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Hartheim scots pine plantation

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Soil Moisture Variation and Plant Water Stress at the Hartheim Scots Pine Plantation

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Summary

During two measurement campaigns in 1992 (the Hartheim Experiment HartX- and an additional experiment in autumn), measurements of soil moisture were carried out in a *Pinus sylvestris* stand at Hartheim on the Oberrhein. Several methods were used to determine soil water status. They were compared in terms of suitability for estimating stand evapotranspiration (ET) via soil water depletion. Measurements of tree water potential suggested that conductance of the trees was affected by soil water depletion during the period of the HartX campaign in spring 1992. We interpret the observations to indicate a lesser influence of soil water availability on tree transpiration during the autumn experiment.

Eddy correlation and xylem sapflow measurements provided reference ET values with which to compare the stand ET calculations based on soil moisture measurements. Profile measurements of soil moisture showed that particularly in springtime when the lower soil layers are saturated with water, the water transport from depths below the major rooting zone is a very important factor affecting evaluation of stand ET. Decreases in soil water storage may be determined best with permanently installed soil moisture sensors such as used in tensiometric or TDR measurements that provide high resolution of changes over time.

1. Introduction

The most important linkage between terrestrial vegetation and the atmosphere operates via the partitioning of absorbed radiation to either latent or sensible heat. This partitioning depends on the canopy conductance for water vapor which is

strongly influenced by the water status of the soil (Kelliher et al., 1993; Running, 1984; Shuttleworth, 1989; Wicke, 1988). Even very initial drying of the soil is sensed by the roots of woody plant species and signals are transported via the xylem transpiration stream to restrict canopy water use (Davies and Zhang, 1991; Tenhunen et al., 1994). To realistically assess water and energy fluxes in a forest stand, transpiration and canopy conductance must be viewed in terms of seasonal and annual fluctuations in soil water availability.

Among tree species naturally occurring in Europe, *Pinus sylvestris* is the strongest competitor in dry habitats (Ellenberg, 1978). In addition to changes in canopy conductance, the effects of water stress on *Pinus sylvestris* are many, including increased root mortality and turnover (Persson, 1980), decreased tracheid size and annual wood increment (Merkel, 1987), and decreases in sapwood stored water (Jansson and Halldin, 1979). The already well-documented production ecology of *Pinus sylvestris*, together with the unique meteorological situation of the Hartheim pine plantation, makes it a very valuable resource and natural laboratory for investigating the linkage between soil water and atmospheric energy exchange as well as the biological processes controlling this linkage.

It was, therefore, advantageous during the experiments to document soil water status and to define these conditions in the context of annual changes in water availability at this site. Furthermore, the long-term research potentials at Hartheim make it desirable that continuous automated monitoring of soil moisture be carried out with increased spatial resolution. This means that data records obtained with new methods must be compared with existing long-term gravimetric observations of soil moisture content to ensure the best continuity in site information. If lateral water fluxes and deep drainage are negligible at Hartheim (Hädrich and Stahr, 1992), then the changes in soil water storage over short periods should provide an estimate of water uptake by the plants and be related to latent energy flux.

In our investigation, we compared gravimetric, tensiometric, capacitive and time-domain-reflectometry (TDR) determinations of soil water use with evapotranspiration (ET) rates measured with 1) an eddy correlation installation, determining windspeed with a sonic anemometer and air humidity by means of a krypton hygrometer (SONIC), 2) a one-propeller Eddy correlation system (OPEC; Gay et al., this issue) and 3) estimated via sapflow measurements (Köstner et al., this issue; Granier et al., this issue). To extend information about the response of trees to water stress and to assess whether the pine trees were affected by water stress during the HartX campaign, additional measurements of xylem water potential, soil water content and xylem sapflow were carried out during summer 1993. The soil moisture measurements in 1992, especially for two periods in spring 1992 (HartX, from 11 to 23 May) and in autumn (8 September to 20 October), are discussed with respect to the apparent water status of the plantation trees.

2. Site Description and soil Properties

A general description of the experimental site (geographical coordinates: 47°56' N, 7°37' E, altitude 201 m above sea level) is given by Jaeger and Kessler (this issue). The development of the soil at the site has been determined by flooding of the Rhine River. On this extremely level site, flooding no longer occurs due to channeling of the Rhine. This has led to a decrease in ground water table to seven meters below ground level. Thus, for our

considerations deep drainage and capillary rise of groundwater are negligible.

Before being planted with pine trees in 1961 the upper of the two soil layers at Hartheim was ploughed and homogenized. The depth of the silty A_n-horizon varies between 15 and 80 cm with an average of 40 cm. The C-horizon consists mainly of alluvial gravel, which is sometimes interrupted by sandy veins. The root zone of the pine trees extends to an approximate depth of 35 cm (Schäfer, 1977), although our observations showed that some pine roots run along the silt/gravel interface. In locations with deep soil deposits, understory grasses were found to intensively root between 0 and 30 cm depth. The hydraulic properties of the upper soil imply a good storage capacity and hydraulic conductivity. But shallowness of the soil reduces the absolute soil water storage capacity to 80 mm (varying between 30 and 160 mm, assuming that field capacity is at 31.4 vol.% and the wilting point at 11.7 vol.%-Hädrich, cited in Garthe 1985). Trüby (1983) calculated soil water storage capacity between 73 mm and 81 mm for an area close to the experimental site with comparable soil physical properties. This low water storage capacity together with annual variations in climate conditions determine the onset of summer drought and the degree to which trees are subjected to water stress.

3. Methods

3.1 Gravimetric Determination of Soil Water Content (θ_g)

Gravimetric determinations of soil moisture were carried out daily from 12 to 22 May, averaging over the entire depth of the upper soil layer as summarized by Eq. 1:

$$\theta_g = \frac{\rho_s}{\rho_w} \cdot \int_{z=0}^{z_i} \frac{m_w(z) - m_d(z)}{m_d(z)} \quad (1)$$

θ_g is the volumetric soil water content of the profile, z_i the thickness of the A-horizon, m_w and m_d moist and dry weight of the sample, and ρ_s and ρ_w the bulk density of dry soil and water. The samples ($n = 10$ to 20) were taken randomly with varying distance to the trees from a small area of about 10 m^2 . This location was changed daily when a new set of samples was taken. For routine

monitoring the samples are taken every two weeks. Daily arithmetic mean value and standard deviation of volumetric soil water content were determined to obtain information about the spatial variability of soil moisture at the small plot scale. It was quickly established that short time changes in soil water were poorly detected with gravimetric methods because the spatial variability at the plot scale was large in relation to daily changes in soil water storage (see also 4.2). A comparison between meteorological ET estimates and soil moisture depletion was therefore only carried out with 'fixed sensors' as described in 3.2 to 3.4. Nevertheless, the gravimetric determinations are important for system characterization and serve as the reference method in soil moisture determinations.

3.2 Capacitive Determination of soil Moisture (θ_c)

A capacitive sounding system (Schenk, Vienna) measuring the relative dielectric value, D_r , surrounding the probe at a length of about 5 cm was installed 20 cm below ground level in the center of a tree row. By means of the mixing law, D_r can be expressed as the sum of dielectric values of the liquid, solid, and gaseous material which forms the soil (Roth et al., 1990; Heimovaara et al., 1994). D_r of the solid air is negligibly small and D_r for the solid phase can be treated as a constant due to its constant volumetric fraction. The relative dielectric value of soil water is the product of fractional soil water content and the dielectric constant D of water. Thus, total D_r of the soil increases with soil water content. The capacitive device was calibrated in the field by means of the gravimetric soil moisture measurements. Using data from a period of more than one year (March 1992 to August 1993), the entire range of soil moisture occurring at the site was sampled and included into the calibration curve. As such, the capacitive sensor does not measure absolute water content locally but provides a continuously recorded index for the gravimetric determinations while maintaining system integrity over the long-term. The site specific calibration curve function was determined as

$$\theta_{(f)} = \frac{f}{38.7707 - 0.1984 \cdot f} \quad (2)$$

where f is the output frequency of the instrument.

The soil moisture records during summer 1992 were taken in time steps of 10 minutes and summarized to hourly mean values for further processing.

3.3 Time Domain Reflectometry Measurements (θ_{tdr})

Similar to the capacitive method, time domain reflectometry (TDR) measures soil water content indirectly. Soil- D_r is determined by measuring the travel time of an electromagnetic wave along parallel wires which are inserted into the soil. The velocity of the wave depends directly on D_r of the soil surrounding the probe, which as explained in 3.2 is mainly determined by soil water content (Topp et al., 1980; Roth et al., 1990).

For the autumn experiment, five two-wire sensors (Campbell-Tektronix system) probing a soil layer from 0 to -30 cm were installed vertically into the soil. They were randomly distributed between the tree rows with a horizontal spacing of about 5 m to consider spatial variability in soil moisture. Three additional TDR-probes were installed horizontally (in depths of 5, 15 and 40 cm below the soil surface) to obtain the soil moisture time courses for different soil layers. The measurements of soil moisture with the TDR device were taken hourly.

3.4 Tensiometer Measurements (θ_t)

For profile measurements of the soil water potential, two tensiometers (UMS, Munich) were installed within a distance of less than one meter to the capacitive sounding system at the beginning of March 1992. The instruments registered the soil water potential at a depth of 20 and 40 cm with a time resolution of one hour. To make tensiometric results comparable to the other methods which were measuring volumetric soil moisture, we used a field desorption curve which converted soil water potential into volumetric soil water content. This relationship was obtained by nonlinear regression of volumetric soil moisture (θ_c) and soil water potential (ψ_s) recorded with the tensiometer in a depth of 20 cm. Infiltration events were excluded from this calculation. The converted data were smoothed by moving means over five hourly values to calculate the diurnal courses.

3.5 Calculation of Evapotranspiration from soil Moisture Measurements

To compare the soil water decrease with estimates of evapotranspiration based on Eddy correlation and sapflow data we calculated soil water reduction in time using

$$ET_{(\theta, dt)} = (\theta_{(t)} - \theta_{(t+1)}) \cdot dz \quad (3)$$

with ET evapotranspiration in mm derived from measurements of soil water reduction, $\theta_{(t)}$ fractional volumetric soil water content at time steps t and $t + 1$ and dz length of mean soil profile in mm. This approach initially assumes that waterflux at the interface between the upper soil layer and the gravel layer as well as tree water storage are negligible for the calculation of ET.

3.6 Xylem Predawn Water Potential (ψ_{pd})

The strong influence of changes in xylem predawn water potential (ψ_{pd}) on canopy conductance and on maximum transpiration rates of conifers has been observed in a number of investigations. To determine soil water availability to the pine trees, measurements of xylem predawn water potential and of gravimetric soil water content were con-

ducted during the course of summer 1993. Xylem water potential was measured with a pressure chamber (PMS P70, Corvallis). Four branches were sampled from the upper crown level from July to October 1993 once a week. During the HartX-campaign in 1992, ψ_{pd} was measured every two days from 13 to 19 May.

4. Results and Discussion

4.1 Soil Water Regime in 1992

Figure 1 illustrates the course of soil water content and precipitation during 1992. The time course of drying and rewetting was similar to conditions represented by monthly mean values of soil moisture from 1975 to 1990 (Kessler et al., 1988). As a result of high precipitation and restricted plant water use in winter, the maximum soil water content at field capacity was observed at the beginning in February and in March. Soil water depletion that began in April was surprisingly not affected by a longer rainy period at the beginning of June. This reflects an increased importance of interception during this time of the year. Due to low precipitation rates in early summer 1992, the plants were subjected to an extended period of low

Fig. 1. Daily precipitation (upper panel), gravimetric soil moisture (mean values ± 1 standard deviation) in comparison to monthly mean values (1975–1990) (lower panel) and capacitive soil moisture in relation to gravimetric mean values in 1992 (center panel). The dashed lines indicate field capacity (FC) and wilting point (Wp)

water availability from July until the end of August. This can be seen in the more or less constant soil moisture content close to the wilting point. The recharge of the soil water store began slowly at the end of August, interrupted by short periods with relatively high evapotranspiration rates (cf. Figs. 5 and 6). At the end of the year, field capacity was almost reached.

The total annual precipitation in 1992 amounted to 510 mm which was 20% less than the mean annual precipitation (647 mm) from 1978 to 1985 (cf. Jaeger and Kessler, this issue). This reduced precipitation input is apparent when soil moisture data for 1992 is compared with the long-term mean values (Fig. 1). From April to September, θ_g remained permanently below the monthly mean values. The maximum difference amounted to 7.8 vol.% in August.

During 1992, differences between θ_g and θ_c usually did not exceed one vol.% (Fig. 1). Since θ_g

averages over depth and θ_c is a point measurement the distribution of soil moisture in the rooting zone appears quite uniform for most of the time during the year. The greatest differences between the two values occurred at the beginning of October when θ_g reached 22.4 vol.%, while θ_c remained below 15 vol.% (cf. Fig. 5). Measurements of the vertical distribution of soil water with TDR indicated a strong gradient in soil moisture between a depth of 15 and 40 cm during this period. Due to reduced hydraulic conductivity at the end of the summer, it is likely that a wetting front was formed in the upper soil layer which was probably above the capacitive sensor at the beginning of October.

4.2 Soil Moisture during HartX in May 1992

Due to high incoming global radiation, temperatures and water vapor pressure deficits (Jaeger

Fig. 2. Comparison of soil water depletion during HartX recorded with different methods. The open circles and the dashed line indicate tensiometric soil moisture at a depth of 20 cm, shaded circles and coarsely dashed line show tensiometric soil moisture at a depth of 40 cm, squares show gravimetric soil moisture ($\pm$ standard deviation), and the broad line and triangles represent capacitive soil moisture determination

Fig. 3. Schematic representation of the method applied to determine ET from tensiometric soil moisture data at a depth of 20 and 40 cm

and Kessler, this issue) high potential ET occurred during the HartX period. Neither large amounts of dewfall nor precipitation affected the soil water store. The rates of soil water depletion were typical for late springtime. The daily mean values and the course of soil moisture for all methods which were applied during this period are shown in Fig. 2. The tensiometers and the capacitive device show a steady reduction of volumetric soil moisture. In contrast to the tensiometer measurements, gravimetric samples show a large variation from one day to another caused by spatial variability in soil properties and throughfall. The mean standard deviation varied between 1.55 vol.% (18 May) and 4.53 vol.% (16 May). Linear regression of gravimetric measurements shows a negative trend. According to this regression, the soil water content decreased 2.79 vol.% (1.0 mm/d) from 12 to 22 May ($r^2 = 0.19$). The differences in daily mean values between θ_t at -20 cm and θ_c were not larger than ± 1 vol.%. This is influenced by the calibration method for θ_t (see 3.4). The two methods cannot be treated as independent of each other.

The tensiometers in Fig. 2 showed a greater decrease of θ_t at -20 cm than at -40 cm. Apparently the upper soil layer dried more rapidly due to a higher root density and surface evaporation. The assumption that vertical water flux at the C/A_h interface is negligible, which is certainly true in late summer when soil water potential in the lower soil is close to the wilting point, probably does not

Fig. 4. Rate of water transport from the rooting zone estimated from measurements of hourly soil water potential at 20 cm and 40 cm depth for 11 to 23 May. The data were smoothed by a running mean over five values. Positive values indicate loss to the atmosphere, negative values indicate recharge from deeper soil layers

hold for the springtime period. At water saturation, the hydraulic conductivity in the lower soil was high and a negative potential gradient in the profile produced water flow from the lower to the upper soil. The negative water flux rates during the nighttime indicated in Fig. 4 illustrate water uptake from lower soil layers. Neglecting this recharge would lead to an underestimation of ET. We considered the information of θ_t in both depths (-20 and -40 cm) and calculated the gradient of soil moisture for the time steps t and $t + 1$ as shown in Fig. 3. The area between the two lines indicated for t and $t + 1$ from ground level to their intersection provides an estimate of change in water storage ($\theta_{(t)} - \theta_{(t-1)}$) in the upper soil layer. We rearranged equation 3 to

$$ET_{(\theta, dt)} = dz \cdot \sum_{t=1}^i |(\theta_{(t)} - \theta_{(t-1)})| \quad (4)$$

From 12 to 22 May θ_c decreased a total of 4.57 vol.% equivalent to 1.66 mm/d decrease in soil water content for the upper soil layer of 40 cm thickness. θ_t at a depth of 20 cm showed the same decrease (Fig. 2). By applying Eq. 4 to the measurements of θ_t and including recharge from deeper layers ET increased to 2.03 mm/d. These estimates are compared with SONIC eddy correlation measurements (2.28 mm/d) and with xylem sapflow-rates (2.12 mm/d, cf. Köstner et al., this issue) in Table 1. The ET estimates calculated from

Table 1. Daily Evapotranspiration Rates during HartX from 12 to 22 May 1992 [mm/d] Estimated with Different Methods as Described in the text. $ET_{(\theta_c)}$ from $\Delta\theta_c$ multiplied by profile depth, $ET_{(\theta_t)}$ according to Eq. 4, SONIC and OPEC estimates from Gay et al., this issue

Day	$ET_{(\theta_c)}$ [mm/d]	$ET_{(\theta_t)}$ [mm/d]	SONIC [mm/d]	OPEC [mm/d]	sapflow [mm/d]
12th	3.72	2.13	—	—	—
13th	2.64	2.06	—	—	2.8
14th	0.88	2.13	2.02	2.9	2.6
15th	2.48	2.26	2.43	3.0	2.6
16th	-0.4	2.25	2.47	3.1	2.7
17th	1.96	1.85	2.83	2.7	2.1
18th	1.56	2.1	—	2.8	2.0
19th	0.36	2.13	2.06	2.6	2.0
20th	2.24	1.84	1.84	2.3	1.6
21st	0.72	1.94	2.0	1.8	1.4
22nd	2.08	1.66	2.58	—	1.4
Mean	1.66	2.03	2.28	2.65	2.12

soil water depletion were approximately 15–30% lower. In contrast to tensiometric measurements, the diurnal data from the capacitive device was very noisy and the daily differences in soil moisture were highly variable. Thus, the results for the capacitive device presented in Table 1 should be considered as very crude estimates. Concerning the time trends in ET, the best agreement was obtained between θ_i calculated with Eq. 4 and SONIC eddy correlation measurements.

There are at least three contributions to the differences between meteorological and soil moisture estimates of ET:

1. The water flux rates obtained with these soil moisture measurements may not be representative for the entire stand. This would be caused by differing root density distributions at different locations which control water uptake. The permanent methods were installed as far as possible from the trunks and it is likely, that root distribution at this point is less dense. This would lead to an underestimation of plant water uptake. Better results might be obtained, when the spatial variability of soil moisture is measured at a number of points. This was considered in the autumn campaign (see below). Also, the source location for the SONIC measurements is uncertain and possibly located at greater distance from the intensive study site than where soil moisture was recorded.
2. The hypothesis that water storage is restricted to the upper soil layer from 0 to –40 cm could not be verified for the HartX period. The profile measurement of soil water potential indicated,

that water uptake from the lower soil is very likely in springtime. The quantification of this uptake with two point measurements is inadequate. Furthermore, single roots reaching below –40 cm might play an important role in plant water uptake. To solve this problem water potential measurements in the gravel layer and an excavation of the rootsystem would be helpful.

3. The signals of the capacitive device and gravimetric measurements were noisy. Thus, the estimation of ET calculated from θ_g and θ_c was very uncertain. The tensiometric determination of soil moisture was the only method we used during HartX which seems to be suitable for exact soil water balance calculations due to its sufficient resolution in time.

4.3 Soil Moisture in Autumn 1992

The atmospheric conditions from 22 to 27 September 1992 were such that global radiation was only 50–70% of that measured during the HartX campaign in spring. Furthermore, the daily mean temperature was about 4 °C less than in May. Figures 5 and 6 show the time course of soil moisture measured with the TDR system. All vertically installed probes showed the same trend, although there was a constant offset between them. This offset may reflect soil-specific differences at the five test locations but was not further examined. The mean standard deviation from the single probe to the averaged hourly value for all probes is about 1.6 vol.% which is in the range of spatial variability determined from gravimetric

Fig. 5. Precipitation (shaded bars), TDR and capacitive soil moisture data from 9 September to 19 October 1992. The TDR mean is based on hourly measurements from five probes over a depth of 0–30 cm, the capacitive values on four measurements a day from one probe at –20 cm

Fig. 6. Precipitation (shaded bars), TDR measurements from single horizontal probes in different soil layers (-5 cm, -15 cm and -40 cm) and capacitive soil moisture measurements at -20 cm from 9 September to 19 October (hourly values)

data. Comparing θ_{tdr} with precipitation measurements, the TDR system appeared to provide good estimates of incoming water added to the soil profile (Fig. 5). The horizontally installed TDR-probes (Fig. 6) show a lower variability of soil moisture over time at greater depth. The upper soil layers are governed by a higher temporal variation in water content caused by variable precipitation inputs and root water extraction. Since there was only little change in soil moisture at -40 cm, we integrated the water loss measured by vertical TDR probes from 0 to -30 cm which was the length of the probes in the soil to obtain ET for the period 22 to 27 September according to Eq. 3.

The comparison of daily mean values of θ_c with θ_{tdr} (Fig. 5) shows that the measured trends over the period of 41 days were similar. In contrast to θ_{tdr} , the capacitive system at -20 cm was insensitive to precipitation events excepting rainfall on 16 and 17 October. Since the two systems were installed at different locations (horizontal distance approximately 30 m), the question whether this behaviour was caused by physical differences between the methods, by a different soil hydraulic behaviour (see 4.1) or by different root distribution cannot be answered completely. Since the TDR curve represents the mean value of five independent measurements for an integral soil volume and the capacitive data originate from a single location, the TDR data are more reliable for the calculation of evapotranspiration rates during the autumn campaign.

4.4 Evapotranspiration from soil Moisture Data (Autumn Campaign)

From 22 to 27 September, hourly ET rates from the TDR measurements were calculated on the basis of Eq. 3. This period was chosen because essentially no precipitation occurred ($P = 0.02$ mm). The data were smoothed by calculating the running mean over five values. Figure 7 summarizes the diurnal courses and the mean diurnal trend for this period. The highest decrease in soil moisture took place between 2 pm and 4 pm each day, approximately 1.5 to 3.5 hours after the radiation maximum had been reached. On 22 and 23 September, strong winds may have led to higher ET rates, although the available energy was not very high on these days. Over the six-day period, the daily ET maximum seemed to shift from early afternoon to mid-afternoon.

The daily ET sums calculated from TDR are compared with OPEC measurements, SONIC Eddy correlation and xylem sapflow measurements in Table 2. During the six-day period θ_{tdr} decreased 9.3 mm (2.33 vol.% integrated over a depth of 40 cm). SONIC and OPEC measurements suggest that a slightly larger decrease of 10.1 and 10.9 mm (2.53 vol.% and 2.73 vol.%) should have occurred. Sapflow measurements indicated lower soil water depletion (6.9 mm or 1.73 vol.%). The sapflow values are, however, based only on a single tree measurement, so we must disregard the absolute values in this case. Köstner et al. (this issue) propose at least eight sapflow installations

Fig. 7. Smoothed diurnal courses of TDR based evapotranspiration estimates for six days during the autumn 1992 campaign

for an adequate evaluation of sapflow rates. Furthermore, the contribution of the understory vegetation to stand ET is not measured with this method. Concerning trends, there was a good correspondence between $ET_{(t,dr)}$ and estimates of ET via the sapflow method. ET values determined via TDR and SONIC devices compared well and the total sums of ET for the whole period determined with OPEC, SONIC and TDR are in close agreement. Considerable dewfall which occurred on all days of this period (except 23 September) might play an important role in explaining the differences between the methods. ET estimated via eddy correlation includes dew evaporation, and this could be the reason for higher total ET sums shown for SONIC in Table 2.

Table 2. Comparison of Daily Evapotranspiration Rates for 22 to 27 September 1992 in [mm/d] Estimated with Different Methods as Described in Table 1

Day	$ET_{(t,dr)}$ [mm/d]	SONIC [mm/d]	OPEC [mm/d]	Sapflow [mm/d]
22nd	1.7	2.2	1.4	1.2
23rd	2.0	2.2	1.6	1.3
24th	1.5	1.4	1.9	1.2
25th	1.6	1.5	2.1	1.3
26th	1.4	1.3	2.1	1.0
27th	1.1	1.6	1.8	0.9
Sum	9.3	10.1	10.9	6.9

4.5 The Plant's Reaction to Changes in soil Water Availability

The measurements of xylem predawn water potential of *Pinus sylvestris* at Hartheim from July to October 1993 are related to gravimetric soil water content in Fig. 8. Nonlinear regression of the data according to the function shown in the figure resulted in $r^2 = 0.97$ ($n = 20$). Above a soil moisture of 15 vol.% ψ_{pd} is only slightly affected by soil water availability. Below this value, a sensitive response in ψ_{pd} is observed. During HartX we measured ψ_{pd} -values between -0.62 and -0.8 MPa.

Stomatal and canopy conductance are a function of ψ_{pd} . Running (1984) estimated this dependency for *Pseudotsuga menziesii* and *Pinus contorta* ssp

Fig. 8. ψ_{pd} - θ_g relation for *Pinus sylvestris* at Hartheim observed in summer 1993

latifolia. If the dependency is transferable to *Pinus sylvestris*, leaf conductance during HartX should have been reduced to 70% of maximum leaf conductance. According to the $\psi_{pd}-\theta_g$ -relation for *Pinus sylvestris* at Hartheim we would predict ψ_{pd} values of -0.5 to -0.6 MPa for the period of 22 to 27 September. Again we would expect a slight decrease in leaf- and canopy conductance (about 85% of the value of maximum leaf conductance) during this period. Ongoing studies are directed at clarifying the relationship between soil water availability and canopy conductance.

5. Conclusion

The intention of this study was to find out 1) how reliable estimates for ET could be derived most efficiently from soil moisture measurements and 2) whether conductance of the pine trees at Hartheim decreased during the HartX-campaign due to soil drying increasingly limiting stand ET.

Daily rates of $ET_{(\theta)}$ were calculated based on all methods of soil moisture measurement applied in the HartX- and in the autumn-campaign. Estimates of gravimetric determinations were unreliable due to the problem of high spatial variability. Gravimetric data remain useful for the determination of long-term changes in soil moisture as well as for direct evaluation of spatial variability which should not be neglected in the design of ecosystem studies. The capacitive device produced a noisy signal which may have been the result of diurnal temperature effects. Smoothing the data did not lead to better results. Nevertheless, θ_c provided reasonable ET estimates over long-term periods (two weeks) in springtime. Tensiometers and TDR provided very stable signals. The best estimates of daily ET were obtained from TDR in autumn. These results compared well with eddy correlation measurements. The analysis of the HartX data in comparison to the autumn campaign showed that in springtime the lower soil layers (below the 40 cm rooting zone) have an important influence on good estimates of $ET_{(\theta)}$. In autumn, when the lower layers are dry and their hydraulic conductivity is low, it is sufficient to measure the changes of soil moisture in the uppermost layers in order to estimate ET well. To obtain good estimates for $ET_{(\theta)}$ in spring, we recognize the need for parallel measurements of θ and ψ_s in soil profiles including the soil layers below the root

zone. Concerning water stress effects on the trees, the $\psi_{pd}-\theta_g$ relation has indicated that water stress effects probably influenced the magnitude of ET during HartX and lesser during the autumn experiment.

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