Calculation of the Transpiration and Net Carbon Dioxide Assimilation in Norway Spruce, based on Sap Flow Data

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1. Abstract

The aim of this study was to establish a way to calculate carbon dioxide assimilation values from sap flow measurements and to validate them by comparison with data obtained from eddy covariance measurements. The trees chosen for the sap flow measurements were evenly distributed within the stand. The sampling was conducted between the 1st of September and the 28th of October 2011 in Skogaryd, south-western Sweden.

It was found that the sap flow values would decrease the later in the year the measurement was conducted and that factors like the vapor pressure deficit (VPD), the photosynthetic photon flux density (PPFD) and the temperature (T) have a strong impact on the sap flow. It has also been found that the calculated carbon assimilation values based on the sap flow data and the carbon dioxide assimilation data based on eddy covariance measurements, were of similar magnitude but were not directly comparable since respiration data from the sap flow measurement period were not available.

In general it was found that the sap flow data were a useable starting point for calculating the carbon dioxide assimilation of the canopy.

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3. Introduction

The IPCC 2007 has predicted an increase in global mean temperature, which will be caused mainly by anthropogenic emissions. There are several models which predict an increase between 1,8 °C (B1 scenario) and 4,0 °C (A1F1 scenario) of the global mean temperature until the end of the century. The factor, these models are depending on, is the increase of carbon dioxide (CO_2), or carbon dioxide equivalents concentration in the atmosphere, which is predicted to be between 730 to 1020 ppm until the year 2100 (IPCC, 2007).

Yet, there are uncertainties in these models since it is not known how our planet will respond to an increase in the carbon dioxide level. In order to make more reliable predictions it is important to know to what extent the ecosystems can buffer this change and how much of the additional carbon dioxide can be taken up and bound to organic matter.

3.1. The Carbon Cycle

Carbon dioxide is an important greenhouse gas and found in the atmosphere at a concentration of 390 ppm (state 2011) (NOAA, 2011). It is part of the carbon cycle, and plays, as already mentioned above, an important role in the global warming process.

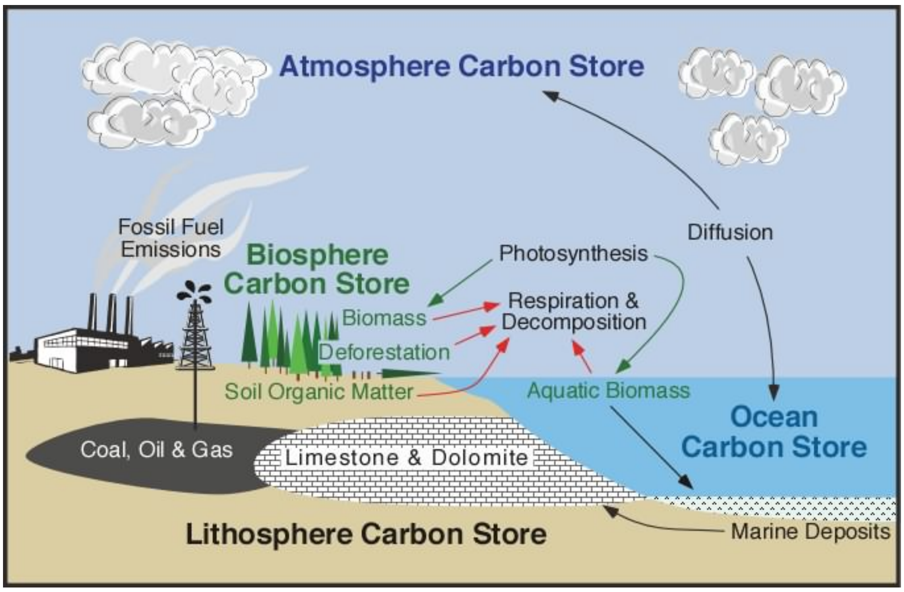

Figure 1: Global Carbon Cycle (http://www.physicalgeography.net, 2012)

In Figure 1 it can be seen that the biosphere can function as carbon storage, but it is also known that depending on environmental factors this storage capacity can change substantially (Dixon et al., 1994). To know if an ecosystem functions as a source or sink for carbon dioxide, one has to know how much carbon dioxide is taken up and released by this system. Therefore it has been the topic of many studies to identify how plants react to elevated carbon dioxide, higher temperature and the change of other environmental factors (e.g. Kellomäki & Wang, 2000).

Besides acquiring information on the reaction of plants to elevated carbon dioxide, it is important to know how much carbon dioxide can be taken up by a whole ecosystem in order to predict the impact of certain types of ecosystems to the atmospheric carbon dioxide concentration and the global carbon cycle and therefore also on global climate change.

3.2 The Eddy Covariance Technique

There are different methods to measure the uptake of carbon dioxide by an ecosystem. Most studies that have been conducted on the exchange of gases between biosphere and atmosphere have been using chamber or cuvette techniques (Baldocchi et al, 1988).

Another technique, which is now commonly used, is the eddy covariance technique (e.g. Zah et al, 2007; Van Dijk & Dolman, 2004). The eddy covariance method can estimate the carbon dioxide exchanges of an ecosystem by measuring the amount of molecules of carbon dioxide that are going up from an ecosystem in an eddy and measuring the amount of molecules that go down into the ecosystem (Burba et al, 2010). In order to get to the net flux of carbon dioxide of an ecosystem one needs some additional data on the respiration of the ecosystem to subtract these values from the flux data.

3.3 Sap Flow as a Way to Measure Assimilation of CO_2

A different method to measure the amount of carbon dioxide that is taken up by an ecosystem is based on the measurement of the sap flow within trees. This method alone does not give information about the ecosystem being a sink or source to carbon dioxide but it can be used to make an estimate of the assimilation of carbon dioxide by trees.

In order to make predictions about carbon dioxide being bound or released by the ecosystem, one needs to combine estimates of plant CO_2 uptake with estimates of the CO_2 fluxes by the soil, including the roots.

Since the overall equation for photosynthesis is the following;

$$6\,CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

And as Fick's Law states that the assimilation of CO_2 is dependent on the stomatal conductance (g_s), which can be calculated by using the sap flow data of the trees; the uptake of water can be used as a basis for calculating the net assimilation of CO_2 by the tree, in case data on the c_i/c_a ratio is available.

3.4 The Dependency of Sap Flow on VPD, PPFD and Stomatal Conductance

The use of water in the green parts of the plant is dependent on several factors such as the vapor pressure deficit (VPD) which when high, forces the plant to transport more water from the root to the leaf, since more water is evaporating from the leaf. On the other hand, a very low VPD can lead to a decrease of the sap flow since no water can evaporate from the leaf.

3.4.1 Vapor Pressure Deficit

In a system with different concentrations of molecules, in this case H_2O molecules, the system always tends to equalize the concentrations. This is very important for the evaporation of water and thus the plant's transpiration.

The VPD normally describes the saturation of a gas towards another component. In this case it is describing the difference between the water vapor pressure inside a leaf and the actual water vapor pressure in the air around the leaf.

It can be considered that the saturation of the air inside the leaves is about 100% whereas in the air around the leaf it is normally below 100%. This alone would already lead to the exchange of air from inside the leaf to the outside. If the leaf furthermore has a higher temperature than the surrounding air, there will be an even larger difference between the vapor pressures inside and outside the leaf, which will lead to evaporation of water from inside the leaf to the outside. The VPD can therefore be considered the main driving force for transpiration. (Prenger & Ling, accessed 9.5.2012)

3.4.2 PPFD

Another factor to have an impact on the sap flow is the photosynthetic photon flux density (PPFD). The higher the PPFD, the higher the rate of photosynthesis in the leaf will be, which will also lead to an increase of the sap flow, since more CO_2 is bound which leads to an increased stomatal conductance and therefore to a higher transpiration of H_2O. Since, VPD and PPFD are the factors that affect sap flow the most, their impact has to be taken into account when calculating the carbon dioxide assimilation from the sap flow (Bresinsky et al, 2008).

3.4.3 Stomatal Conductance

Another factor affecting the sap flow is the conductance of the stomata. With a very low conductance no gas exchange between the leaf and the surrounding air can take place. Hence, no carbon dioxide can be bound and no water evaporated, the sap flow will be slowed down. Then again, with a very high conductance much water can be evaporated, which leads to an increase in the sap flow (Bresinsky et al, 2008).

3.5 Aims and Objectives

In this study the focus will be on the deduction of the net assimilation of carbon dioxide from the measured sap flow data.

The aims are to measure sap flow data and then calculate the conductance at different layers, the PPFD at different layers as well as the carbon dioxide concentration within the leaf at different layers and from there to calculate the assimilation of carbon dioxide of the whole stand and compare it with data from eddy covariance measurements. The final aim is to validate if sap flow data can be used to estimate the carbon dioxide assimilation of the trees in a stand.

4. Materials and Methods

4.1 Sites and Sampling

The sap flow data, used in this study, was measured on seven trees between the 1st of September 2011 and the 9th of September 2011. After the 9th of September five more trees were added to the measurement system so that between the 9th of September 2011 and the 28th of October 2011 twelve trees were included in the study. The used trees were all Norway spruce growing in Skogaryd, a field site in Southern Sweden between Vänersborg and Uddevalla (approximate coordinates 58.368N; 12.142E). The field site consists of three smaller sites, with different measurements running since 2006. The trees included in this study were all growing on peat soil. The whole plot is 8100m^2 and the trees in this area are mostly Norway spruce (82% of total basal area) with some pine (13%) and birch (5%) trees. Since the majority of the tree population is Norway Spruce, only this species was selected for measurements. The selected trees were as evenly distributed as possible, as can be seen in figure one, at the south-west side of the mast situated in that square of 90 times 90 m, so that they would be within the footprint area of the tower equipped with Eddy covariance instrumentation. Additionally they were selected by their size to represent the frequency distribution of size classes within the whole plot.

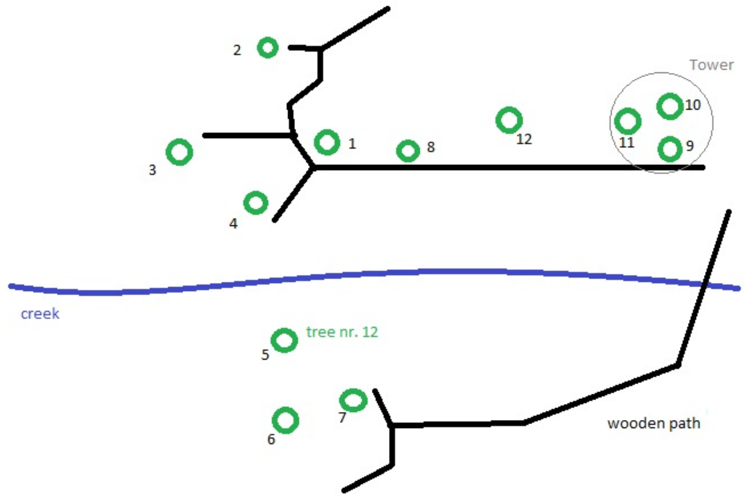

Figure 2: Distribution of selected trees (green) with wooden paths (black) the mast (grey) and the small creek passing the area (blue)

The intention was to set up all measurement systems at the same height of ca. 1,4 m, though due to irregularities in the bark or already installed systems for other measurements, it was not possible to use this height for all trees. Therefore, the system has been installed in the lowest part of the tree, over 1,4 m, that was suitable. Furthermore, the systems were all installed on the northern side of the trees, minimizing effects by heating from the sun.

The used biometric data, such as stem diameter was measured between June and October of 2010. In 2010 the stand was thinned with mostly spruce and birch being taken away.

4.2 Used Gear

The measurement system used to conduct this study was the Cermak Sap Flow System (EMS 51, EMS, BRNO), which was connected to a data logger, the measurement module can be seen in Figure 3. The program used to analyze the raw data was the software provided by EMS BRNO called Mini32. Afterwards the data was further processed with Microsoft Excel.

4.3 Theory

The EMS 51 system is based on tissue heat balance, which in general means that a section of the stem is heated "from the inside by an electric current" (J.Cermak, 2004) which can then pass through the tissues. Since the heat cannot pass through the bark in large amounts, it is more evenly distributed inside the xylem tissue and the change of the measured current can be directly related to the sap flow (J.Cermak, 2004).

In this specific system, four electrodes are inserted into the tree stem, each one being 25 mm wide and 1 mm thick and 8 cm long with usually around 6 cm being inserted into the xylem. Three of them are inserted parallel to each other with a distance of 2 cm between them; the fourth electrode is inserted 10 cm lower than the three others. A needle is then inserted into every electrode. The needles in the three upper electrodes are heated electrodes whereas the lower needle works as a reference electrode. The output signal by these electrodes is in mV representing the temperature difference between the heated and the reference electrodes (www.emsbrno.cz, accessed 9.5.2012). The whole setup can be seen in Figure 3.

Figure 3: EMS 51 system, first part showing the inserted steel electrodes inserted in tree trunk, second part showing the heated and unheated needles inserted in the electrodes, third part showing the measurement module connected to the needles and electrodes. (Photo by: Anke Hartmanns)

4.4 Mathematical background

The module connected to the needles keeps the temperature difference between the heated and the non-heated electrodes at 1 K. The outgoing signal [mV] is then stored and further processed in the connected data logger.

4.3.1. Sap Flow

Here the following formula is used to calculate the sap flow rate Q [kg s^{-1}] from the heat input power P [W = J s^{-1}],

$$(1) \qquad P = Q * dT * c_w + dT * z$$

Where dT [°C] is the temperature difference in the measuring point, c_w [J kg^{-1} $°C^{-1}$] the specific heat of water and z [W $°C^{-1}$] the coefficient of non-xylem heat losses.

Equation 1 can then be converted into the following,

$$(2) \qquad Q = \frac{P}{c_w * d * dT} - \frac{z}{c_w}$$

With d [cm] being the effective width of heating space (5,5cm). The first term of this equation equals the heat conducted by sap flow, whereas the second term equals the non-xylem heat losses.

4.3.2 Up Scaling

This way the sap flow is calculated in kilogram per hour and centimeter circumference. The baseline then is subtracted, which means that the values measured around one o'clock in the night are being set as zero, since the data still includes values that result from heat losses from the heated space by diffusion and thereby suggest a non-existent sap flow. Afterwards the values are being up scaled to the whole tree using the circumference and the phloem thickness. The equation used is the following,

$$(3) \qquad Q_{tree} = Q * (C - 2 * \pi * P)$$

With C [cm] being the tree circumference and P [cm] the phloem thickness. The resulting value for the sap flow per tree is further on transformed into kilogram per day and tree.

To proceed, the biometrical data is used and all the trees of the stand are grouped into classes, dependent on circumference. Each class is, following the method described by J.Cermak, two centimeters broad.

All Q_{tree} for each day are then collected and the mean for each tree in the time span between the 26th of August 2011 and the 9th of September 2011 and between the 9th of September 2011 and the 27th of October is calculated. These two time spans result in the fact that some trees were connected later than others and therefore there is less tree data available for the first period, which has to be taken into account. For these two time spans the means, of every trees measured on, are summed up.

The means of the tree sap flow values are also plotted against the circumference; showing a relationship between the two factors. A linear regression is then done for both time spans, which will be used during the up scaling process to stand level.

This regression, dependent on the circumference and the mean sap flow of every tree class, is then used to calculate the mean sap flow performed by one tree in the specific category. By multiplying these values with the actual number of trees in that class and summing these values up, the stand sap flow of one day can be calculated. Afterwards the value for the whole stand per 30 min is calculated and related to the ground area.

4.3.3 Calculation of the Net Assimilation

With these data and data on the relative humidity, air temperature, photosynthetic photon flux density (PPFD) (P. Weslien, unpublished data), the air pressure and the vapor pressure deficit (VPD), a conductance for the stomata can be calculated using the following equation,

$$(4) \qquad g_c = \frac{Q_{forest} * AirP}{VPD}$$

Using Lambert-Beers Law the PPFD at different layers of the canopy can be calculated,

$$(5) \qquad PAR_n = PAR * e^{-k*LAI}$$

With k being a constant value of 0.45 (L. Tarvainen, unpublished data) In this case the canopy was divided into five different layers of one square meter except for the top layer, only being 0.6 m since the whole leaf area index (LAI) amounted 4,6. In the following a relative reference conductance at the different layers can be calculated using the following equation:

$$(6) \qquad g_{ref} = 1 - \exp(PAR * \alpha)$$

Since more information about the closing behavior of stomata is available, this equation is altered to the following:

$$(7) \quad g_{ref} = (0{,}28 + 0{,}72 * (1 - \exp(PAR * \alpha)) * l$$

The 0,28 are derived from the fact that the stomata do not close totally when no light is available but remain 28% open (L. Tarvainen, unpublished data). Since the data is relative the data should stay between zero and one and is therefore multiplied with one minus 0.28 = 0.72. The α is a value representing the response of stomata to light, since the stomata in the lower canopy levels are more sensitive to light (L. Tarvainen, unpublished data). The factor l in the end is a factor for the maximum conductance of the stomata at light saturation and a VPD of one, and is also different for every canopy layer.

In this stand the values for α are, from the top to the lowest layer: -0.0081; -0.0145; -0.0106; -0.016; -0.0398, and for l, also from top to lowest layer: 0.107; 0.098; 0.093; 0.096; 0.086.

The resulting values for the conductance of each canopy layer are then integrated and compared to the canopy conductance calculated, based on sap flow for the whole tree, using equation 4. By comparing these two values a scaling factor can be derived to calculate the real conductance (gs) of each canopy layer.

Further on the c_i/c_a ratio at the different layers dependent on the PPFD values, measured at the different levels, and the VPD values is calculated. Within this calculation the same average values for the three top layers are used and two other ones for the two lower layers. The measured ratios are plotted against the different PPFD values to predict the change of the c_i/c_a ratio with increasing PPFD. The c_i/c_a data used for theses regressions was obtained from measurements done by L. Tarvainen. The thus received regression and the PPFD already calculated for the different layers are then used to calculate the c_i/c_a ratio at the different layers. By the calculated c_i/c_a ratio and the measured c_a the c_i can be calculated.

Finally using Fick's Law:

(8) $$A = g_s * (c_a - c_i)$$

The assimilation conducted by the different layers can be calculated and summed up to represent all canopy layers together.

5. Results

The measurements of the sap flow within the trees showed the following results:

5.1 Sap Flow

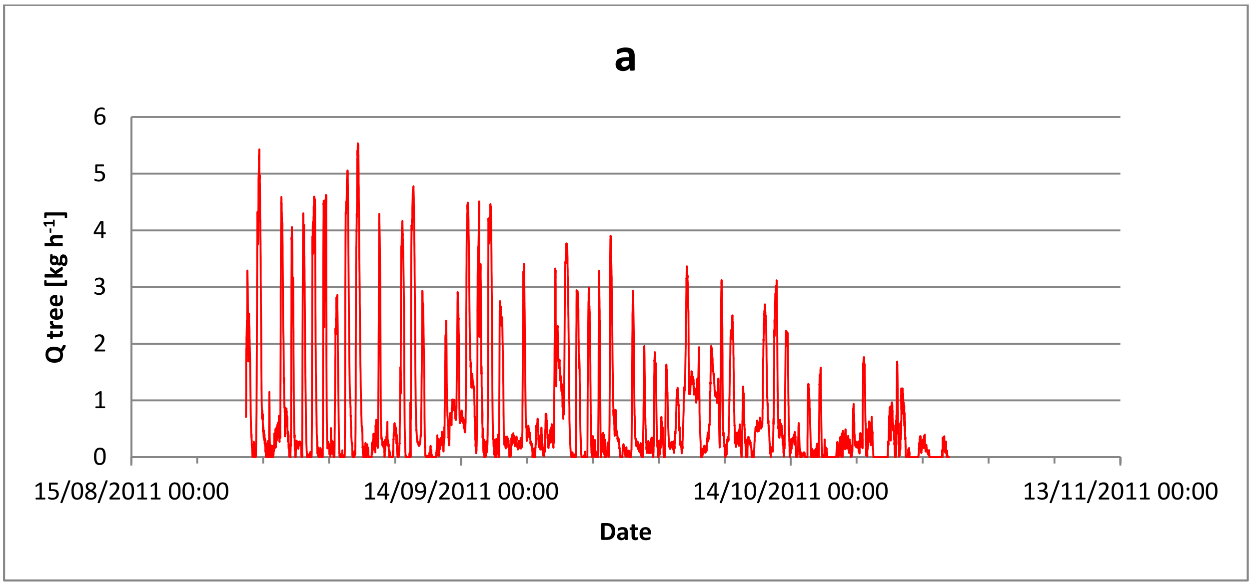

Figure 4a: Sap flow (Qtree) in kilogram per hour for tree number one, plotted against the date.

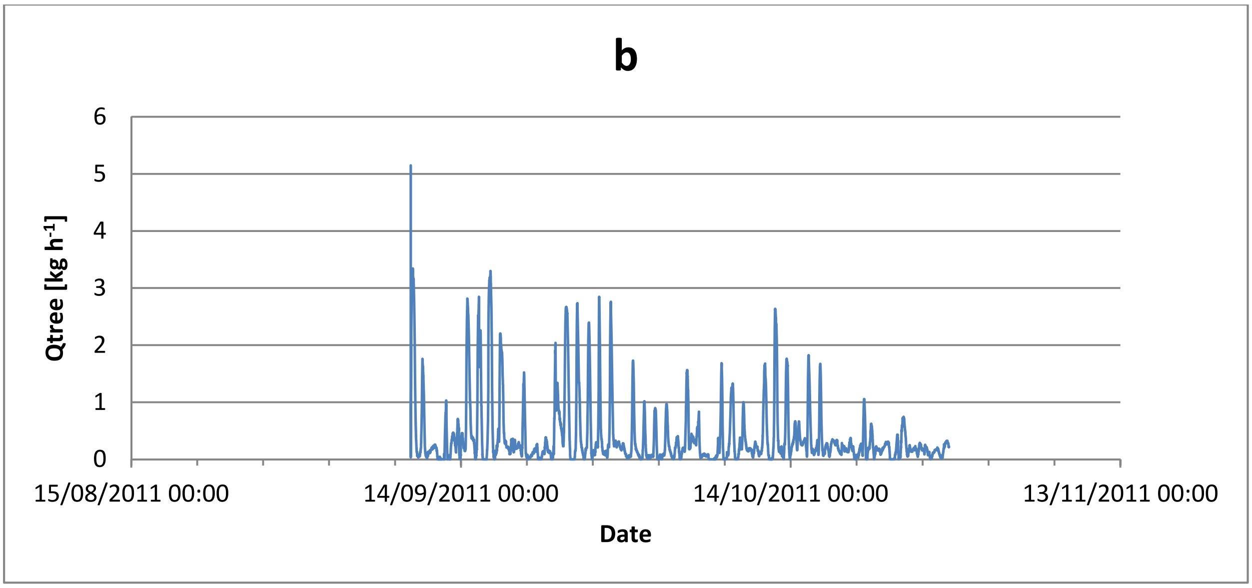

Figure 4b: Sap flow (Qtree) in kilogram per hour for tree number two, plotted against the date.

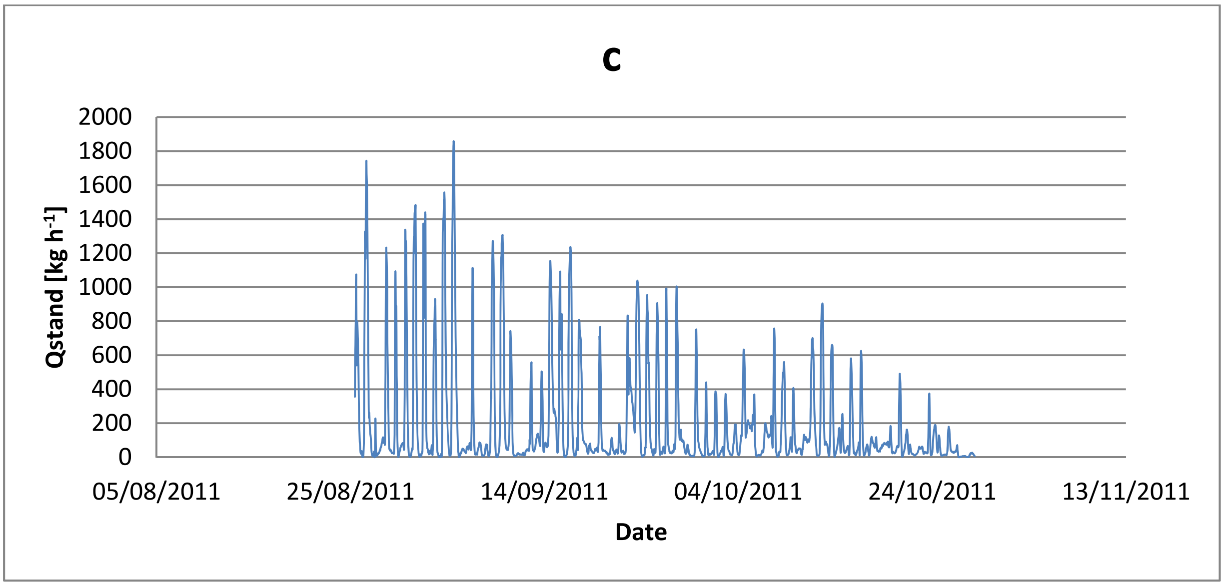

Figure 4c: Sap flow of the whole stand (Qstand) in kilogram per hour plotted against the date.

Figure 4a and 4b show the sap flow in kilogram per hour for one tree each. Whereas, tree one was already connected the first of September, tree two was connected to the measuring system the ninth of September. Both trees show a decrease of sap flow from the start of the measurement till the end of the measuring period. It can also be seen that the sap flow is dependent on the time of the day since every peak represents one day. On some days within the measurement very low or no peaks are shown whereas on other days quite high peaks can be observed. It can also be seen that the sap flow during night times is zero or very low. In general, both trees show the same pattern of low and high peaks with tree two in general showing lower values. Figure 4c shows the sap flow in kilogram per hour for the whole stand (Qstand). It can be seen that the whole stand shows the same pattern as the two single trees with decreasing values towards the end of the measurement and peaks during the daytimes.

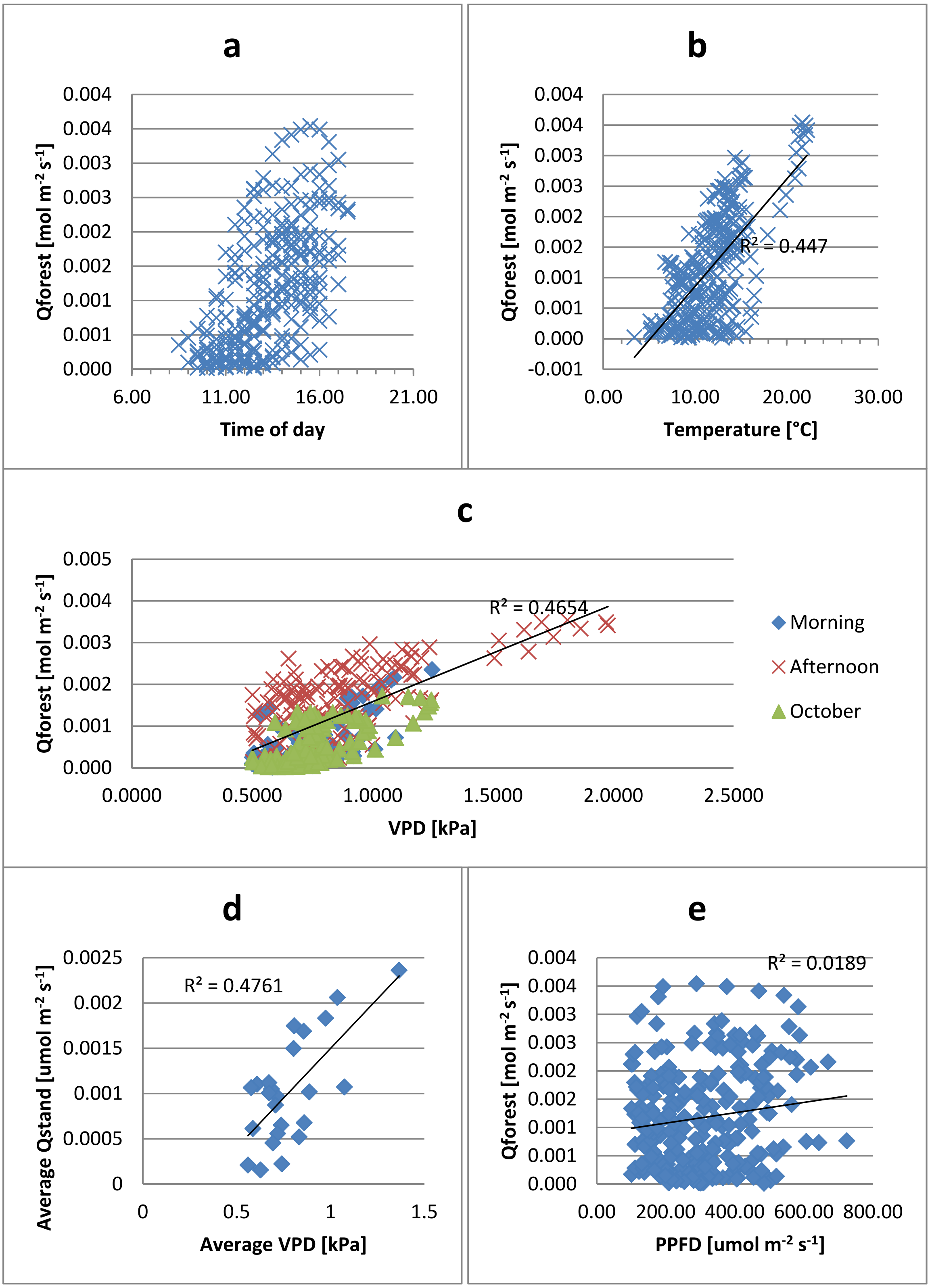

Figure 5 Sap flow in umol per square meter and second plotted against different environmental factors; VPD in kPa, Temperature in °C and PPFD in umol m-2 s-1 and average sap flow plotted against average VPD

In Figure 5 the sap flow of the stand can be seen in dependency of several different environmental factors. In the first part (a) the sap flow is plotted against the time of day and it can be seen that the values are highest between three and four o'clock in the afternoon decreasing towards the evening. In the second part (b) the sap flow is plotted against the temperature. In this case a quite strong dependency of the sap flow on the temperature can be seen. In part c the sap flow is plotted against the VPD in the morning (blue), afternoon (red) and October (green). A dependency between the sap flow on the VPD can be seen since the sap flow increases with the increase of the VPD. Additionally it can be seen that the October data is much lower than the afternoon data and more similar to the morning data of the whole period. In the fourth (d) part the average daily sap flow is plotted against the average daily VPD. Here, too, a dependency of the sap sap flow on the VPD can be seen, since the average Qstand increases with the average VPD. In the fifth (e) part the sap flow is plotted against the PPFD. In this case no strong dependency of the sap flow on the PPFD can be seen since the data is quite scattered.

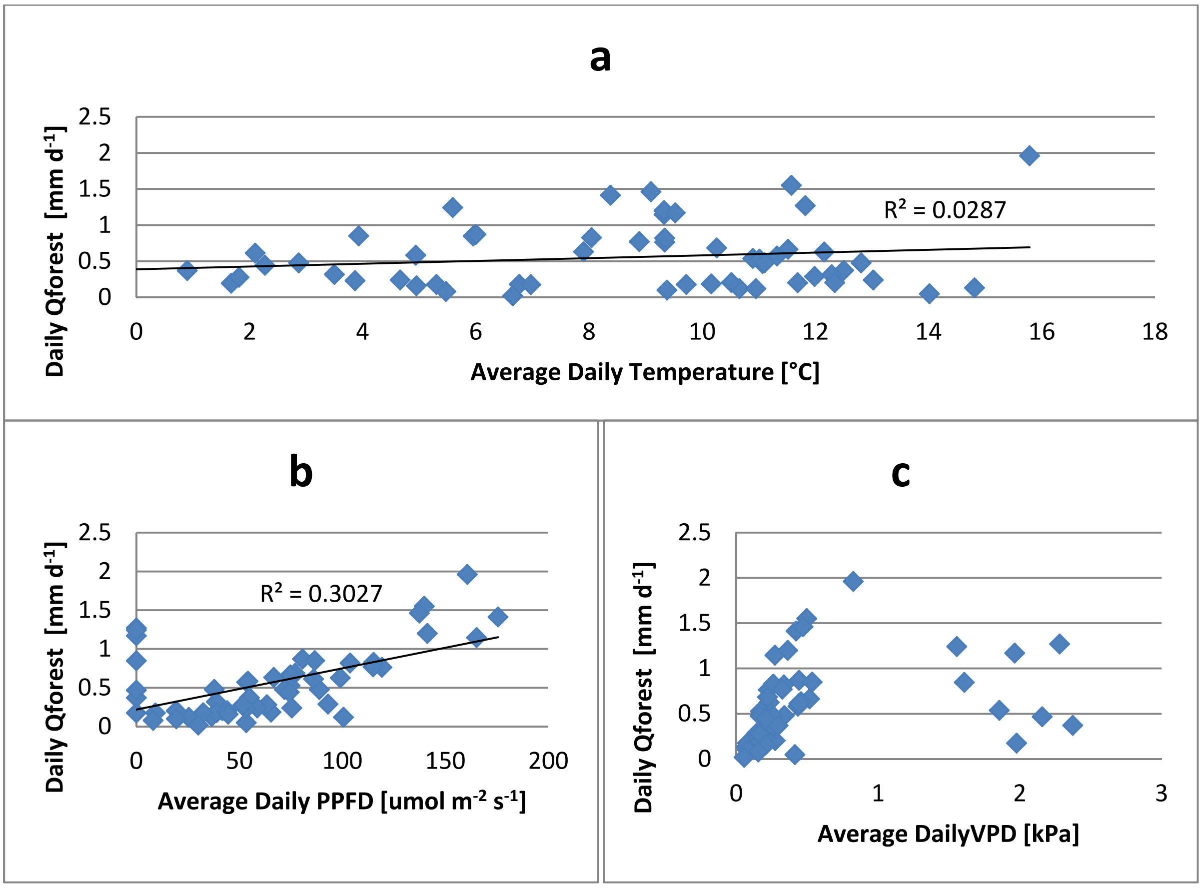

Figure 6: Daily sap flow in mm per day plotted against the average daily temperature in °C, average daily PPFD in umol per square meter and second and average daily VPD in kPa, measured from the 1st of September 2011 until the 27th of October 2011.

Figure 6 shows the daily sap flow of the whole forest plotted against the temperature, the PPFD and the VPD. Additionally to Figure 5 it can be seen in Figure 6 that there is a slight relationship of the daily sap flow and the temperature though it is less pronounced than in

Figure 6. In part b of Figure 6 it can be seen that when looking at the average daily PPFD there is a relationship between it and the daily sap flow. The same accounts for the average daily VPD which shows the same relationship as in Figure 5d but including the data points with a higher average daily VPD which then show a decline of the daily sap flow from an average daily VPD of 1,6 on.

5.2 Canopy Conductance

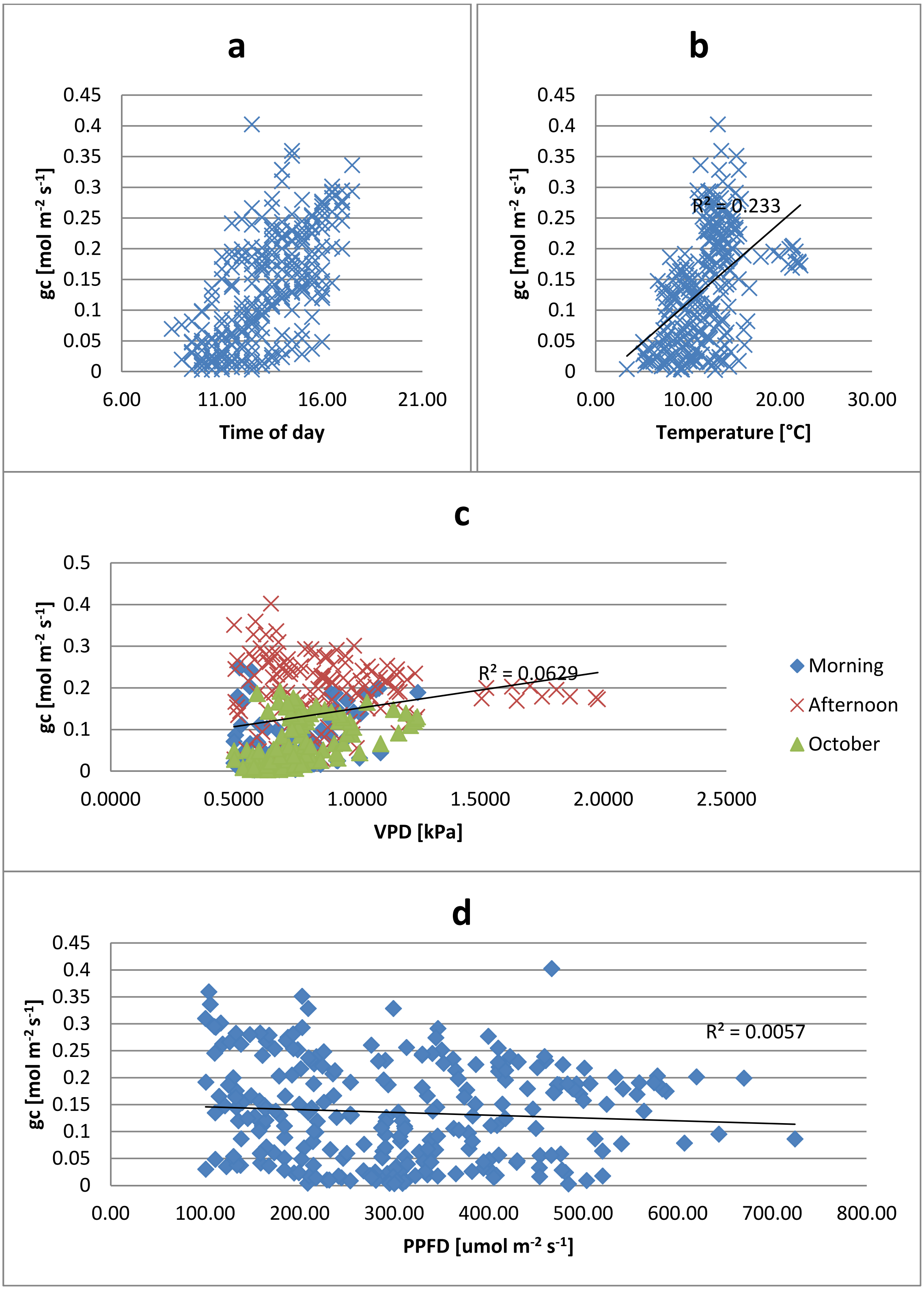

Figure 7: Canopy conductance (gc) in mol per square meter and second plotted against several environmental factors; time in days, VPD in kPa, temperature in °C and PAR in umol per square meter and second.

Figure 7 shows the dependency of the canopy conductance on different environmental factors. The filters used for this figure were for the PPFD ≥ 100 umol m^{-2} s^{-1} and for the

VPD ≥ 0,5 kPa. The values below these were considered to be unreliable due to technical reasons. Part a shows the dependency on the time of day. It can be seen that with the proceeding of the day the conductance first increases and reaches its highest values around midday. Part b shows the dependency on the temperature. It can be seen that with increasing temperature the conductance increases as well with the highest values measured around 16 °C. Part c shows the canopy conductance plotted against the VPD. The values are divided into morning values (blue), afternoon values (red) and October values (green). Here it can be seen that there is a dependency of the conductance on the VPD. It can also be observed that the afternoon data is usually higher than the morning data. The October data also shows lower values than the values for the rest of the measurement. Part d shows the conductance plotted against the PPFD. Since the data is quite scattered no relationship between the conductance and the PPFD can be distinguished.

5.3 Carbon Dioxide Assimilation

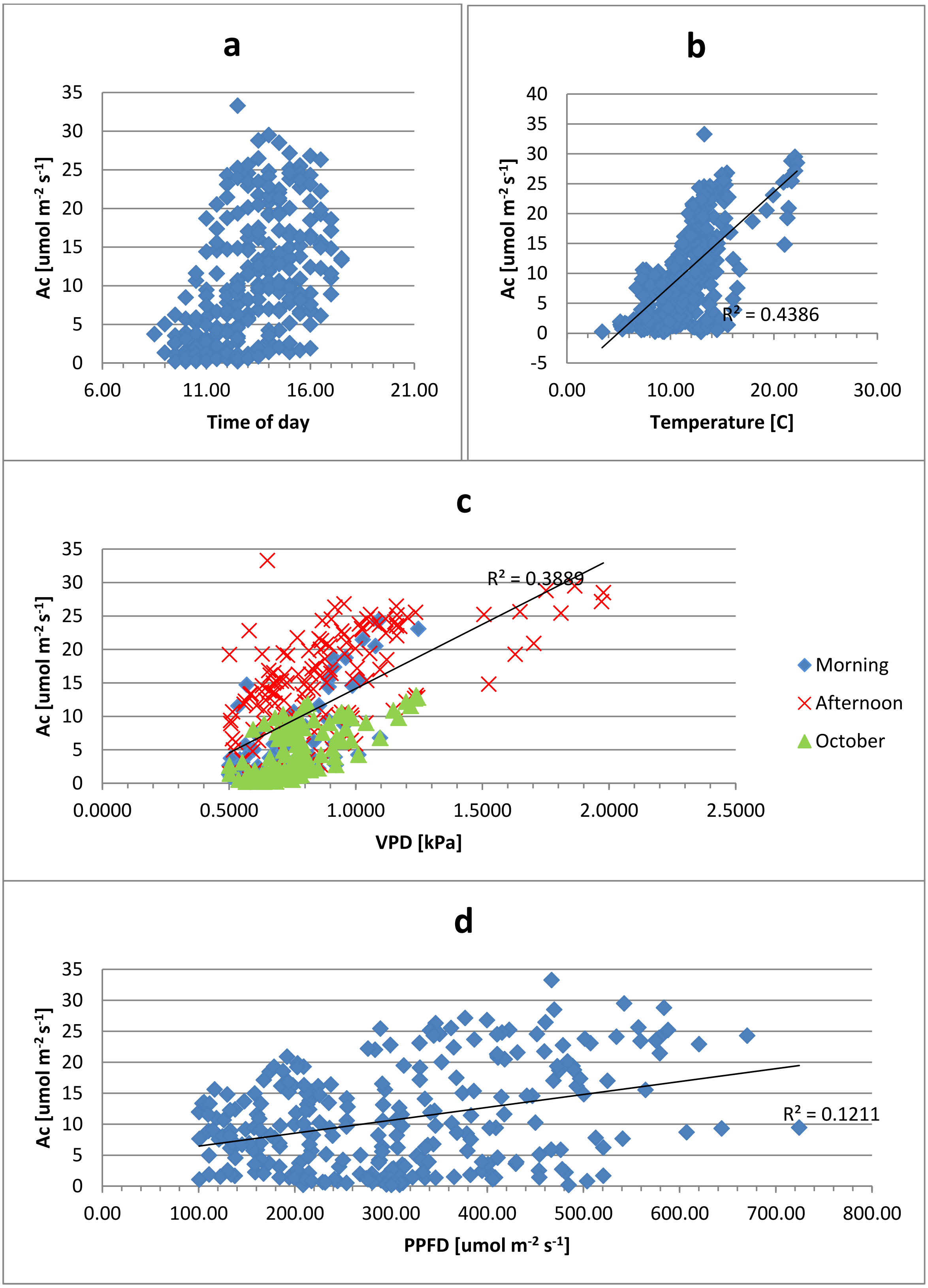

Figure 8: Canopy carbon dioxide assimilation (Ac) in umol per square meter and second plotted against time and different environmental factors; Temperature [°C]; vapor pressure deficit (VPD) in kPa and photosynthetic photon flux density (PPFD) in umol per square meter and second

In part a of figure 8 the canopy assimilation of carbon dioxide is plotted against the time of day. As well as in Figure 7 the filters used for this figure were for the PPFD ≥ 100 umol m^{-2} s^{-1} and for the VPD ≥ 0,5 kPa. The values below these were considered to be unreliable due to technical reasons.

It can be seen that the highest values are being reached between two and three o'clock in the afternoon with lower values before and after. Part b shows the carbon dioxide assimilation plotted against the temperature. In this case a strong relationship can be seen, since the assimilation increases with increasing temperature. Part c shows the carbon dioxide assimilation plotted against the vapor pressure deficit (VPD) for mornings (blue), afternoon (red) and October data (green). It can be observed that the assimilation of carbon dioxide in general shows a strong dependency on the VPD but with significant differences between the morning, afternoon and October datasets. The afternoon data is in general higher than the morning data and the October data shows very low values, comparable to the morning data of the measuring period.

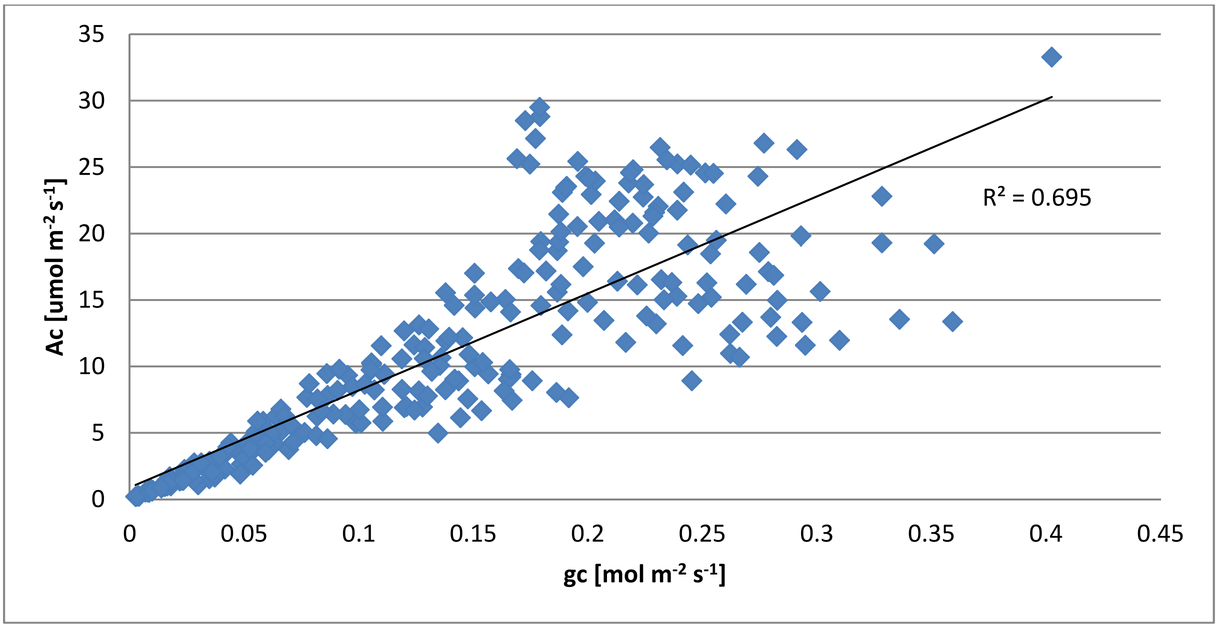

Figure 9: Assimilation of carbon dioxide based on sap flow data in umol per square meter and second plotted against canopy conductance in mol per square meter and second.

Figure 9 shows the assimilation of carbon dioxide (Ac) plotted against the canopy conductance (g_c). It can be seen that the assimilation of carbon dioxide is very strongly dependent on the canopy conductance, which is not surprising since in Equation 8

(Fick's Law) it can be seen that the calculation of the assimilation is partly based on the conductance.

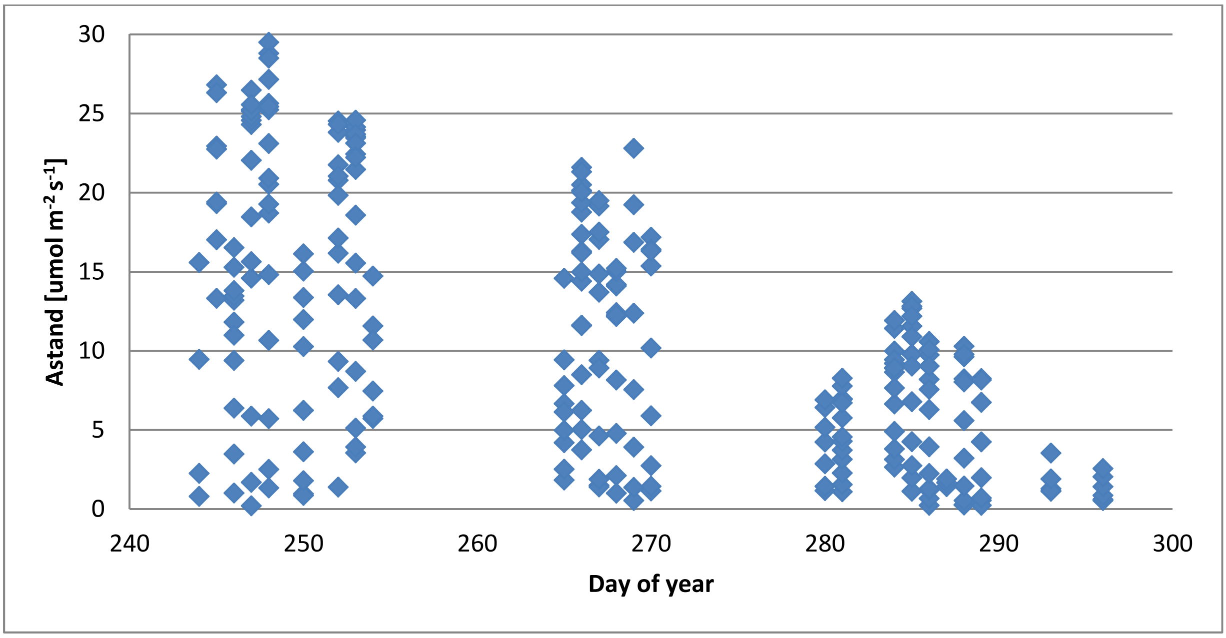

Figure 10: Net assimilation in umol per second and square meter dependent day of the year, measured with the EMS 51 system.

Figure 10 shows the net assimilation of carbon dioxide by the whole stand dependent on time measured with the EMS 51 system. It can be seen that the values for the assimilation are higher in the beginning of the measurement than at the end. In the beginning they go up to 30 umol per second and square meter whereas in the end the only reach three umol per second and square meter. In between days with high assimilation days with no or very low assimilation can be seen. Some days no values are plotted because either the VPD or the PPFD were below the filters mentioned in part 5.3 and 5.4.

5.4 Eddy Covariance

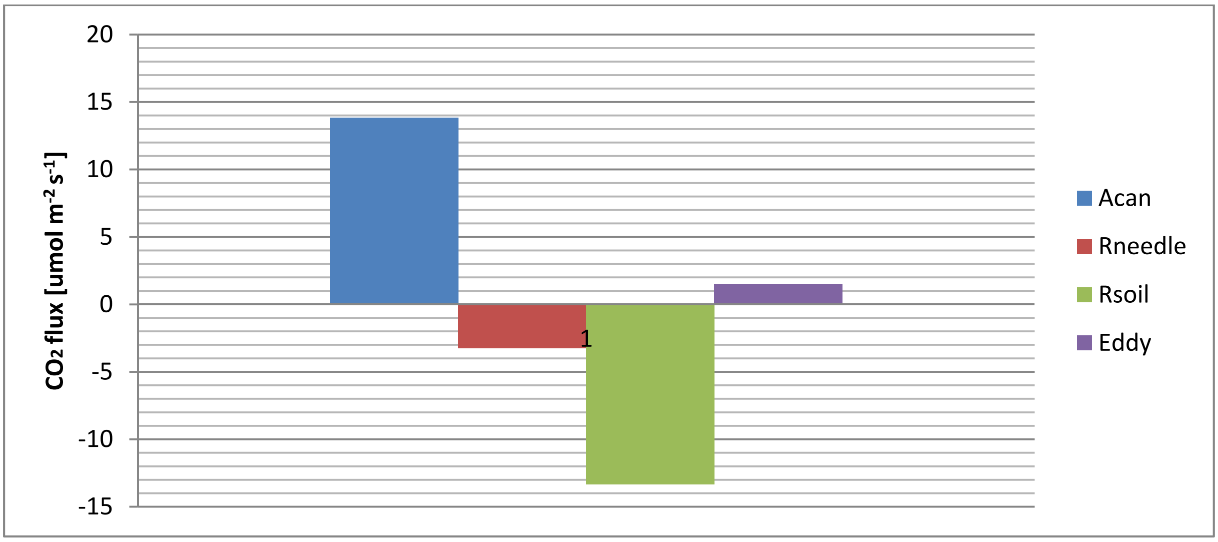

Figure 11: Mean Carbon dioxide fluxes measured September 2011; in umol per square meter and second

Figure 11 shows the mean carbon dioxide fluxes of September 2011. The first column represents the flux is based on the sap flow data, the second one is the average needle respiration of the different canopy layers including the respiration of the stem per unit ground area. It was calculated with data for needle respiration, (L. Tarvainen, unpublished data) and the assumption that the stem respiration "contributes to 9% of the total carbon loss by the ecosystem respiration (Zha et al., 2004). The third column represents the average soil respiration for September, based on data from 2008 (A. Nousratpour, unpublished data and the fourth column represents the average carbon dioxide flux based on the eddy covariance technique. It can be seen that the values for the data based on the sap flow measurements is the highest. The data for the two respirations is very negative whereas the eddy covariance data shows a very low but positive value. In this graph a positive flux means that CO_2 is taken up and a negative one that it is being released by the ecosystem. The assimilation of CO_2 by the canopy is related to the eddy covariance data by the Eddy flux being the assimilation of CO_2 minus the respiration of the stem, needles and soil.

6. Discussion

6.1 Dependency of Sap Flow on Various Factors

The data plotted in figure 4a and b shows a decrease of sap flow within the trees and figure 4c within the whole stand, with the proceeding of the measurement. Since the measurements were conducted with the start of autumn the PPFD, as it can be seen in figure 12, is decreasing with time as well. Since the photosynthesis and the stomatal conductance is dependent on the PPFD and through the conductance also the transpiration, this decrease of radiation could be a reason for the overall decrease of the sap flow. On the other hand figure 5 and 7 show that neither the sap flow nor the canopy conductance are really reliant on the PPFD, although a slight increase of the sap flow with increasing PPFD can be observed. This observation is supported by Figure 6 showing a stronger tendency for the daily sap flow to be dependent on the average daily PPFD.

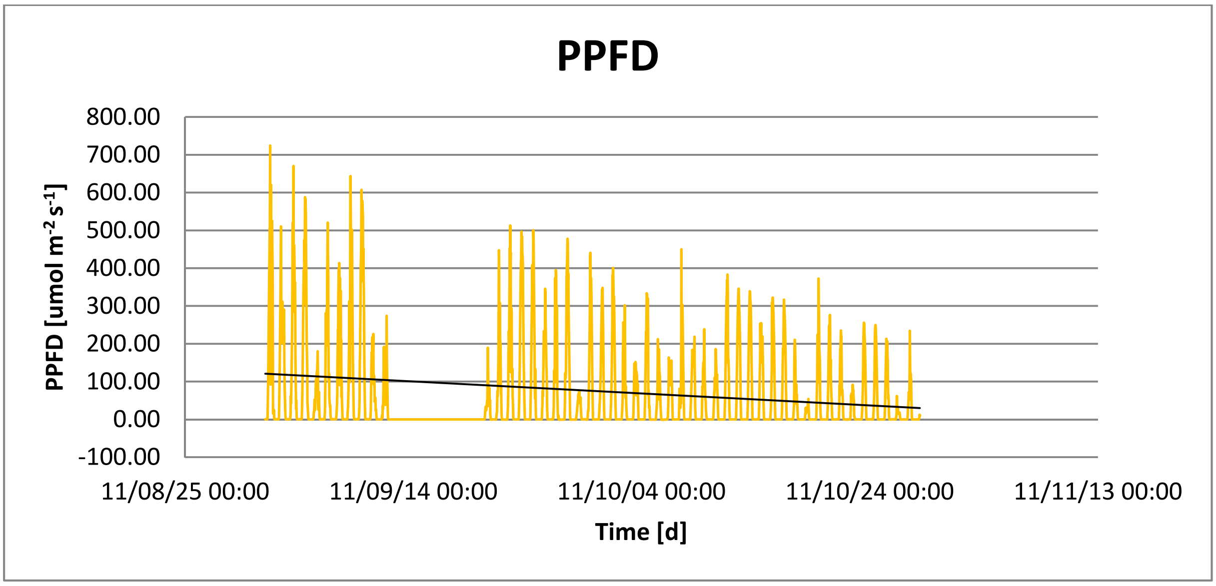

Figure 12: Photosynthetic active radiation (PAR) in umol per second and square meter, dependent on time in days

Another reason for the decrease of the sap flow could be the temperature. It has been shown by Alexander at al. (1995) that the photosynthetic activity is not only dependent on the PPFD but also on the temperature. In figure 13 it can be seen that the temperature is decreasing with time as well. Since Neilson et al. (1972) have shown that with decreasing temperature the photosynthetic activity and therefore the assimilation of carbon decreases, this could be another reason for the lower sap flow within the trees towards the end of the measurements, since less CO_2 is assimilated, which means that the stomatal conductance will be lower and less water vapor can pass through them, leading to a lower transpiration and thereby a lower sap flow. In Figure 5 and 7 a dependency of the sap flow and the conductance on the temperature can be seen which might indicate that temperature is an important factor although the causal factor might also be the VPD with the temperature just co varying with the VPD. Supporting the results shown in these two figures are the results shown in Figure 6. It can be seen that the daily sap flow is associated with the average daily temperature, as well. Though the relationship in Figure 6 is not as pronounced as in Figure 5 and 7, one has to account for the different data sets used for the different figures, as for Figure 6, data has been used that has been, due to extreme VPD values and other factors such as low light, considered to be not very reliable, as mentioned in part 5.2 and 5.3.

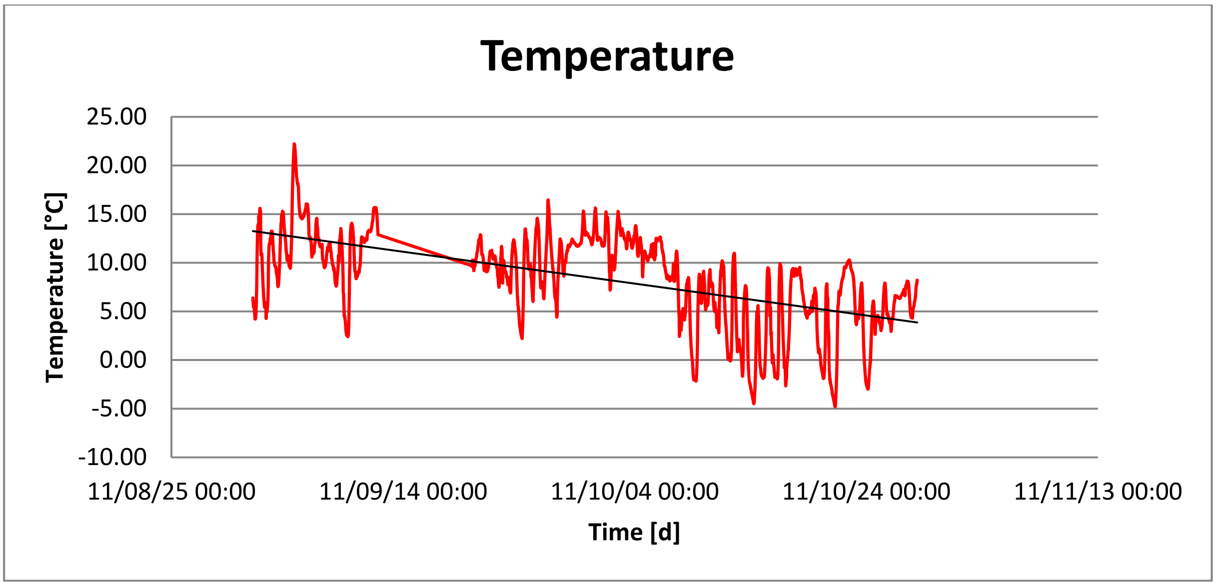

Figure 13: Temperature in °C dependent on time in days.

Yet, the transpiration of water by the leaf is not only dependent on the temperature but as Day (2000) has shown, also on the VPD. In figure 14 it can be seen that the VPD, as well as the PPFD and the temperature slightly decreases with time, which leads to less transpiration from the leaf and thereby to a lower sap flow. This assumption is supported by the data shown in Figure 5 which shows a dependency of the sap flow on the VPD and the data shown in Figure 6c, which shows the same distribution of the data as in Figure 5d, but includes more data points; from earlier measurements when additional data for the necessary calculations was not available; which make the relationship less pronounced.

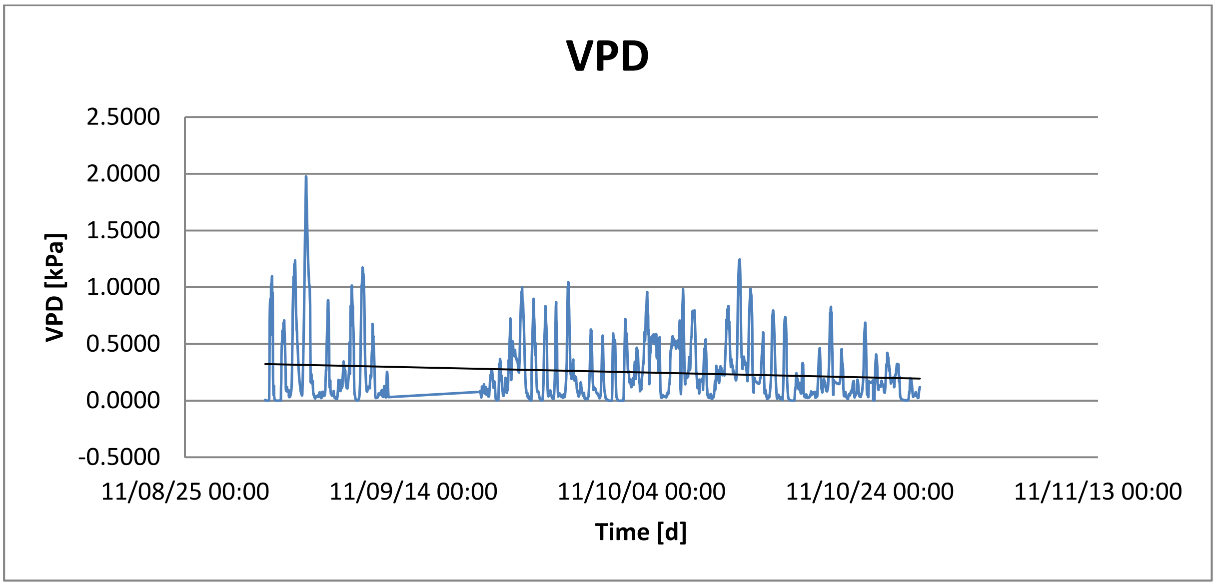

Figure 14: Vapor Pressure Deficit (VPD) in kPa dependent on time in days

In general it can be said that all three factors, as well as others not mentioned here, indirectly affect the sap flow by affecting the transpiration by the leaf. Though, these three factors affect the sap flow in different intensities. In Figure 5 it can be seen that the dependency of the sap flow on the PPFD is rather weak compared to the dependency on the temperature and the VPD.

6.2 The EMS 51 Method

Since the sap flow, which is the basis to the calculations, is affected by the factors mentioned above, the calculated assimilation of carbon dioxide will be as well. The dependency of the assimilation of carbon dioxide has been accounted for in the equations that have been used. In the last equation to calculate the net assimilation of carbon dioxide the conductance is used which has been calculated dependent on the VPD, air pressure and PPFD. Additionally to that the internal carbon dioxide concentration, which is used to calculate the assimilation, has been calculated dependent on the VPD and the PPFD. Since the assimilation of carbon dioxide is directly dependent on the conductance, which can be seen in Figure 9 and the conductance is mainly dependent on the VPD and the temperature and only slightly on the PPFD a decrease of assimilated carbon dioxide with time can be expected and is to be observed.

In Figure 10 it can be seen that the assimilation is highest during the day time. This can be explained by the conductance being strongest during days and the VPD mostly being highest during day time, as well as the temperature being closer to the optimum temperature for photosynthesis of 11,3 °C to 24,5 °C (Roberntz, 2000).

6.3 Comparing EMS 51 and Eddy Covariance Data

It was planned to validate the data based on sap flow measurements with data from eddy covariance measurements. As it can be seen in Figure 11 the respiration data for the measuring span is quite high and would nearly outbalance the assimilation values. Since the eddy covariance data includes the respiration of the ecosystem the data received from these measurements is very low and therefore, cannot be used to validate the data calculated on basis of the sap flow measurements. What one can see when using a constant value for the soil, needle and stem respiration is that both datasets range within the same dimensions. Therefore the respiration datasets are added up and then, since they are negative added to the assimilation data or subtracted from the eddy covariance data.

To compare these dataset with each other one would need an additional set of data about half-hourly respiration data since with a constant value, changes of transpiration within the days and weeks are not taken into account.

6.4 Shortcomings

The data received by the conducted measurements was in some cases not to be used for any further analysis since the weather conditions had been in a way that made the data unreliable, such as low VPD or low radiation. To receive a more reliable data set one would need to start the measurement in the beginning of spring and proceed measuring during the whole summer until the end of autumn since then long time trends could be taken into account when, e.g. setting the baseline for the sap flow data, as this is a source for initial and great error. In this study the baseline might be one of the main sources for errors since it was done without any weather data available and no long term trends to be taken into account. Especially towards the end of the measurement the setting of this baseline got very inaccurate since it was mostly hard to distinguish the peaks of the days from the night time data, since the sap flow was very low at this time of the year. Another shortcoming is that the eddy covariance data is including the respiration by the ecosystem, as already mentioned above. To compare the eddy covariance data with the sap flow data the respiration was tried to be subtracted but since only monthly data about the soil and needle respiration was available the values didn’t account for daily changes of these factors and were not used in this study. To make the data from the eddy covariance measurements better comparable to the sap flow based data, one would need to measure respiration of the soil and needles on a more regular basis.

7. Conclusion

Although the data used for this study might not be completely reliable it can be seen that the two different systems of measuring lead to results that are of similar magnitude. Therefore the established way to scale from the sap flow per tree to the whole stand and calculating carbon dioxide assimilation values from these data seems to be valid. With adding half-hourly data of respiration to the eddy covariance data one might even see that the resulting data are very similar to the ones based on the sap flow measurements. The used system can therefore be seen as an alternative to the eddy covariance measurements when it comes to measuring the carbon assimilation conducted by an ecosystem during a sufficiently long time span in the warmer season of the year. This way of measuring the carbon assimilation might be useful in areas like the tropics where trees grow much higher and towers with eddy covariance measurements might as well as for other reasons be difficult to install and knowledge about carbon assimilation is important as these forests and their degradation and deforestation might play an important role in the proceeding of global climate change.

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