covariance tower. For the purpose of this paper, measurements taken at a depth of 5cm were used and the four half-hourly values recorded at each plot were averaged for half-hour overall site values. For Rumperöd, soil moisture and temperature are recorded at three depths in two plots near the measurement tower. Measurements taken at a depth of 10cm were used in this case and the two half-hourly values recorded for both plots were averaged to get half-hour overall site values. There was only one set of measurements taken closer to the surface at each site. The measurements taken at these depths were chosen because this layer would likely be that with the most activity occurring with impact on the trees such as diurnal variations with changes in air temperature (Florides and Kalogirou 2005) and higher organic content than those below (Hiederer 2009).

Data for Rumperöd were acquired from the site research engineer. The raw data had already been worked with and fluxes were calculated and flagged for quality by EddyPro Software (2016). The calculated fluxes go through the steady state and developed turbulent conditions tests and then have quality flags assigned according to the policy of Mauder and Foken (2004). The use of this policy results in data quality flags 0, 1, and 2 with zero being the highest. Quality flags of two are those that should be removed from the dataset. Flux values with quality flags of one are generally considered to be good enough for general analysis, however, in order to lessen the time required to analyze individual values, these were removed as well (LI-COR 2019).

Data Treatment

Rumperöd NEE Gap Filling

The process of quality sorting and gap filling the Rumperöd eddy covariance flux data began by removing CO_2 flux values with quality flags of one and two and leaving behind only those with a quality flag of zero. The CO_2 flux values were then plotted against time to see the diurnal and seasonal variations and unrealistic values were removed. This process was based on the conditions under which these unrealistic values occurred and a general threshold value of 30 µmolC $m^{-2}s^{-1}$. Table 1 shows the amount of data removed based on quality flags and the total amount of data that needed to be gap filled after individual value analysis.

Table 1:Percentage of Rumperöd NEE data that was removed and gap filled. The second column shows the percentage of data that was made up by quality flags 1 and 2 as well as missing data per year. The second column shows the total amount of the CO_2 flux data that needed to be gap filled per year once low quality flags and NaN values as well as those determined to be unrealistic were removed.

Year	Low Quality Flags (%)	Final Data to be Gap-Filled (%)
2015	26.6	26.7
2016	31.1	31.2
2017	40.2	40.3
2018	34.2	34.3

After the lower quality values were removed from the data set based on flags, conditions, and the threshold value, a file was prepared to the specifications of the REddyProc version 1.1.6 gap filling model for eddy covariance data available from the Department of Biogeochemical Integration at the Max Planck Institute for Biogeochemistry located in Thuringia, Germany. This tool is useful for gap filling and flux partitioning of data. Throughout the process, all input factors are gap filled including NEE, latent heat, sensible heat, global radiation (R_g), vapor pressure deficit (VPD), relative humidity (rH), and air temperature (T_{air}).

REddyProc gap fills data using a process derived from a combination of methods presented by Falge et al. (2001) and Reichstein et al. (2005). The algorithm has three scenarios and three methods for gap filling depending on which scenario the data to be gap filled meets. These scenarios are: only data to be gap filled are missing, data to be gap filled and T_{air} or VPD are missing, and all previously mentioned data as well as R_g are missing. For the first scenario, an average value is used from times with similar meteorological conditions using a lookup table. Conditions with only some missing meteorological data are handled by using only R_g within seven days to find an average value in similar conditions. Lastly, when all data is missing, an average value at the same time of day is used to fill in the data gap.

Flux partitioning is done in order to break up NEE into the two fluxes it is made of, gross primary production (GPP) and ecosystem respiration (R_{eco}). This process takes place using either a night- or day-based method. For the purpose of this study, the night-time method based on Reichstein

(2005) was used. The night-based method first goes through a process of estimating temperature sensitivity of R_{eco}. Then, the seasonal course of the reference temperature is estimated for the year being linearly interpolated in periods when not found. These estimates are then used to partition gap filled NEE into GPP and ecosystem respiration (Wutzler et al 2018). For more information regarding the differences between methods the reader is referred to Wutzler et al. (2018).

Manual Gap Filling

Some data used for each site were not complete due to a variety of possible reasons. This required gap filling using various methods and replacement data.

At Hyltemossa, air temperature data measured at 27 meters above ground level for 2015 and 2018 had periods of time where the sensor did not work properly, and measurements were therefore missing. This required gap filling using temperature data measured by a sensor in the profile setup located at 24 meters above ground level. A correlation between the data sets was plotted in Office 365 Excel 2016 manufactured by Microsoft located in Redmond, Washington, United States over a time span when both were complete in order to find a relationship and equation to use in order to most accurately convert the profile measurements. About 13% and 0.2% of the air temperature data for 2015 and 2018 was gap filled using this data, respectively.

Havsteda Mo temperature data were used to fill gaps in Rumperöd data as there were no profile measurements available at this site. These temperature measurements were directly inserted where gaps occurred. This method of gap filling was chosen due to highly variable and inconsistent relationships found between the temperature data collected at both sites. Therefore, a reliable correlation could not be found, and it was chosen to simply use the original SMHI values in place of those missing. This SMHI data was used to fill 0.8% of 2015, 0.1% of 2016, 22.7% of 2017, and 5.7% of 2018 temperature data for Rumperöd.

Some photosynthetic photon flux density (PPFD) data were also missing for both sites and needed to be gap filled. This was done using five-minute averages of incoming shortwave solar radiation. These five-minute averages were used to calculate half hour averages and then multiplied by two to estimate PPFD (Mayer et al. 2002). All PPFD values for Rumperöd were calculated by multiplying measured shortwave radiation by two as no PPFD had been measured or calculated previously.

Calculations

Environmental Conditions

Monthly averages of precipitation were calculated for each site in order to compare absolute precipitation values. To put these in perspective based on previous conditions at each site, thermopluviograms were created. These thermopluviograms are useful for visualizing changes in meteorological conditions of a selected time compared to averages based on previous years (Deutscher Wetterdienst 2019). Deviations in 2018 from the conditions of the previous four years (2014-2017) were determined by calculating monthly averages of precipitation and temperature. This comparison of 2018 values to only four-year long averages were chosen due to the timespan over which data was available. The differences in 2018 monthly values from the four-year averages in degrees and percent were calculated for temperature and precipitation, respectively.

In order to determine whether these conditions qualified as drought, standard precipitation index values were calculated for each year and site. The equation presented by Sönmez et al. (2005) (Equation 1) was used (X_i: Precipitation value for time in question, $\bar{X}_i$: Mean precipitation value for reference time span, σ: Standard deviation of data from whole time span):

Equation 1: $SPI = (X_i - \bar{X}_i)/\sigma$

The values resulting from this equation for each year were categorized as different severities of drought based on classes defined in the same study. Values ranging from 0 to -0.99 were mild drought, -1 to -1.49 was moderate drought, -1.5 to -1.99 was severe drought and values greater than two would be extreme drought.

Soil moisture and air temperature were simply plotted together using Microsoft Exel 2016 in order to compare their changes between and within the years. The same was done for soil temperature.

Cumulative Fluxes

Cumulative NEE for both sites was calculated in Microsoft Excel 2016 and plotted against time in order to compare differences between years, most importantly the response of 2018. Cumulative NEE was calculated by converting the initial CO_2 flux values (calculated by EddyPro and gap filled by REddyProc) from μmol $m^{-2}s^{-1}$ to gC m^{-2}half-hour^{-1}, and then adding the half-hourly values successively. Cumulative values for both real and modeled GPP and Reco were calculated in the same manner.

Response Curves

Temperature and light response curve functions were fitted to model potential GPP and respiration and determine whether these variables were limiting these ecosystem functions at the time of the drought. The curve functions were both fitted to one month´s worth of data from 2018 for the light response and 2017 for the temperature response. This was done in order to minimize influence from other factors that could be stronger when considering longer time periods. Both response curves and their coefficients were obtained using the curve fitting tool in MatLab R2018b update 4 version 9.5.0.1067069 manufactured by Mathworks, Inc. located in Natick, Massachusetts, United States.

The light response curve plot consisted of daytime PPFD values on the x-axis and daytime NEE values on the y-axis. Day/nighttime values were determined by when PPFD was above or below 10 μmol of photons $m^{-2}s^{-1}$, with above 10 qualifying as daytime conditions. The response curve was fitted using data from June rather than a month closer to freezing temperatures in order to limit errors due to light reflectance from snow and ice on the ground. The choice of June specifically was arbitrary as any summer month would fit these conditions. The equation provided by Falge et al. (2001) (Equation 2) was then altered to calculate only GPP rather than NEE and used to fit the curve and get values for coefficients Fc_{sat} (net photosynthesis in light saturated conditions (μmolC

$m^{-2}s^{-1}$)), R_d (respiration at dawn and dusk (μmolC $m^{-2}s^{-1}$)) and alpha (canopy light-use efficiency (μmolC $m^{-2}s^{-1}$).

Equation 2: $GPP = -(Fc_{sat}+R_d)*[1-e(-alpha*PPFD)/(Fc_{sat}+R_d)]$

For the temperature response curve, night temperature in degrees Kelvin was plotted on the x-axis and NEE on the y-axis. Night values were determined by filtering those when PPFD was less than or equal to 10. The year 2017 was chosen for this response curve because there was plenty of precipitation and therefore likely no moisture limitation on respiration in accordance with methodology from Lloyd and Taylor (1994). The month of May was chosen for this response curve. Initially, June was to be chosen in order to analyze the same month as the light response curve, however June data did not display the expected relation between temperature and respiration. This lack of a relationship was an exception from the rest of the data, therefore another month with the expected trend was chosen as it would be more representative of the site. An Arrhenius-type temperature dependence function according to Lloyd and Taylor (1994) (Equation 3) was then used to fit the curve and obtain values for the coefficients R_e (respiration at reference temperature 283.15 K (μmolC $m^{-2}s^{-1}$)) and E_a (activation energy (J mol^{-1})). R is the universal gas constant (8.314 J $mol^{-1}K^{-1}$) and T_{air} is the temperature in Kelvin at which respiration will be modeled.

Equation 3: $R_{eco} = R_e*e((E_a/R)*((1/283.15)-(1/T_{air})))$

These functions were then used to model GPP and respiration based on incoming light and temperature values. These were then compared to actual cumulative R_{eco} and GPP on site to determine whether temperature or light were limiting R_{eco} or GPP, respectively, in 2018 when the drought occurred.

GPP and Ecosystem Respiration vs. Soil Moisture

The relationship between GPP and soil moisture was determined by filtering GPP and soil moisture values occurring only in conjunction with light saturation values based on the repose curve (PPFD > 1200 μmol of photons $m^{-2}s^{-1}$) in order to remove light dependency. This was done for a four-month time span ranging from the beginning of May to the end of August in order to focus on changes during the growing season and minimize the influence of factors such as soil moisture that change over longer periods of time. These values were then plotted against each other to analyze how GPP related to soil moisture values.

The relationship between R_{eco} and soil moisture was examined in 1-degree Celsius intervals in order to minimize dependency on temperature. The same time span was chosen as the moisture and GPP comparison for the same reasons. Degree classes with more than 100 values were chosen in order to get a more accurate representation of the relationship, as too few values would not provide a reliable indicator. Classes that met this condition for 2018 were then plotted for all years in order to compare the trends and soil moisture values at different temperature classes between stations.

Results

Environmental Conditions

Initial comparisons of precipitation between the two sites showed consistently higher amounts at Rumperöd (Table 2). In the wettest shown year (2017) Hyltemossa received 946.2mm of precipitation whereas Rumperöd received 1,341.2mm. In 2018, Hyltemossa received 462.2mm and 683.3mm fell in Rumperöd. SPI calculations show that drought conditions were present in both 2016 and 2018 with values of -0.6 and -1.2 at Rumperöd and -0.8 and -1.3 at Hyltemossa (Table 3). These values show that 2016 had mild drought conditions and 2018 was moderate. Figure 1 (a, b) demonstrates the difference in soil moisture and temperature between the years. As can be seen, 2018 had the highest temperatures which occurred during the summer months. A general trend of lower soil moisture with higher temperatures is also visible.

Based on Figure 2 (a, b), it is clear that most months of 2018 received less precipitation compared to those same months from the three years before, specifically with all months of the growing season being both drier and warmer than the calculated averages. August and January at both stations were wetter and warmer than previous years. At Hyltemossa, August was 37% wetter and 1.3 °C warmer, January was 26% wetter and 1.6 °C warmer and October was 15% wetter and 0.9 °C warmer. In Rumperöd, August was 88% wetter and 3.7 °C warmer and January was 12% wetter and 1.2 °C warmer. March, February, and December were colder and drier at both stations, with all other months being hotter and drier in Rumperöd. These other months were April (43% drier and 1.8 °C warmer), May (77% drier and 4.1 °C warmer), June (73% drier and 2.6 °C warmer), July (75% drier and 4.6 °C warmer) September (27% drier and 0.4 °C warmer), October (13% drier and 1.3 °C warmer), and November (76% drier and 0.9 °C warmer). April, May, June, and July were also warmer and drier in 2018 at Hyltemossa than the previous three years with precipitation decreases of 43%, 85%, 65%, and 76% and temperature increases of 2.4, 3.9, 2.8, and 4.1 °C, respectively. In Hyltemossa, September and November were much drier (-65% in September and -84% in November) but very close to the calculated average temperature with changes of only -0.1 and 0.1 °C, respectively.

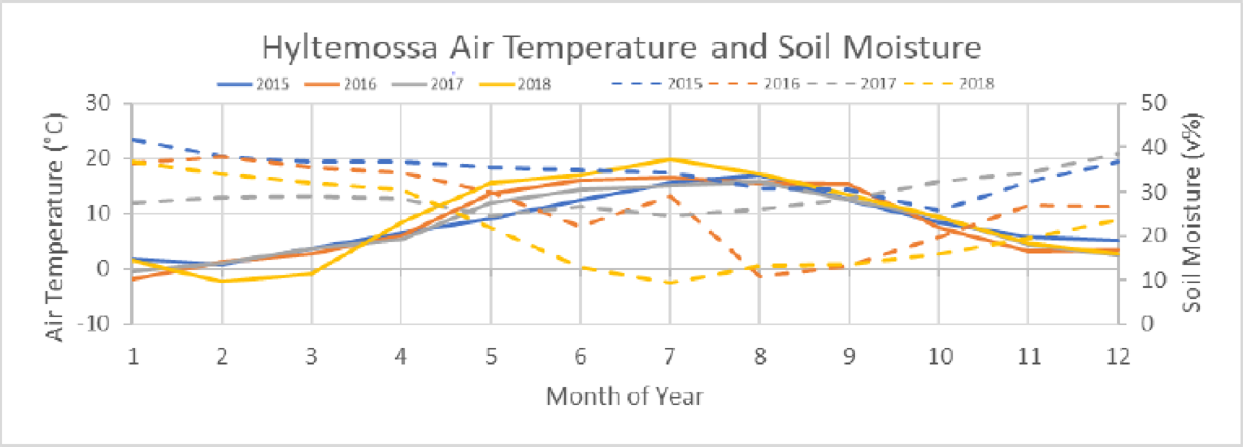
Soil temperature at both sites was very similar in 2018 between the two forests (Figure 3 (a, b)). Both locations had a peak soil temperature around 14.5 °C in August and their lowest values in March (0.8 °C in Hyltemossa and 1.2 °C in Rumperöd). All other years are also very similar, except for the end of 2017 where there is a sharp decline in temperature after August with a decrease of 3.8 °C within one month in Rumperöd whereas the decrease in Hyltemossa remains gradual and a decrease of only 1.4 °C occurred. Figure 4 (a,b) shows that both sites had similar amounts of incoming PPFD with Hyltemossa receiving about 7,500 and Rumperod 7,600 (mol of photons m^{-2}).

Table 2: Monthly sums of precipitation of each year for both forests as well as yearly totals. Data recorded at Klippan and Havsteda Mo climate stations used as proxies for Hyltemossa and Rumperöd, respectively. (Data Source: SMHI).

	Hyltemossa Precipitation (mm)				**Rumperöd Precipitation (mm)**			
	2015	**2016**	**2017**	**2018**	**2015**	**2016**	**2017**	**2018**
Jan	**100.3**	**39.2**	**16.9**	**65.9**	**103.8**	**51.7**	**16.6**	**64**
Feb	**42.1**	**52.1**	**51.1**	**20**	**20.2**	**72.2**	**68.8**	**15.8**
Mar	**67.2**	**34.3**	**38.5**	**35.5**	**83.4**	**32.1**	**50**	**48.2**
Apr	**37.1**	**43.7**	**51.2**	**25.1**	**49.7**	**88.5**	**81.3**	**41.5**
May	**68.7**	**20.7**	**31.6**	**6.1**	**143.5**	**19.3**	**26**	**14.7**
Jun	**68.3**	**40.8**	**93.5**	**23.4**	**107.6**	**61.4**	**201**	**33.7**
Jul	**100.7**	**102.2**	**99.6**	**23.8**	**116**	**124**	**166**	**33.5**
Aug	**54.4**	**60.7**	**95.4**	**95.8**	**51.2**	**74.4**	**132.5**	**161.4**
Sep	**58.5**	**34.4**	**109.2**	**23.6**	**68.3**	**30.5**	**176.9**	**67**
Oct	**9.8**	**58.4**	**135.6**	**78.2**	**9.7**	**140.7**	**232**	**110.7**
Nov	**135.9**	**52.9**	**95.6**	**15.6**	**142.7**	**95.2**	**75.6**	**25.5**
Dec	**102.2**	**35.7**	**128**	**49.2**	**108.3**	**45**	**114.5**	**67.3**
Total	**845.2**	**575.1**	**946.2**	**462.2**	**1,004.4**	**835.0**	**1,341.2**	**683.3**

Table 3: Yearly Standard Precipitation Index values for both forests calculated according to Sönmez et al. (2005.)

Year	**Hyltemossa SPI Value**	**Rumperöd SPI Value**
2015	**0.5**	**0.1**
2016	**-0.8**	**-0.6**
2017	**1.0**	**1.5**
2018	**-1.3**	**-1.2**



(a)

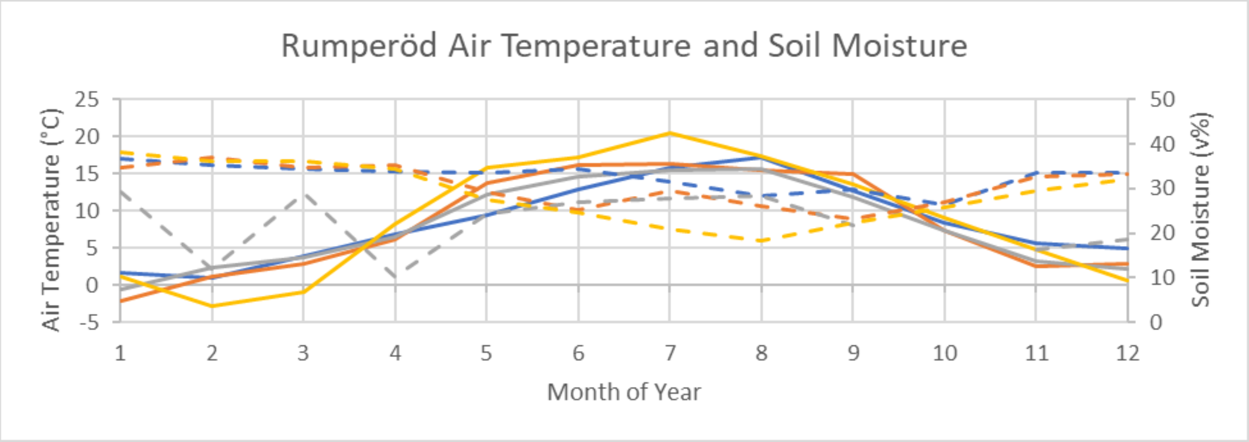


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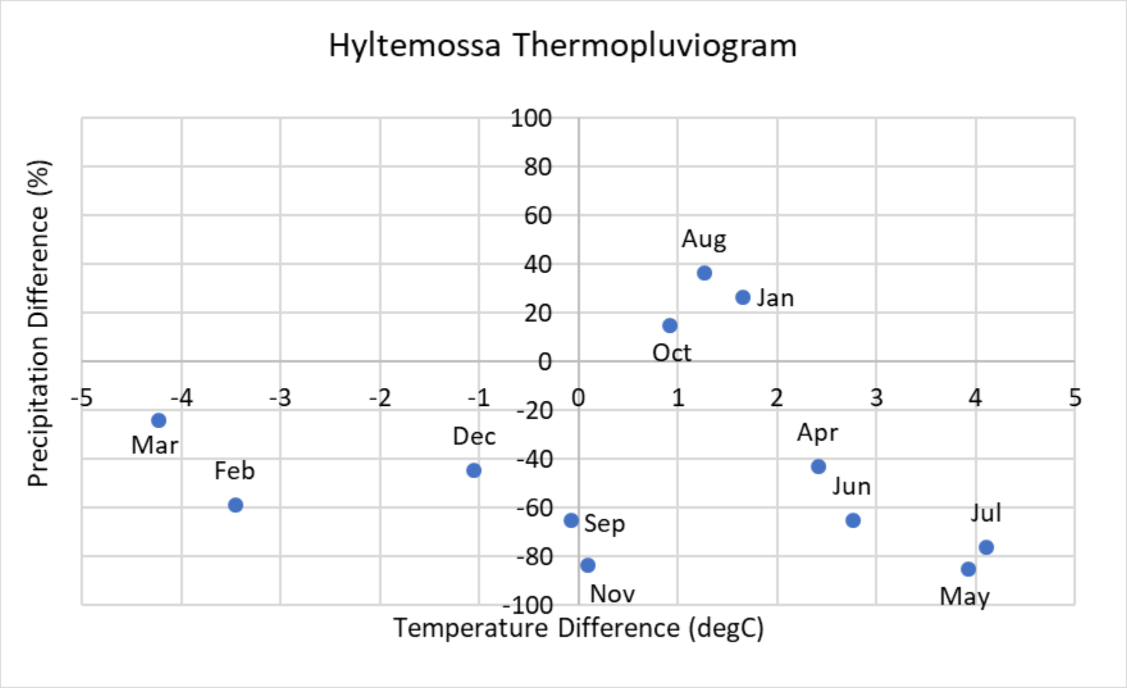
Figure 1: Monthly average air temperature (°C) and soil moisture (v%) in Hyltemossa (a) Rumperöd (b). Air temperature is represented by solid lines and soil moisture is represented by dashed lines.



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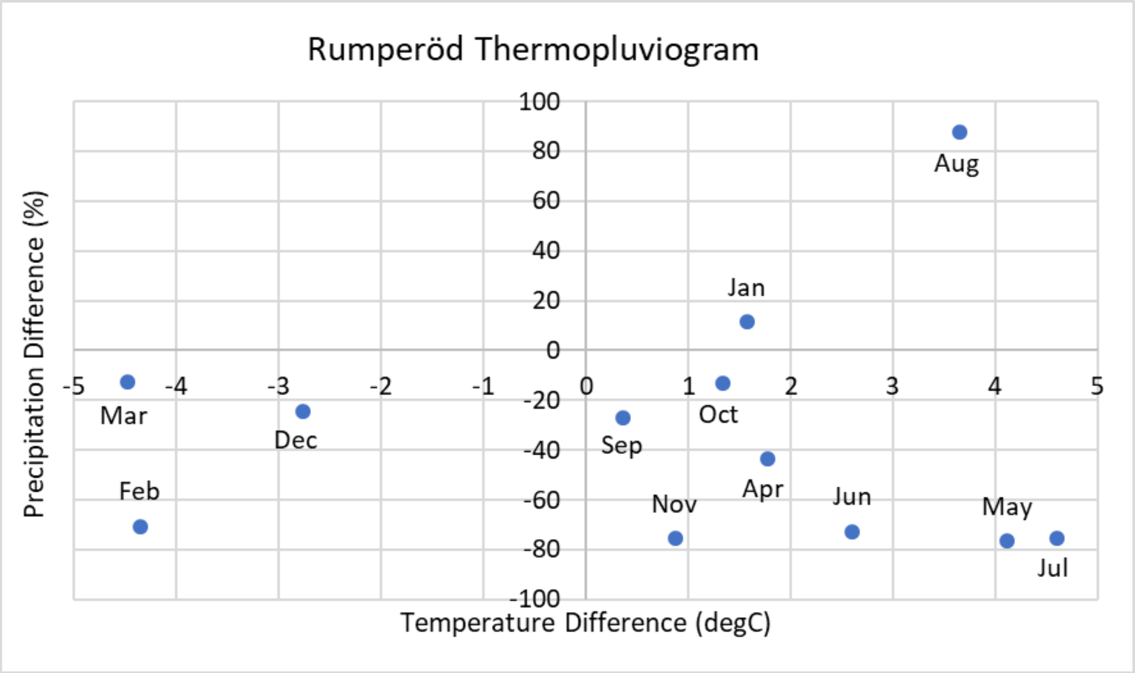
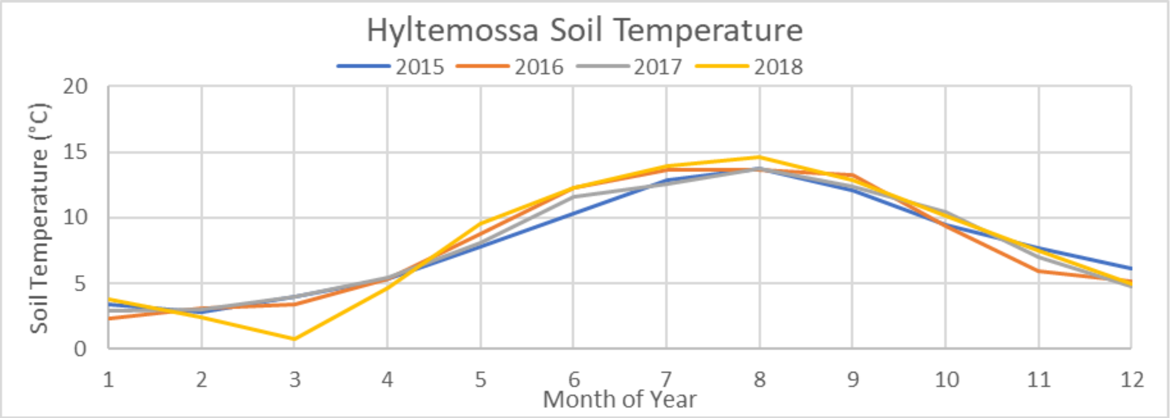


(b)

Figure 2: Deviations of 2018 monthly values of temperature and precipitation from averages based on the previous four years in degrees Celsius and percentage, respectively at Hyltemossa (a) and Rumperöd (b).



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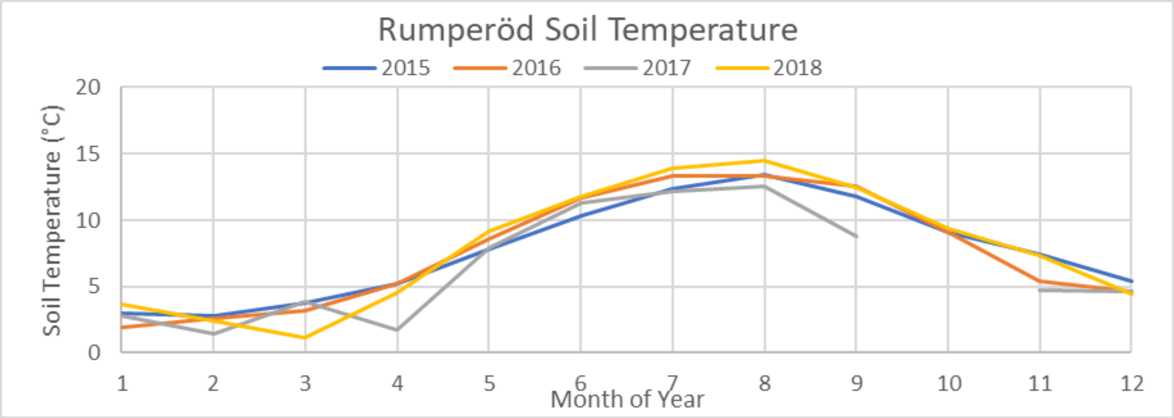

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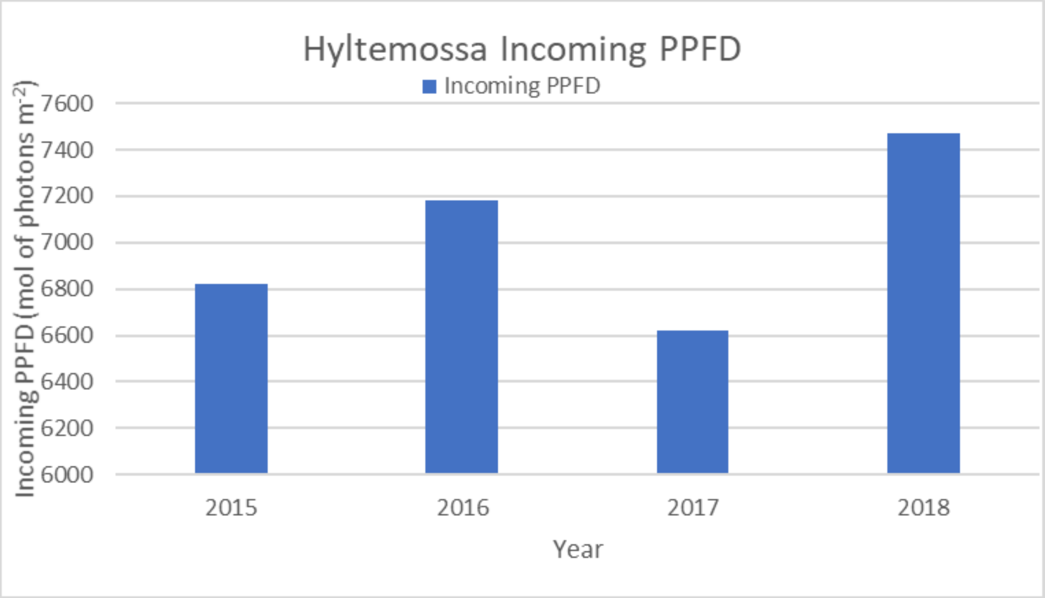
Figure 3: Monthly average soil temperature (°C) at Hyltemossa (a) and Rumperöd (b).



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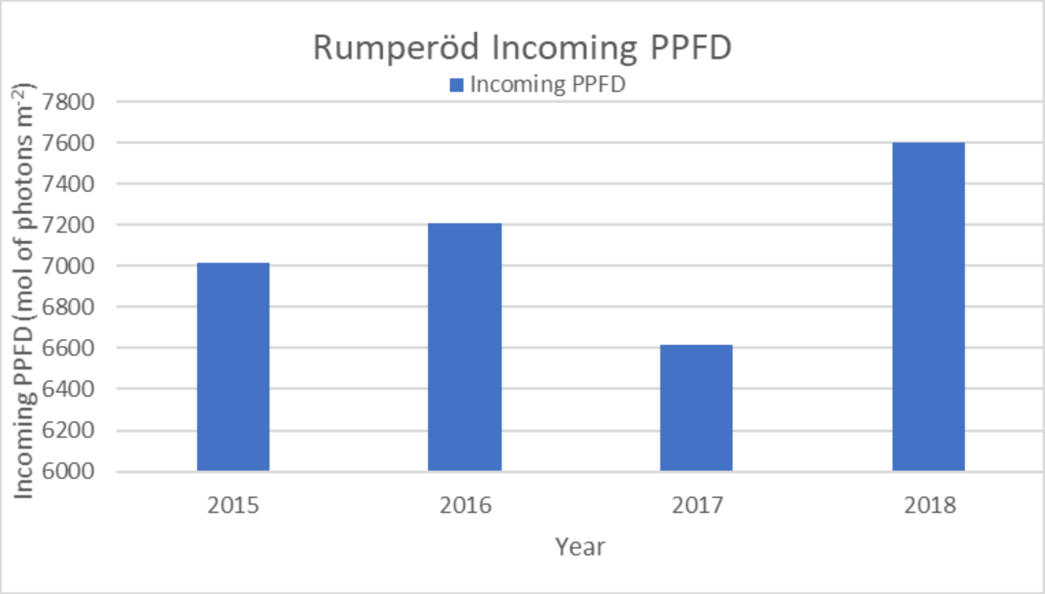


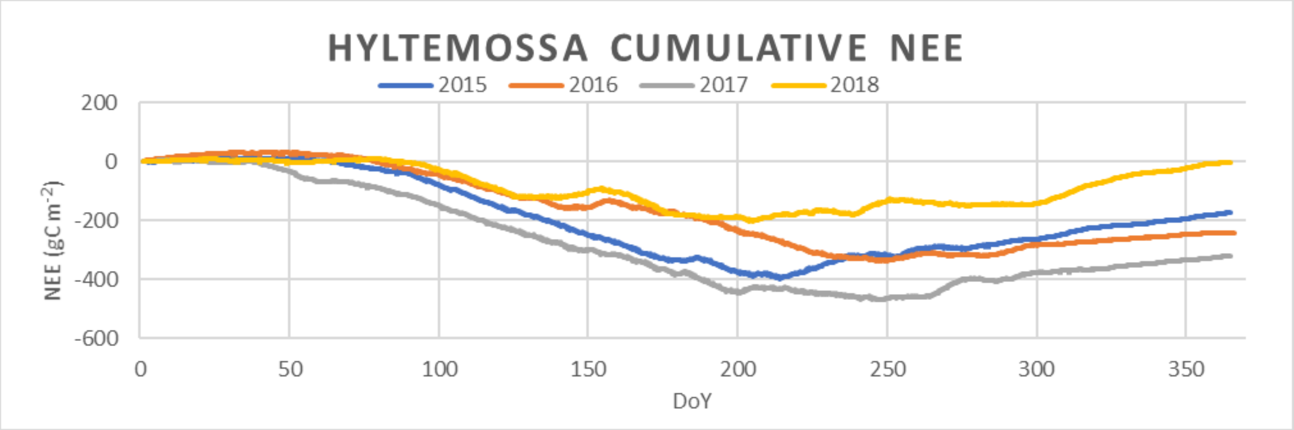
(b)

Figure 4: Incoming PPFD (mol of photons m^{-2}) for 2015-2018 at Hyltemossa (a) and Rumperöd (b).

Cumulative Fluxes

NEE

Cumulative NEE calculations show large differences in sink capacity between the two forests in 2018. As can be seen in Figure 5(a), Hyltemossa experienced a significant decrease in carbon sequestration compared to previous years with 3.4 gC m^{-2}yr^{-1} compared to 174.1 gC m^{-2}yr^{-1} in 2015, 241.6 gC m^{-2}yr^{-1} in 2016, and 318.8 gC m^{-2}yr^{-1} in 2017. Rumperöd sequestration was consistent with all years other than 2016 at 175.8 gC m^{-2}yr^{-1} compared to 176.3 gC m^{-2}yr^{-1} in 2015, 366.8 gC m^{-2}yr^{-1} in 2016, and 173.3 gC m^{-2}yr^{-1} in 2017 (Figure 5(b)). Despite both stations receiving less precipitation in 2016 than 2015 and 2017, they experienced higher uptake in 2016 compared to these years, with Rumperöd actually having the highest sink capacity that year.



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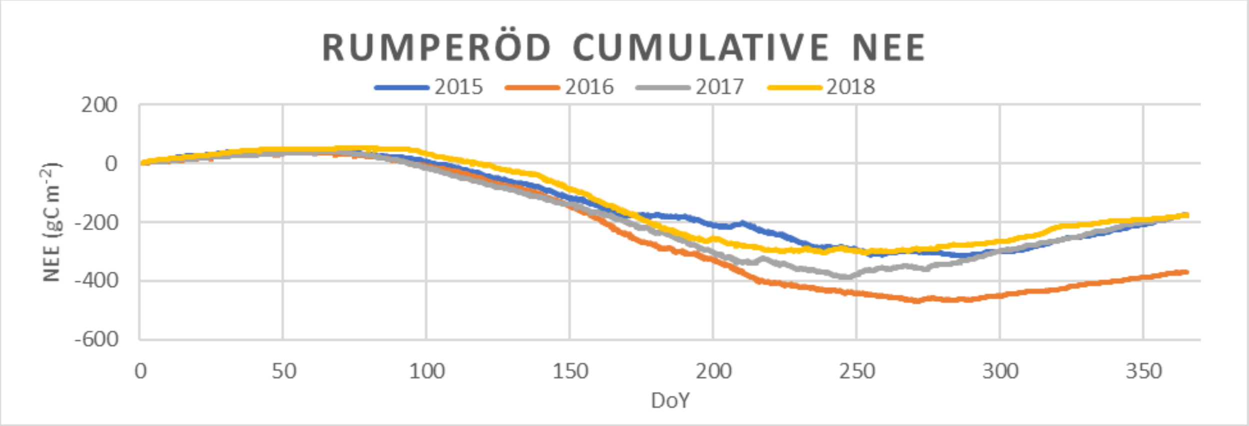
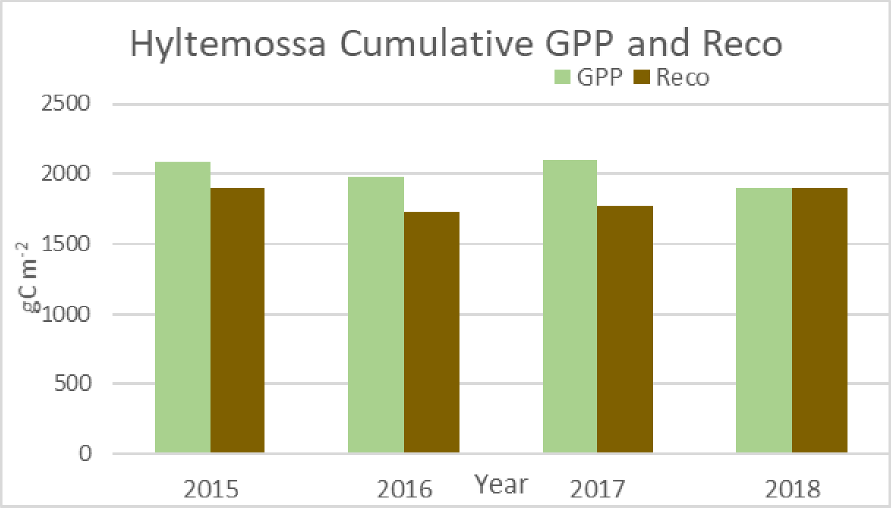


(b)

Figure 5: Half-hourly NEE values (gC m^{-2}) for the Hyltemossa (a) and Rumperöd (b) forests plotted against the day of year at which they occurred.

GPP and Reco

As can be seen in Figure 6 (a, b) below, both forests also experienced different responses in GPP and respiration in 2018. In Hyltemossa, both processes emitted and took up about the same amount of carbon at 1,898.9 gC m^{-2}yr^{-1} taken up through GPP and 1,895.5 gC m^{-2}yr^{-1} released by respiration. Previous years' values at Hyltemossa were 2,090.8 gC m^{-2}yr^{-1} in GPP and 1,896.9 gC m^{-2}yr^{-1} in respiration in 2015, 1,976.4 gC m^{-2}yr^{-1} and 1,734.8 gC m^{-2}yr^{-1} in 2016, and 2,094.8 gC m^{-2}yr^{-1} and 1,776 gC m^{-2}yr^{-1} in 2017. In contrast, Rumperöd still experienced clear differences between the two processes with 1,558.3 gC m^{-2}yr^{-1} in GPP and 1,382.5 gC m^{-2}yr^{-1} in respiration in 2018. The years 2015 to 2017 had GPP and R$_{eco}$ values of 1,690.5 and 1,514.1, 1,667.2 and 1,300.4, and 1,624.7 and 1,382.5, respectively. Rumperöd had a considerably higher cumulative GPP value than that of respiration in 2016. The reaction in 2017 in Hyltemossa is slightly less obvious when compared to previous years despite that being the best year in carbon uptake for the location.



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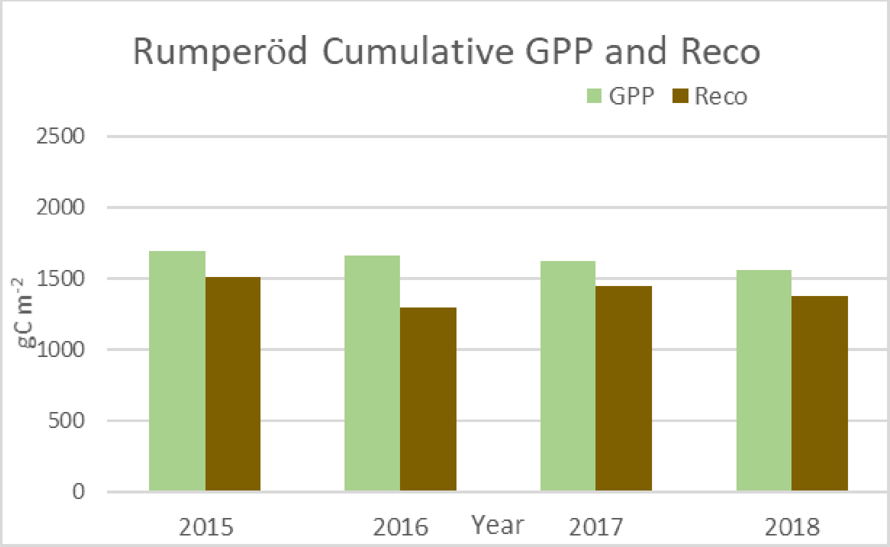
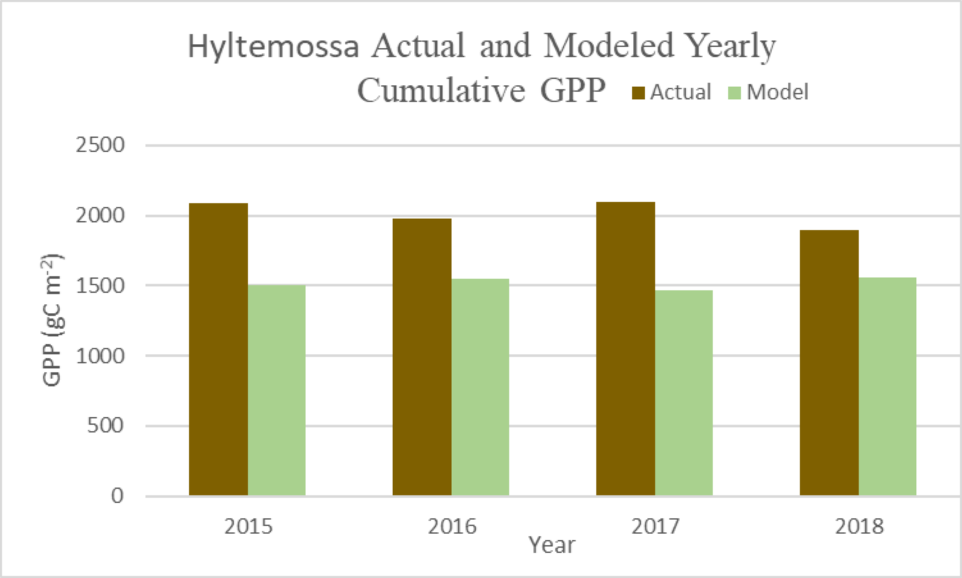


(b)

Figure 6: Yearly cumulative GPP and Reco values (gC m^{-2}*) at Hyltemossa (a) and Rumperöd (b).*

Modeled vs. Actual Flux Values

Actual GPP and modeled GPP for each location are compared in Figure 7 (a, b). These show that based on the amount of light that was incoming throughout the year GPP should have been highest in 2018 at both sites. However, as the figures based on actual values show, both locations experienced the lowest cumulative GPP in 2018 compared to 2015-2017. The year 2016 should have also had one of the highest cumulative GPP values in Hyltemossa according to the model with an almost identical reaction estimation as 2018. It is also apparent that actual GPP values are consistently higher than those predicted by the model for Hyltemossa whereas they are lower in Rumperöd.



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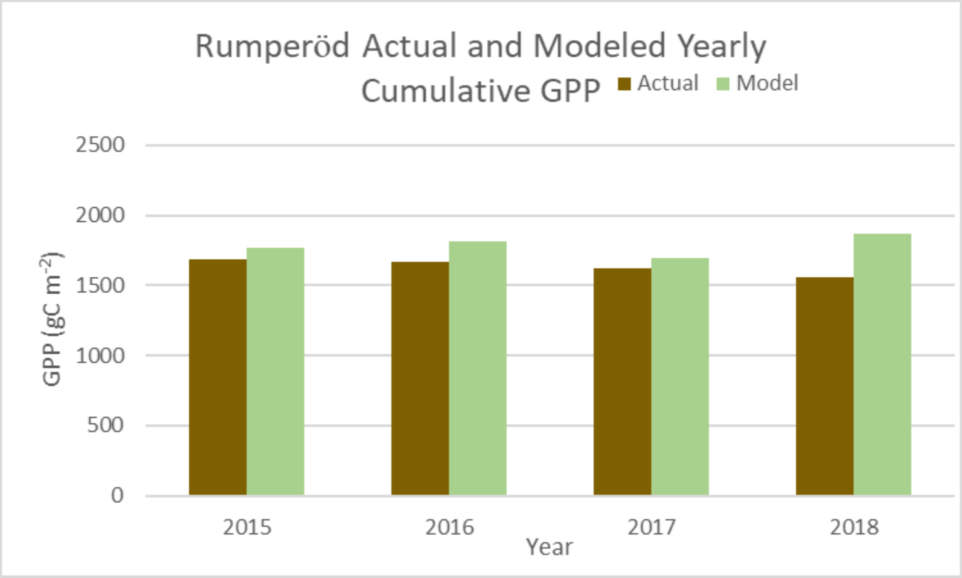
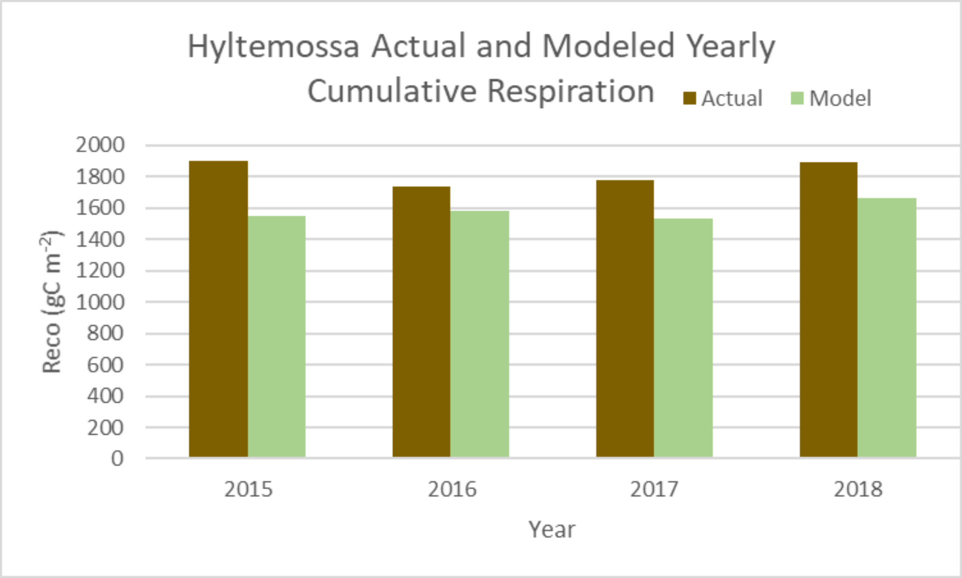


(b)

Figure 7: Actual and modeled yearly cumulative GPP at Hyltemossa (a) and Rumperöd (b).

Respiration (Figure 8 (a, b)) in Hyltemossa met expectations based on the model with cumulative respiration values highest in 2018 based on both real data and modeled. In Rumperöd, however, respiration was also modeled to be highest in 2018 but was second to lowest based on true values, with the year of lowest respiration occurring in 2016. The models for both years look almost identical when comparing years within each site but actual values in both absolute and relative terms are very different between sites.



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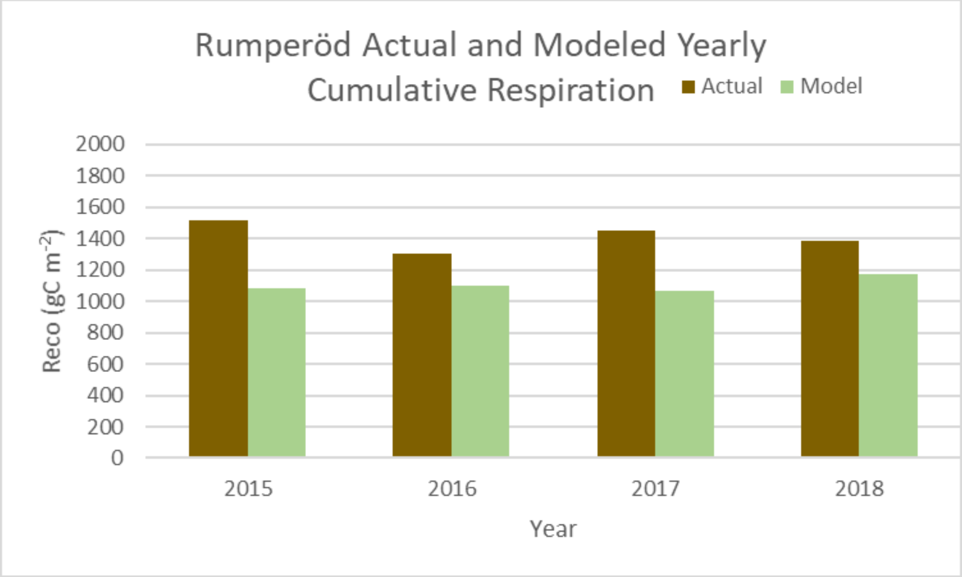

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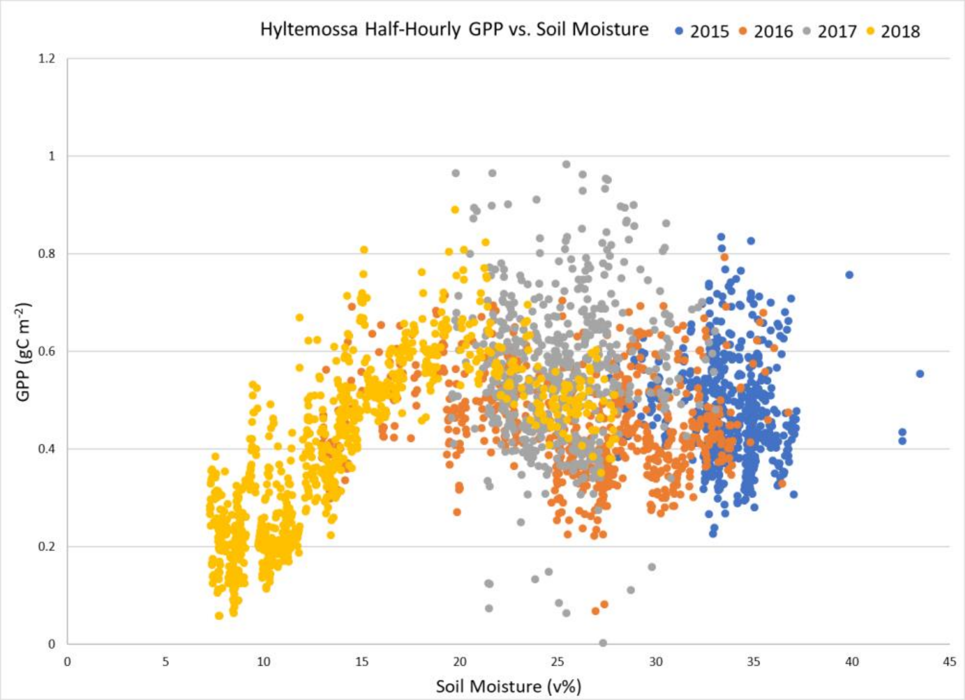
Figure 8: Actual and modeled yearly cumulative Reco at Hyltemossa (a) and Rumperöd (b).

GPP and Ecosystem Respiration vs. Soil Moisture

In order to further analyze the reactions of these fluxes, they were compared to soil moisture. As can be seen in Figure 9 (a, b), GPP at both sites reacted differently with changes in soil moisture volume percent. In Hyltemossa, there is a clear decrease in GPP when soil moisture falls below 20% where the maximum half-hourly GPP values reach around 30-40 gC m^{-2}. No other years have soil moisture as low except for 2016 which has just a few values below 20%. The reaction of GPP to changing soil moisture values shows little order or pattern when soil moisture is above 20%. Rumperöd, however, experiences a sharp peak in GPP ranging from just over 1 to around 0.3 gC m^{-2} around 25% soil moisture, and slow curves downwards on the drier and wetter values with a small increase again on the dry end. The wet values around 30-45%, where little relationship is apparent, also show a wider range of GPP values than those on the wet end of values for Hyltemossa.



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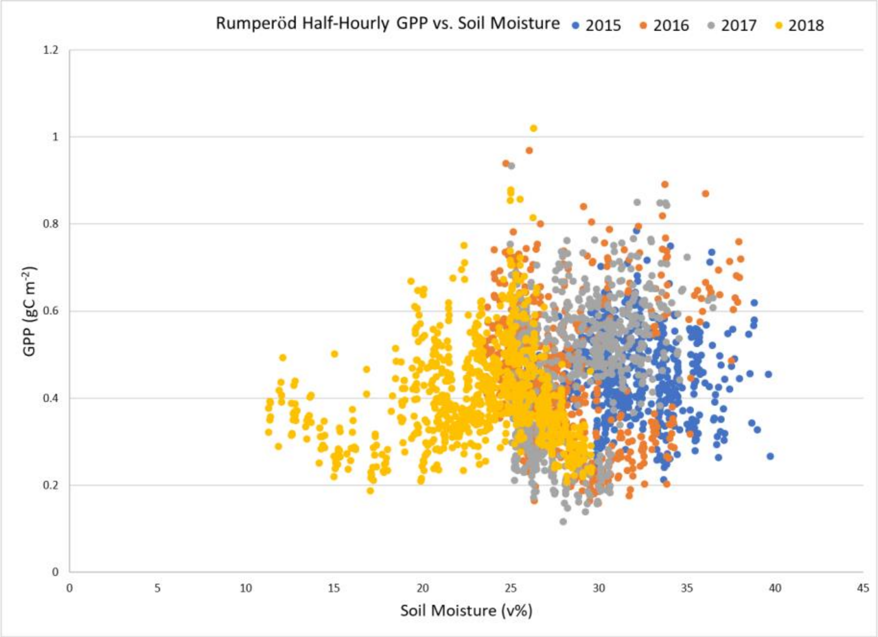
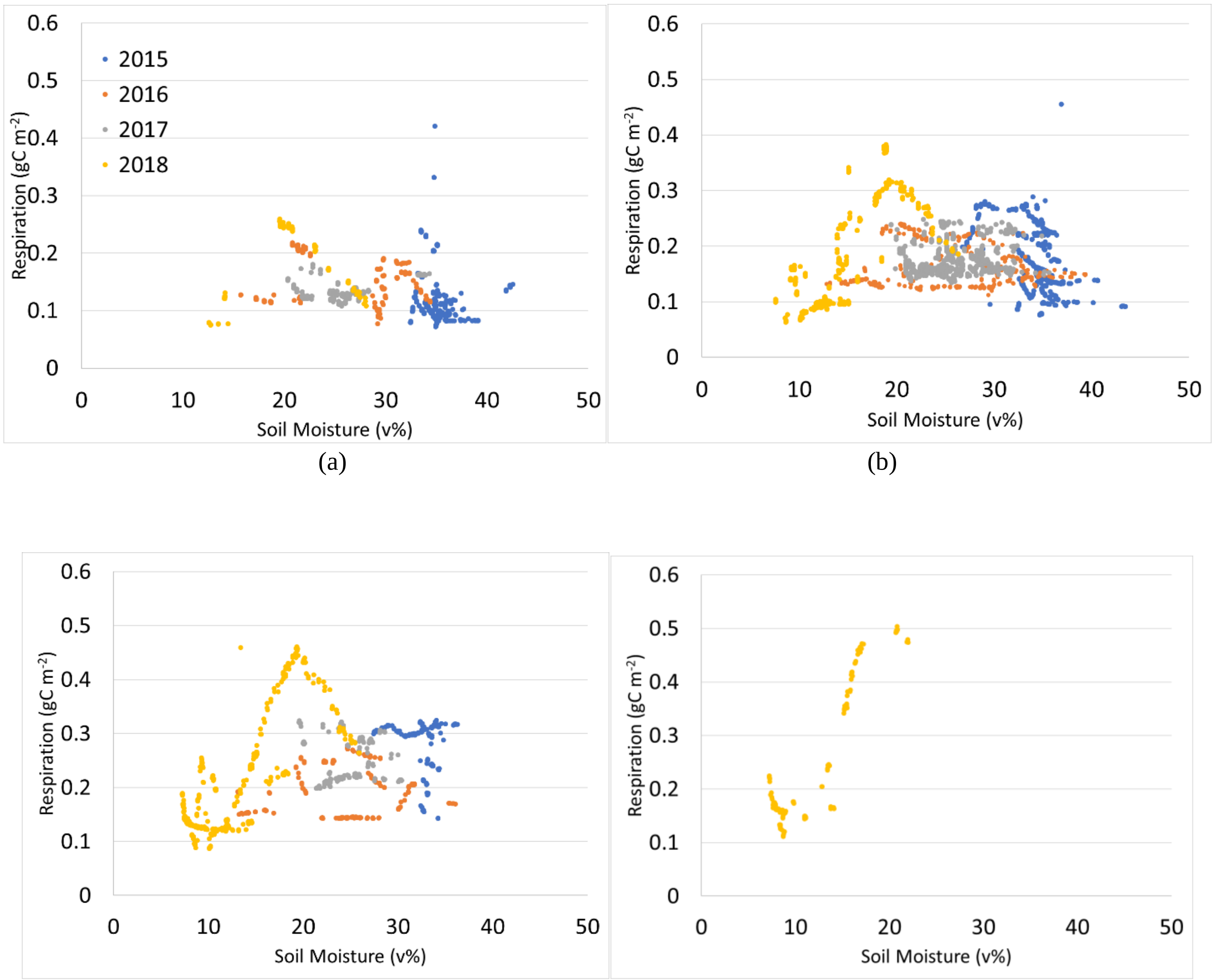


(b)

Figure 9: Half-hourly average GPP (gC m^{-2}) vs. soil moisture (volume %) at Hyltemossa (a) and Rumperöd (b) during time of light saturation (PPFD>1,200 µmol of photons m^{-2}s^{-1}) over a four-month period (beginning of May to end of August).

Figures 10 (a, b, c, d) and 11 (a, b, c, d) show respiration response to soil moisture at each site for different temperature classes of one degree. Here only four temperature classes are shown but all can be found in the Appendix. As one can see for Hyltemossa, the relationship with moisture becomes stronger in the higher temperature classes. At moisture values above 20%, the half-hourly R_{eco} values dip back down to a range between 5 and 25 gC m^{-2} and remain there for all temperature classes and all years. Before this decrease in respiration with decreasing soil moisture values, there is a peak at around 20% moisture. The value of respiration at this peak differs between temperature classes with the highest values occurring in the warmer temperatures and ranging from about 12 gC m^{-2}half-hour^{-1} to 23 gC m^{-2}half-hour^{-1}. The strongest changes are seen in the decrease in 2018 when soil moisture reaches levels below 20%. In Rumperöd, very little relationship is seen in any of the years and temperature classes. When all years are plotted together, however, there is a visible increase in respiration when soil moisture increases. There is still, however, no apparent soil moisture value where respiration is at the highest level unlike at Hyltemossa.



(a)

(b)

(c)

(d)

Figure 10: Half-hourly respiration response to soil moisture in different temperature classes at Hyltemossa: 9-10 °C (a), 13-14 °C (b), 20-21 °C (c), and 25-26 °C (d)

(a) (b)

(c) (d)

Figure11: Half-hourly respiration response to soil moisture in different temperature classes at Rumperöd: 9-10 °C (a), 13-14 °C (b), 19-20 °C (c), and 26-27 °C (d)

Discussion

As the thermopluviograms show, the growing season was both hotter and drier in 2018 than the previous four years at both forest sites. The SPI calculations also show that the stands experienced drought conditions in that year. This is consistent with reports of drought throughout Europe and within southern Sweden (EDO 2018, Liberto 2018). Despite Rumperöd usually receiving more precipitation, the thermopluviograms show that they both experienced similar deviations from their normal conditions. The SPI values also indicate that he severity of drought at both sites was very similar. According to Seidl et al. (2017), Norway spruce trees living in an area that receives less than 750-800mm of precipitation per year are more sensitive to drought. As Table 2 shows, Hyltemossa received precipitation less than 750mm in both 2016 and 2018. Rumperöd also received less than 750mm of precipitation in 2018, but only by 66.7mm whereas Hyltemossa missed the mark by 287.8 mm. This would imply that Hyltemossa is more vulnerable to drought due to more frequent and extreme dry conditions. This threshold of precipitation values, however, could also be influenced by soil type and therefore should not be considered ultimate values for determining drought sensitivity, but simply considered. Both sites have sandy soil which drains more quickly than others and could require more water in order for there to be enough water accessible to plants. Tree species in the area could also affect how much precipitation is necessary for the trees to function as interception would occur less in the winter and fall seasons when deciduous trees have no foliage and therefore allow more water to reach the soil and reduce demand for water due to decreased photosynthetic activity. Both sites have around the same soil moisture in the beginning of the year, however Hyltemossa experiences its lowest soil moisture a month earlier than Rumperöd at around half the volume percent of moisture. The decrease at Hyltemossa appears to be more constant and gradual up until this low point whereas Rumperöd is slightly more sudden and steeper. This could be due to the new growth of leaves suddenly demanding more water whereas foliage at Hyltemossa remains mostly constant due to the coniferous population. The soil moisture values at the end of the year also show large differences between sites with higher amounts in Rumperöd. This could be due to the trees once again losing leaves and allowing more precipitation to reach the surface and trees using less (Miyazawa and Kikuzawa 2005).

This substantial difference in precipitation and soil moisture values and therefore potential difference in drought response is exhibited in the cumulative NEE. As mentioned before, Rumperöd experienced uptake values similar to that of previous years, whereas Hyltemossa was the least efficient in sink capacity of all previous years by a considerable amount. This shows an obvious difference in how the forests reacted to deviations from normal temperature and moisture conditions. NEE, however, is made up of both ecosystem respiration and gross primary production, the processes that release and take up carbon, respectively.

Light availability and temperature conditions at both sites were used to estimate potential activity of R_{eco} and GPP. Comparing the modeled and actual GPP, both sites should have experienced their highest uptake in 2018 based on the amount of light that was incoming. Both sites, however, experienced their lowest GPP levels in 2018. These results mean that the forests did not uptake as much carbon as they could have based on light conditions so some other factor, such as moisture deficit or high temperatures, must have limited the forest from producing at this rate. These lower values agree with results found by Gao et al. (2017) that GPP was inhibited during severe drought conditions at Hyytiälä, Finland in 2006. Ciais et al. (2005) found European-wide decrease in GPP in response to the 2003 drought coinciding with reduced carbon uptake and Liu et al (2018) found that GPP decreased during drought in forests in the United States.

Modeled respiration shows that it also should have been highest in 2018 as it was driven by temperature data for both sites. In Rumperöd, respiration was second to lowest in 2018 and in Hyltemossa 2018 was just under the highest respiration value which occurred in 2015. This low respiration in Rumperöd means that despite experiencing the lowest GPP in 2018, respiration was also low, which would create a balance similar to that of previous years. Hyltemossa’s low GPP and still relatively high respiration would result in less uptake by the ecosystem and an increase in release, therefore resulting in more positive overall NEE. These lower values of respiration at both stations but especially Rumperöd are in contrast with results from Liu et al. (2018) who found that respiration increased in drought conditions in forests throughout the United States.

Figure 9 (a, b) shows that GPP greatly decreased (by about 50%) with lowering soil moisture values in Hyltemossa whereas in Rumperöd there was a peak production around 25% moisture but an unclear relationship at values lower and higher than that. This shows that GPP at Hyltemossa reacted more consistently to lowering soil moisture values than Rumperöd. The same was found for respiration with Rumperöd showing even less of a relationship with soil moisture and Hyltemossa showing an increase in respiration until about 20% soil moisture and then a decrease. In 2018, this decrease in respiration at higher soil moisture values was not as relevant as moisture was mostly below this threshold value. This proves that as soil moisture decreased, Hyltemossa experienced a stronger reaction with decreasing respiration and GPP. However, respiration at Hyltemossa for 2018 was one of the highest years. This is likely due to the optimal respiration occurring at 20% soil moisture volume in the beginning of the season when there were higher levels of precipitation. This increase in respiration can be seen in Figure 8a where respiration experiences a sharp incline and then continues to increase at a less steep rate. These optimal rates likely compensated for the decline in respiration that occurred later on when moisture decreased due to lack of precipitation. This stronger reaction in Hyltemossa could be due to the single-species composition of the forest, as Norway spruce has been found to have shallow roots whereas beech has the ability to extend roots downwards with increasing competition or decreasing water or nutrient availability at the surface (Puhe 2003, Rust and Savill 2000).

Decreasing respiration despite higher temperatures was also seen in a study by Ciais et al. (2005) and could likely be due to the water limitation outweighing the benefits of the increased air temperature. Gupta and Singh (1981) also found a positive relationship between respiration, air temperature, and soil moisture which also supports the relationship of decreased respiration with decreased soil moisture that would occur at higher temperatures due to increased evapotranspiration (Lechuga et al. 2017). Liu et al. (2017) found that tree response to drought conditions is dependent on soil type. Considering that both forests are grown in similar soil, this would mean that other factors are likely more responsible. However, their study also found that reaction was dependent on acidity or alkalinity of soils and this should therefore be measured at both sites in order to evaluate any potential differences and their cause.

Tree species present at each location are also potential factors in each forest's reaction to the drought conditions. Norway spruce and other coniferous forests growing in southern Sweden are limited by water (Belyazid and Guiliana 2019, Bergh et al. 2005, 1999). This tree species has also been found to be very vulnerable to environmental changes when grown outside of its natural area, which is rather large and widespread but does not include the southern tip of Sweden (Seidl et al., 2017, Hartl et al. 2014, Spiecker 2000). Both forests are predominantly populated by Norway spruce, however Hyltemossa is almost exclusively Norway spruce whereas Rumperöd has more occurrences of a larger variety of tree species. This almost exclusively coniferous population in Hyltemossa can decrease overall forest health when drought occurs due to the vulnerability to cell damage in these conditions and inability to revert to previous levels of functionality in trees after drought conditions (Rosner et al. 2018). The trees that contribute to increased biodiversity at Rumperöd could be beneficial to drought resilience and recovery as European beech has been found to have high resilience to drought conditions and quick recovery afterwards (Pflug et al. 2018). This higher diversity and presence of resilient species could be a factor in Rumperöd's lack of decline in carbon sequestration in 2018.

It has been found that trees in less dense and competitive environments are more efficient and less sensitive to drought (Lechuga et al. 2017, Falge et al. 2001). Increasing age and basal area of forests has also been found to decrease drought resilience (Seidl et al. 2017). Despite the young age of Hyltemossa, the age of trees is largely homogeneous, whereas Rumperöd has a mixture of young and older trees due to the less uniform harvesting method. This would imply that resilience is likely lower in Hyltemossa. Seidl et al. (2017) also found that stand variables such as age, basal area, and previous disturbances were more important for resilience to drought than climatic variables, meaning that management of the forest is important in ensuring the ability of the trees to survive and experience the least damage possible during drought conditions.

Overall, there is some uncertainty and error involved with eddy covariance flux measurements (Gao et al. 2017, Aubinet et al. 2012, Baldocchi 2003). However, the data from the two sites was processed similarly with fluxes calculated and quality flagged by EddyPro. Some error could be introduced in the quality sorting process of removing inaccurate values as this is a somewhat subjective process where decisions must be made when the supporting data does not provide a clear decision on whether values should be removed or left in the data set.

Precipitation data is also likely to have some factor of error due to having to use data from nearby SMHI stations rather than measured at the actual site. Although likely minimal, precipitation can differ across small distances. Therefore, it would be more ideal to have complete and reliable precipitation measured at the two sites for use instead. Precipitation measurements in general are also known to be uncertain due to the impact of temperature on the gauge and potential equipment malfunctions. It would also have been preferred to use soil temperature for the temperature response curves rather than air temperature. Soil temperature could not be used due to gaps in data and no reliable way to gap fill using air temperature.

More information regarding site characteristics would be useful for this study and future others. There is currently little specific information for the sites especially regarding understory vegetation species and the amount of each tree species present. This information would be especially important for Rumperöd where there are multiple other tree species that may aid in dampening drought response such as beech as mentioned before, and therefore the amount of these species present would be important to know and take into account.

In the future, it would be recommended to look at other environmental variables such as vapor pressure deficit and evapotranspiration in order to analyze differences in drought reaction between forests, as these variables have been found to have relationships with drought and effects on stomatal conductance and therefore forest productivity (Gao et al. 2017). GPP estimates using satellite could also be used to compare results and determine whether satellite-based estimations are viable for overcoming the limitation of eddy covariance tower measurements and allow for global modelling and extrapolation of drought response as previously explored (Anderegg et al. 2018a, Dubois et al. 2018). Other sources for differences in reaction such as topography and soil characteristics (water retention curves) should also be examined and/or measured and documented in order to further understand the ecosystem. Forests can increase net primary production (NPP) during recovery after disturbance, so future measurements at these sites should be evaluated to determine if this recovery and increase has occurred and if one forest recovers differently than the other (Fu et al. 2017). Van Ruijven and Berendse (2010) found increased recovery from drought with increasing biodiversity which should be considered when following and comparing recovery between the forests.

Conclusion

Overall, both forests reacted very differently to the conditions of the 2018 drought despite experiencing similar drought severity and deviations in precipitation and temperature during the growing season compared to monthly averages calculated based on the previous four years. Fluxes and other environmental data were calculated and compared in order to determine similarities and differences in conditions and reactions. From this, it is clear that the hypothesis of Hyltemossa reacting more strongly is indeed true. Rumperöd was able to continue carbon sequestration at about the same rate as 2015 and 2017, whereas Hyltemossa experienced a significant decrease in net sink compared to all three previous years.

When analyzing GPP and respiration, it is apparent that Hyltemossa reacted more strongly to these environmental changes. Based on studies that describe the effects of forest management and different tree species resilience to drought, it is highly possible that one reason for these differences in forest reaction are management related such as species diversity and crowding. However, due to the complexity of ecosystem interactions and variables that impact the reactions of each forest (e.g soil characteristics, topography, etc.) the exact cause of these differences cannot be conclusively stated.

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Appendix

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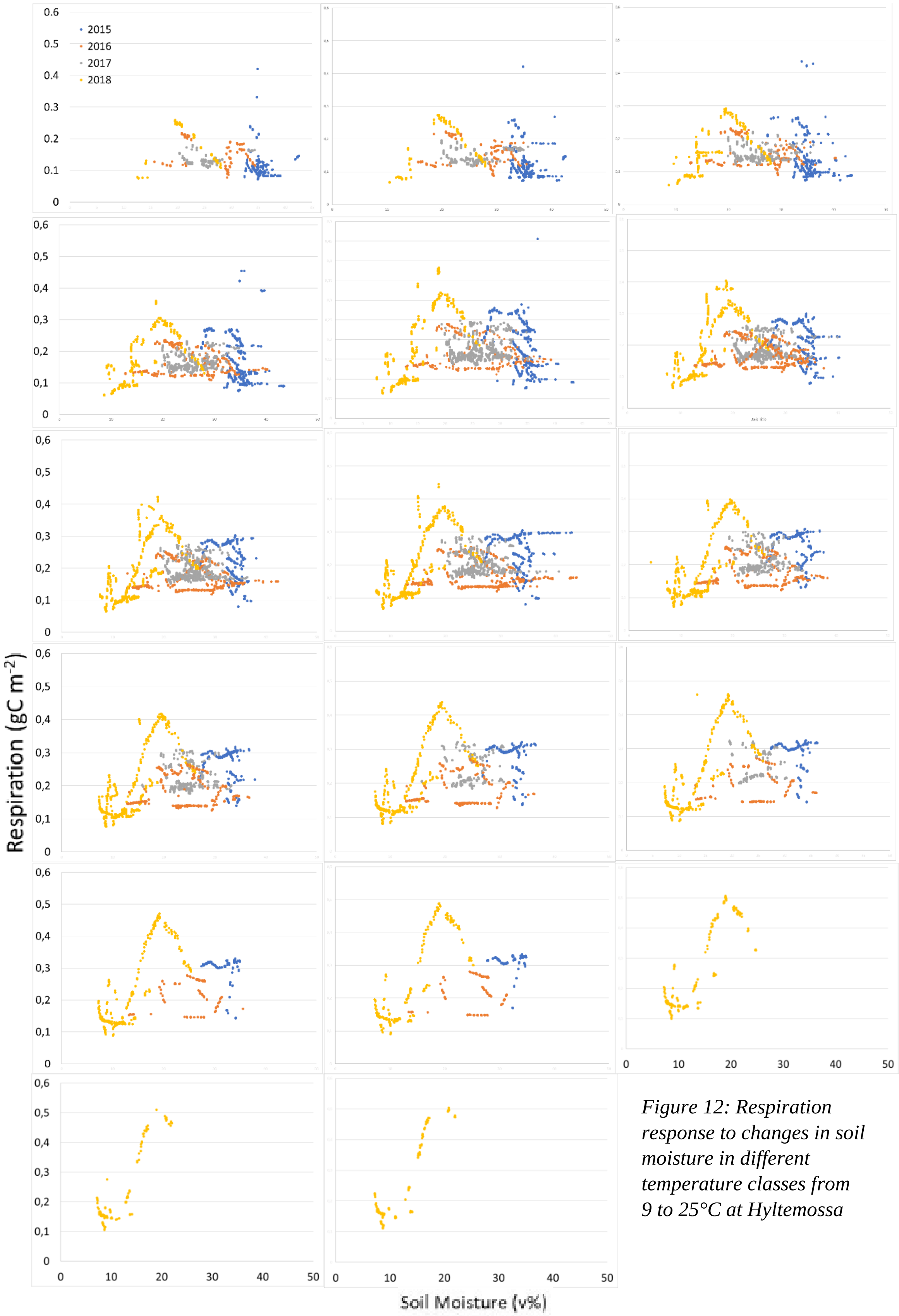
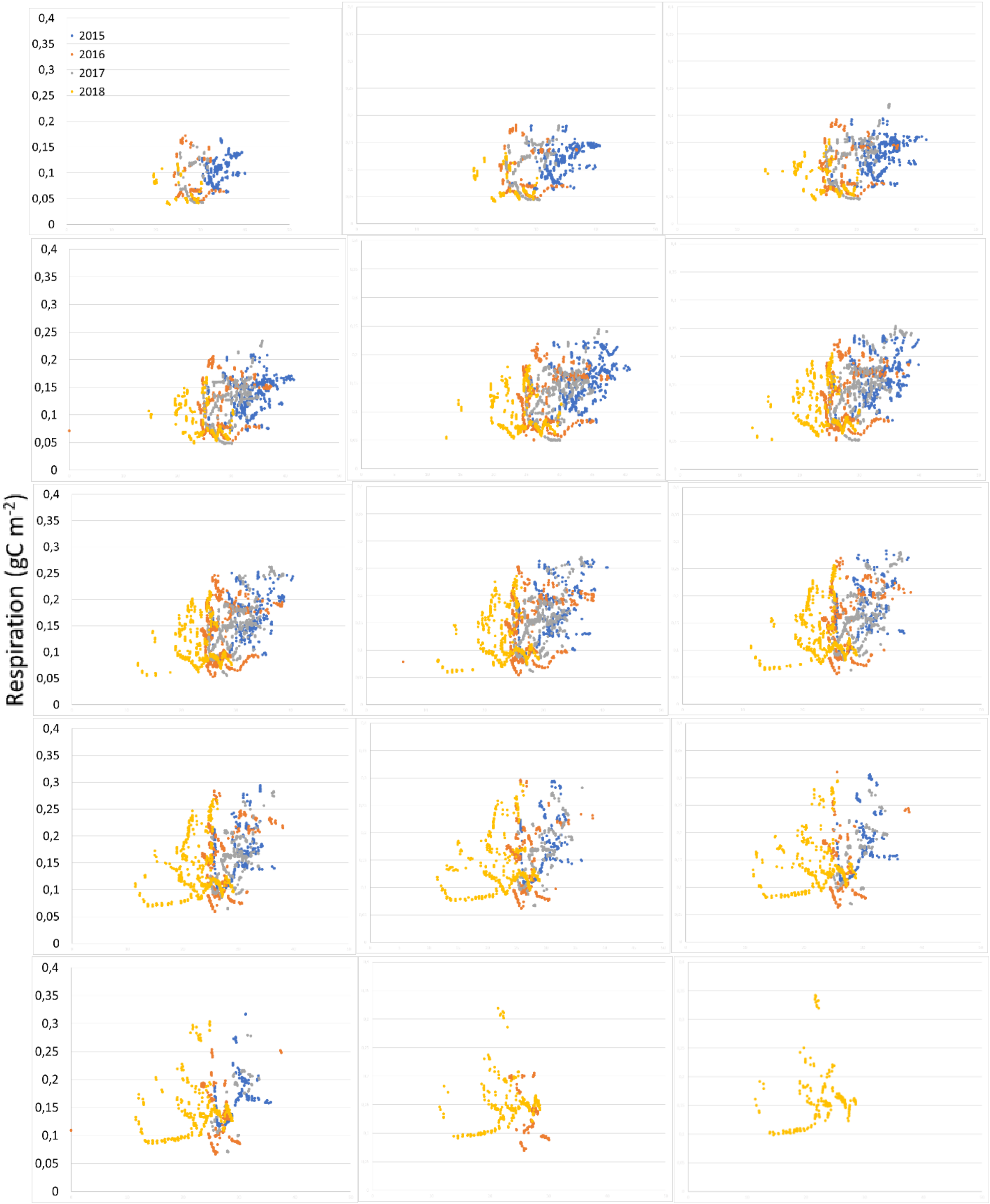


Figure 12: Respiration response to changes in soil moisture in different temperature classes from 9 to 25°C at Hyltemossa



2015
2016
2017
2018
Respiration (gC m^{-2})
0,4
0,35
0,3
0,25
0,2
0,15
0,1
0,05
0

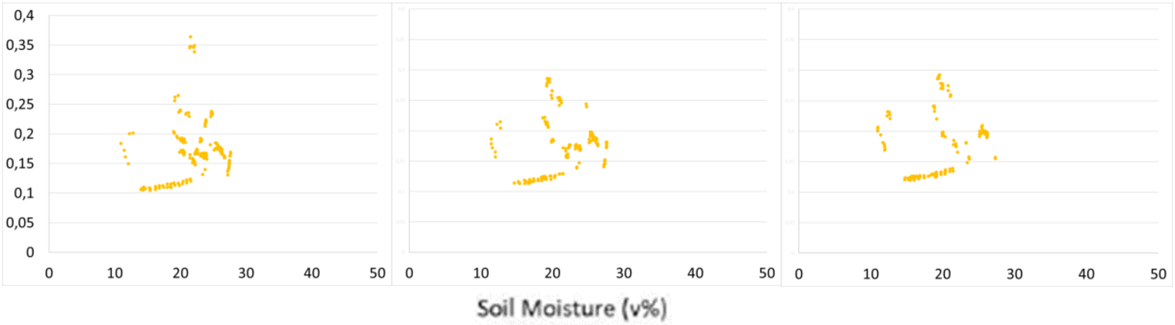


Figure 13: Respiration response to changes in soil moisture in different temperature classes from 9 to 26 °C at Rumperöd.