Title	Interannual environmental-soil thawing rate variation and its control on transpiration from Larix cajanderi, Central Yakutia, Eastern Siberia
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Abstract: Sapflow measurements were carried out in a larch forest in eastern Siberia, an area of wide permafrost distribution. Canopy transpiration and canopy conductance were scaled up from these values. The objective was to analyze the relationship between environmental variables, mainly vapour pressure deficit (D), soil moisture and soil thawing rate with canopy transpiration and canopy conductance. Maximum sapflow rate was 42.4 kg d-1 tree-1 with bigger trees showing a more accentuated response to environmental changes. Canopy transpiration (Ec) showed inter-annual variability, with a maximum value of 1.7 mm d-1 in 2003 and 1.2 mm d-1 in 2004. Soil moisture was higher in 2003 because of higher precipitation (230 mm in 2003 compared to 110 mm in 2004 for the total growing season). Maximum soil thawing rate in 2003 and 2004 was 140 cm and 120 cm respectively, because of different air temperature, soil water content and precipitation regime among other factors. Canopy conductance (gc) was positively correlated with D during fine weather and well-watered days in both years. On the other hand, canopy conductance was well correlated with soil moisture (R2=0.83) in the upper layers (20 to 30 cm depth) during 2003 (wet year) but not in 2004 (dry year), representing its strong but limited control over water fluxes from the forest. By comparison with other studies in this region, canopy transpiration is estimated to contribute to almost 50 % of the total forest evaporation, highlighting the important role of understorey transpiration in permafrost regions. Our results show that it is not only the impermeability of permafrost with the property of keeping soil moisture in the thin active layer but it is also the slow soil thawing rate that plays the important role of controlling the amount of water available for trees roots in the upper soil layers during dry years.

Interannual environmental-soil thawing rate variation and its control on transpiration from *Larix cajanderi,* Central Yakutia, Eastern Siberia.

Short title: Transpiration from *Larix cajanderi* in Eastern Siberia

Authors: M. Larry Lopez C. [1*], H. Saito[2], Y. Kobayashi[3], T. Shirota[2], G. Iwahana[1], T. C. Maximov[5] and M. Fukuda[1].

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Sapporo, Japan.

Thanks for your comments and suggestions. In the text below I try to answer all the questions formulated. If you consider that it is still not enough, please do not hesitate in contacting me. I want to express my apologies if some of the explanation in some cases is too basic but my intention is to make the processes that take place in permafrost regions as clear as possible.

Review for Journal of Hydrology June 2006

Interannual variation of environmental and soil thawing rate and its control on transpiration from *Larix cajanderi*, Central Yakutia, Eastern Siberia

Lopez L., Saito H., Kobayashi Y., Shirota T., Iwahana G., Maximov T.Ch., Fukuda M.
Institute of Low temperature – Novosibirsk Siberia? Cape of Good Hope, South Africa? Lenin street 13?

Authors: *I like the idea of the institute being in Cape of Good Hope but as it is written in the cover letter the Institute of Low Temperature, Hokkaido University is located in Sapporo, Hokkaido, Japan.*

Permafrost regions occurring presumably in the Northern hemisphere are of special hydrological interest because of seemingly strange features of local soils and associated behavior of forest tree species, mostly larch. The authors focused on water loss of boreal forests, in Eastern Siberia typical with low precipitation, where water from thawed permafrost is important for tree survival. They applied sap flow technique and usual meteorological and soil moisture equipment for this purpose over two growing seasons (July-Sept. 2003 and 2004).

Authors: *Here I would like to make something very clear. Water thawed from permafrost is not used by trees, unless there has been a disturbance that has severely broken the stability of permafrost. As it can be observed in figure 4 (of the original manuscript) the active layer (soil layer that freezes in winter and thaws in summer) reaches its maximum thickness at the end of September when leave shedding has already started or water uptake from trees is already very low. Furthermore, root density below 1 meter is close to zero and thus importance of permafrost for tree survival lies not as a water source but as an impermeable layer that avoids water filtration downward. The most important point that I have probably not conveyed properly is the fact that gradual soil layers thawing (Fig. 4) allows the retention of water in the upper layers were the bulk of tree roots distribute and that this deepening shows an inter-annual variation, being slower when water supply is low so as to make more water available for (in the upper layers) tree survival.*

Unfortunately neither methodical nor instrumental information is provided.

Authors: *My deepest apologies for this. I make myself (first author) responsible for not providing the proper information. In the revised text all the methodical and instrumental information is provided.*

So it is not clear e.g., how solar radiation was measured (e.g. by a home-made solarimeter? Delta-T pyranometer? other?).

Authors: *In the revised version this information is provided.*

There is a commercial mark, but missing information which was the type of soil moisture sensors (e.g., gypsum blocks? TDR?) and how they were reasonably calibrated in soils with very high content of organic materials.

Authors: *In the revised version this information is provided.*

It was also not described which method was used for sap flow measurements (e.g. heat-pulse velocity? trunk section heat balance? whole stem heat balance? heat dissipation method? heat field deformation method? heat ratio method?).

Authors: *In the revised version this information is provided.*

Number per tree and scheme of installed sensors are not given too.

Authors: *The number of sensors used per tree was one, all of them where installed on the north side of the tree at 1.3 m (dbh).*

The applied method of integration of sap flow values from measuring points to whole trees is missing (considering usually high variation of flow across sapwood, i.e. its circumferential and radial pattern in stems) and up-scaling technique used for the entire stand level.

Authors: *In the revised version, explanation about the methodology has been added.*

Also no applied equations are given so it is unclear, whether the already described approaches taken from other authors (including Monteith, Brutsaert etc.) were applied properly.

Authors: *In the revised version the equations required have been added.*

The obtained results seem interesting and valuable, but the serious methodical flaws make them and also conclusions so much unsure, that it is impossible to take them seriously.

Authors: *I hope that the new version is convincing enough to show the reliability of the results.*

There are also evidently incorrect data on soil moisture (reaching according to authors several tens of m^3m^{-3}; please check your data having in mind, that water is not so much compressible even in Siberia).

Authors: *The values of soil moisture shown in the study are relatively high for 2003 but they are not rare for permafrost regions. The term 'compressible' should be replaced by* *'impermeable' for a better understanding of soil moisture values in Siberia. Explanations about calibration are included in the revised version.*

When discussing E_c and VPD, do you really think that relationships with correlation coefficient between 0.35 and 0.67 (i.e., $r^2 = 0.12$ and 0.45) are worth to be taken into account?

***Authors**: I have rephrased the sentence and made a new graph including a longer period of data.*

It is at least polite in respect to the readers to leave anonymity and provide a compete address of the corresponding author.

***Authors**: I am really sorry that the Institute's address did not appear in the first page of the manuscript (it does in the third though). It was not my intention to be disrespectful. The first page was generated automatically when I sent the manuscript and most probably I just wrote the institution's name on the field where I was supposed to write the address too.*

The manuscript cannot be accepted for publication in Journal of Hydrology in its present form. It needs a major revision and first of all completing in details all missing methodical information. Then only the repeatedly checked and corrected results can be properly evaluated.

***Authors**: I hope it is now and if not I am nevertheless thankful for the time you have taken reviewing the paper.*

Review: Hydrol5143, Lopez et al

This is a careful study on tree transpiration in a remote area. Thus I recommend publication after some revision. It would have been helpful, if the authors would have numbered the lines.

Thanks for your comments and suggestions. In the text below I try to answer all the questions formulated. If you consider that it is still not enough, please do not hesitate in contacting me. I want to express my apologies if some of the explanation in some cases is too basic but my intention is to make the processes that take place in permafrost regions as clear as possible.

Abstract

Line 6: The unit is not complete. It should be dm^3 d^{-1} $tree^{-1}$ also, Liter is not an SI unit

***Authors**: I have changed the unit of total tree sapflow to kg d^{-1} since it is much easier to compare with other studies (i.e. Arneth, 1996; Wullschelleger, 1998). If the unit suggested is necessary then I will change it.*

Line 10 and 12: Avoid “respectively”. It becomes very confusing if you compare 4 items.

***Authors**: The sentences have been changed.*

Page 3, line 2 and 3 from bottom: You make a valid point about the number of trees to be measured, but in your study you forget about this. I am missing an assessment of how many trees are needed.

***Authors**: It is interesting that you asked this question. I have seen many studies where the number of sensors used is no more than 6 or seven. In the study I mentioned (Kuwada et al., 2000), he used only 4 trees for scaling up. Companies like EMS, Brno sells a set of 12 sensors for sapflow measurements which I consider as a good number (and the company also suggests, I assume) for the dbh distribution shown in this study. The number of sensors we could use was close to this number and could represent reasonably the crown classes.*

Page 5, 1st paragraph: It would be appropriate to show the measuring trees as part of Fig 1. You would realize that you probably measured too many suppressed trees, and you are missing the important class of 25 to 30 cm trees.

***Authors**: I put together table 1 and Fig 1 as suggested by the reviewer. I have checked the distribution of sensors in the trees I selected and the sensors inserted in the codominant trees cover this range (3 out of 4).*

As far as I understand, you are scaling up to the canopy level by using the fraction of sapwood of the measuring trees. This, however, is only justified, if the specific flow is the same between trees. You do not show this value. I suggest that you add a figure showing the specific flow as related to DBH. Based on this figure, I think you must up-scale by DBH-class.

***Authors:** Actually, we have calculated the stand sap flow for each tree class separately which is related to dbh distribution within the forest. Sapflow was measured at only one depth and* *consequently, the scaling up was done according to the factor we had considered from the beginning which was sapwood area.*

In addition: Did you measure a sufficient number of trees? I am aware, that most studies used the convenient number of 10, but is this enough? How would your up-scaling towards a canopy flux change, if you deleted one suppressed, or one co-dominant or one dominant tree? This would give you some estimate of uncertainty.

***Authors**: You are right. The number of trees used was in agreement with the number of trees used in other studies. Undoubtedly, the more the number of sensors the better but I tried to make the best used of what I had at hand. Following your suggestion I deleted alternatively one tree per crown class and the results are shown as follows:*

1. in 2003, one suppressed tree was removed (c-132; c-144; c-211; c-158) and the result of the total transpiration was +0.2%, -1.7%, -2.4%; 4.0% lower or higher respectively. When one codominant tree was removed (c-243, c-151, c-119, c-203), the result of the total transpiration was -8.1%, +1.9%, -3.6%, +3.1% lower or higher respectively.

2. in 2004, one suppressed tree was removed (c-132; c-144; c-211; c-158) and the result of the total transpiration was -2.1%, -1.4%, +4.9%; -1.4% lower or higher respectively. When one codominant tree was removed (c-243, c-151, c-119, c-203), the result of the total transpiration was +1.8%, -4.2%, +2.0%, +7.4% lower or higher respectively.

Page 7: Why don`t you show the comparison with the Eddy flux. This is needed, as you mention, tree transpiration is only 50% of the whole ecosystem water loss. I would request that you show the eddy flux and the xylem flux as related to D. This would indicate, if indeed you are only missing one compartment, the ground vegetation, or if the two measuring systems are different for other reasons.

***Authors**: In the new revised version the comparison with Eddy flux measurements have been included. I made also reference of Dolman et al. (2004) where he makes the relationship D-eddy-flux. If necessary I can send the data.*

Page 9, line 2/3: I do not understand the sentence "soil moisture shows its actual value"??

***Authors**: Soil moisture sensors are not able to give a reliable value when the soil is frozen as it is the case here, which explains the 'jump' in soil moisture value when the soil thaws. Therefore the sentence means that when the layer of soil is thawed the sensor starts measuring the actual value which differs significantly from the value when it was frozen.*

Page 11: For comparisons, the specific flow rate would be important. As far as I know, the study site of Arneth had no permafrost. Also, was the size distribution the same?

***Authors**: Actually the study by Arneth et al. was done on continuous permafrost regions. However, as it is usual for forest researchers working in Permafrost regions they do not pay so much attention to the processes that occur in the belowground of cryosoils and keep analyzing processes in the aboveground as if the belowground was just a normal soil. This is repeated several times in the literature. This is the main reason why the study presented here tries to*

combine above and belowground processes for a better understanding of the effect of the active layer and permafrost interaction on this immense forested territory.
On this area of eastern Siberia there is no place that is not underlain by permafrost. The tree size distribution was similar with Arneth's study.

Page 11, last paragraph: You need to mention Fig. 6 much earlier

***Authors**: the text has been arranged. The graphs are shown according to the flow of the study.*

Page 12: Combine fig 7 and 8 into one figure a and b.

***Authors**: This has been done as suggested.*

Fig. 9 is missing

***Authors**: I asked previously by e-mail if it was necessary to send figure 9 but I was told that it was not necessary, according to the e-mail from the Journal manager on August 11th, 2006.*

Page 15: line 9ff: I do not understand the discussion. I thought, that also your results would indicate that the trees feed on water which thawed. I am lost. It does not really matter, if the trees take up the thaw water or if water is transported up (except for salt). In any case summer rain is not sufficient to maintain transpiration.

***Authors**: The assumption made by the reviewer is correct. Precipitation is not sufficient to maintain transpiration, what I probably did not stress sufficiently was the fact that the gradual thawing of soil allows this small amount of precipitated water or water from melted snow (at the early stages of the growing season) to remain in the upper layers where most of the roots distribute. If the thawing is slow as it was the case in 2004 then more water remains available for tree roots in the upper layers especially during dry years.*
Furthermore, the water that is accumulated in each layer in the previous year (autumn) when the soil froze and then gradually thaws in the next year growing season becomes an extra source of water. In May and June as it is shown in the manuscript soil moisture is high not because precipitation is high or because soil has high retention properties but because the impermeability of frozen soils keeps the water available for the upper thawed layers where the roots distribute.

1. Introduction:

Water loss from boreal forests is of global importance because of their distribution (12.0 to 14.7 million km^2). In eastern Siberia, boreal forest grows over continuous permafrost, of which 54% is occupied by *Larix* (Shvidenko & Nilsson, 1994). Growing evidence of a higher frequency of climatic extremes as a result of global climate change (Karl et al., 1995) makes it necessary to understand the response of forest functioning to environmental as well as ground thermal conditions in permafrost regions. Forests in Siberia exist with an annual precipitation regime of 230 mm, of which half occurred during the growing season (May-September). Annual variability of precipitation in eastern Siberia during the growing season affects greatly the thin active layer (1.0 – 1.5 m depth) where the boreal forest stands. Precipitated water in autumn becomes a water reservoir for the next growing season (Sugimoto et al., 2003) and changes the rate of soil thawing, which is a function of the thermal parameters of soil thermal conductivity and latent heat of the soil moisture (Romanovsky et al., 1997). According to recent studies, active layer depth is increasing due to climatic warming (Osterkamp and Romanovsky, 1999; Fedorov and Konstantinov, 2003; Jorgenson et al., 2006) and this can have a great effect on the soil water supply for *Larix* forests. It has been suggested that during dry years, thawed permafrost, caused by active layer thickness increase, can supply water for trees to keep the forest functioning (Sugimoto et al., 2002).

In eastern Siberia, forest evaporation (Kelliher et al., 1997, Ohta et al., 2001; Dolman et al., 2004) and canopy transpiration have been estimated by different methods. However, measurements have been short-term (Arneth, 1996) or the number of trees necessary for scaling up to canopy transpiration (Cermak et al., 1995) has been insufficient (Kuwada et al., 2000). Long-term measurements and scaling up methods are important when modeling canopy conductance (g_c) because of the large control it exerts on transpiration from coniferous forests in boreal regions (Jarvis and McNaughton, 1986). Under given concentrations of nitrogen in the soil, g_c is mostly limited by a vapour pressure deficit, by soil water deficit or by a combination of both factors (Cienciala et al., 1997). The active layer response to environmental conditions and its relationship with soil moisture and canopy transpiration still needs to be studied in permafrost regions.

The objectives of this study are: 1. to elucidate the relationship between canopy transpiration and the environmental parameters under two different precipitation regimes; 2. to determine the role of soil thawing depth on soil moisture availability and its relation with canopy transpiration; 3. to determine the relationship between g_c-D and g_c - soil moisture.

2. Materials and Methods

2.1 Study site

The site, Spasskaya Pad, is located at 35 km NNW from the city of Yakutsk in eastern Siberia (62°15'N, 129°37'E, altitude 220m). The climate in this area is dry, with annual precipitation of approximately 230 mm and mean annual air temperature of -10°C. The content of the soil upper layers is sandy loam whereas soil horizons in deeper layers are silty loam. The forest is dominated by a 160 year-old *Larix cajanderi* monoculture. Tree density is 1000 trees per ha. The sapwood basal area is 4.7 $m^2 ha^{-1}$ and the mean height is 13 m height. The frequency diameter at breast height (dbh) and tree characteristics are described in Fig 1. The understorey vegetation is mainly composed of *Vaccinium vitis-idaea and Arctous erythrocarpus* Small. According to Ohta et al (2001) the plant area index (PAI) for the fully leaved season is 3.7.

2.2 Measurements

Weather conditions during the period July 7th -September 30th, 2003 – May 20th - September 27th 2004 were recorded continuously every ten minutes (CR10X datalogger, Campbell) at the top of a 32 m height scaffolding tower built by Ohta et al (2001). The variables measured were rainfall (Young Inc., USA), solar radiation (Pyranometer, CPR-PCM-01, Prede, Japan), relative humidity -air temperature (HMP-35D, Vaisala, Finland) and wind speed (Young Inc., USA).

Soil temperature moisture and measurements started on June 7th 2003 (one month before the installation of instruments in the meteorological tower and the sapflow sensors) and May 7th in 2004. Soil temperatures were measured at depths of 0.01, 0.1, 0.2, 0.3, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, and 2.0 m using calibrated thermistors (104ET, Ishizuka Denshi, Tokyo, Japan). Soil temperature probes were calibrated with an ice-water bath. Soil moisture was measured by the FDR method (EnviroSMART, Sentek Pty Ltd, Australia) at depths of 0.1, 0.2, 0.3, 0.4, 0.6, and 0.8 m. Calibrations for FDR sensors were conducted separately for the depth of 0.1

m (the boundary between organic mat layer and mineral soil layer) and the depth below 0.2 m (mineral soil layer). Eleven in-situ soil samples in various moisture conditions were taken and the volumetric water content was determined gravimetrically to construct the calibration curve.

The soil temperature measurements were conducted every 30 sec and stored every 30 minutes as averages. Soil moisture measurements were conducted every 30 minutes and recorded. All data were logged using a CR10X datalogger (Campbell Scientific, Inc.).

2.3 Sap flow and canopy transpiration

Sap flow was measured continuously during the two growing seasons by the thermal dissipation technique (Granier, 1985, 1987) with 20 mm long radial sap flow meters (UP Umweltanalytische Produkte, Germany) installed at a height of 1.3 m in the stems. Sap flow sensors in each crown class were installed following the dbh distribution (Fig.1). Sap flux density (*U*, $m^3\ m^{-2}\ s^{-1}$) was estimated by this technique. Measurements of sap flow was operated each 10 s and 10-minute average values were stored on a CR10X Campbell Scientific (Shepshed, UK) datalogger. Total tree sap flow F was calculated as the product of U by the sapwood cross-section. Sapwood cross-section of the studied trees and total stand sapwood were estimated from cores. Sapwood thickness was manually measured, since it is easy to distinguish the difference in color between sapwood and heartwood, due to differences in water content. The relationship between sapwood and tree diameter (Fig.2) was used to estimate sapwood area for each crown class. Individual tree sap flow values (Granier *et al.*, 1987) were corrected (Clearwater *et al.*, 2001) for differences in needle length (20 mm) and sapwood thickness. Sapflow measurements carried out throughout the two growing seasons in individual trees were scaled up to stand level using sapwood area distribution as described in Granier et al. (1996). Stand sap flow E_c was calculated as:

$$E_c = S_T \sum p_i U_i$$

where S_T is the stand sapwood area per unit of ground area ($m^2\ m^{-2}$), p_i is the proportion of sapwood in the class i and U_i is the average sap flux density in the class i. To avoid short-time lags between courses of sap flow and transpiration, calculations were based on 1 day interval data.

2.4 Canopy conductance

Canopy conductance was derived from the Penman-Monteith equation assuming that stand sap flow E_c was equal to tree transpiration:

$$E_c = \frac{\Delta(Rn - G) + \rho C_p D g_a}{\lambda\left[\Delta + \gamma(1 + {}^{g_a}\!/_{g_c}\right]}$$

where Δ is the rate of change of saturation vapour pressure (PaC^{-1}), R_n is the net radiation above stand (Wm^{-2}), G is the rate of change of sensible heat in the biomass plus heat flux in the soil (Wm^{-2}), ρ is the density of dry air at constant pressure (Jkg^{-1}C^{-1}), D is the vapour pressure deficit (Pa), g_a is the aerodynamic conductance (ms-1), gc is the canopy conductance (ms^{-1}), λ is the latent heat of vaporization of water (Jkg^{-1}), and γ is the psychrometric constant (PaC^{-1}). In this study heat flow in the soil was neglected due to the low incoming energy. Net radiation (R_n) was derived from solar radiation measurements as R_n=a$_1$+a$_2$$R_s$. The coefficients a$_1$ and a$_2$ were determined from hourly daytime values of net and solar radiation measured at a nearby meteorological station. Aerodynamic conductance (g_a, ms^{-1}) was calculated as

$$g_a = \frac{k^2 u}{\left\{\ln\left[{}^{(z-d)}\!/_{z_0}\right]\right\}^2}$$

The displacement height (d) was set as 0.67h and the roughness length as 0.1h, where h is stand height, k is von Karman's constant (0.40) and u is wind speed at height z above the canopy (Brutsaert, 1982). The acceptability of the accuracy of this equation relies on the importance of g_c in equation 2 since $g_c << g_a$.

3. Results

3.1 Meteorological conditions

Inter-annual variation of climate in Siberia is one of the most important characteristics affecting the growing season in the forest. The year 2003 was characterized as rainy (total precipitation from May to September was 230 mm, rainfall data for May 2003 was obtained from a station 8 km away from Spasskaya Pad) and daily average temperatures remained above 20 deg.C during summer. In contrast, 2004 was characterized by lower precipitation (for the same period 110 mm) and lower air temperatures, with few days with daily values higher than 20 deg.C. Wind speed was similar for both years except for some windy days in 2004 when mean daily value reached 7 m s^{-1}. Solar radiation from July to the end of the season was similar in 2003 and 2004 (Fig. 3).

3.2 Soil Moisture and soil temperature

Soil moisture in the upper 10 cm of the active layer experiences the largest variations after rainfall events (reaching a maximum of 34 m^3m^{-3}) followed by smaller increases in soil moisture in deeper layers. Soil moisture increased after precipitation (July 24th), but then decreased steadily reaching a minimum value of 14 m^3m^{-3} in mid August, after a three-week rainless period in 2003. In 2004, the sensor at 20 cm malfunctioned and therefore data for this depth was extrapolated. Soil moisture at the soil surface showed a steady decrease from the beginning of the season (33 m^3m^{-3}, after snow melting) until mid July (13 m^3m^{-3}), when after a total of 19 mm of three continuous days precipitation, it increased again to 21 m^3m^{-3}. A rainless period of two weeks July 7th-23rd was selected for both years to observe how soil moisture was used at different soil depths under to different precipitation regimes. During the rainy year (2003) soil moisture at 10 cm decreased significantly partly as tree water uptake and partly lost to deeper layers by filtration (40.5 %). In contrast in 2004, soil moisture decreased 22.7 % at the same depth. At the same time the change in soil moisture at 20 cm was only 4.7 % in 2003 and 12.0 % in 2004. At 30 cm, soil moisture decreased 3.6 and 4.3 % for the same period of time in 2003 and 2004 respectively. These results reveal a different use of soil moisture by trees when adjusting to water availability in the soil.

Soil moisture shows its actual value after soil thaws, since the sensor is not able to measure accurately moisture when the soil is frozen. In 2003, soil at 80 cm depth thawed approximately on July 20th whereas in 2004, soil at 80 cm thawed approximately on August 16th, almost one month later than in 2003. In 2003, measurements started when the soil thawing depth had reached 37 cm, on June 7th. In 2004, on the same day, the thawing depth was 30 cm. On July 1st the thawing depth reached 76 cm and 56 cm in 2003 and 2004 respectively and on August 15th, the thawing depth was 134 and 107 cm in 2003 and 2004 respectively. Soil thawing, as mentioned above, occurred at a higher rate in 2003 than in 2004 and consequently the thawing depth at the end of the growing season reached approximately 140 cm depth on September 17th in 2003, whereas in 2004 the thawing depth was approximately 120 cm on September 20th (Fig.4). It is important to mention that despite lower precipitation the layer of soil containing high water (and ice) content beneath 120 cm was not made available for tree use during this year and which according to Sugimoto et al. (2003) ranges annually between 0.4 to 0.7 g cm^{-3}.

3.3 Tree Sap flow and soil moisture availability

Maximum values of sapflow of individual trees were higher in 2003 than 2004. Dominant trees (C-159 and C-148) reached values between 2.5 and 3.0 kg h^{-1} respectively on July 14th and 15th and decrease to an average 2.2 kg h^{-1} in response to increases in diurnal *D*. Meanwhile, codominant (C-151, C-203) trees showed lower sapflow rates that ranged between 1.6 to 2.0 kg h^{-1} without any apparent effect caused by changes in diurnal *D* on July 16th. Suppressed trees values ranged from 0.8 to 1.0 kg hr^{-1} showing the same behavior toward *D* as the codominant trees. In contrast, in 2004, the differences among the three different crown classes narrowed. Maximum values for the dominant trees were between 1.4 and 1.7 kg h^{-1}, codominant ranged between 1.2 to 1.4 kg h^{-1} and suppressed trees ranged from 0.3 to 0.4 kg h^{-1} from July 6th to 8th (Fig.5a). Light trapping ability by taller tree canopies made dominant trees start transpiring earlier than smaller trees (between 1 or 2 hours earlier) due to induced stomata opening. The response of tree sapflow to diurnal changes in *D* (Fig. 5b) appears to diminish when soil moisture decrease below 20 m^3 m^{-3} in the upper layers.

The maximum sapflow rate of 42.4 and 26.5 kg h^{-1} corresponded to dominant trees on July 27th 2003 and June 28th in 2004 respectively. In general, daily sapflow rates were lower in 2004. Following the diurnal change in 2003, bigger and high transpiring dominant trees showed larger values than codominant and suppressed trees. In 2004, sapflow from dominant trees decreased, bringing them closer to the codominant trees sapflow rates. The maximum value of sap flow found in this study was lower than the maximum value (67 kg h^{-1}) found by Arneth et al. (1996) for *Larix gmelinii* in another location in eastern Siberia or by Schulze et al. (1985) in Europe, where the value reached 74.4 kg h^{-1} for *Larix* sp. In the study carried out by Kuwada et al (2002), only sapflow total average values were presented and not individual tree values, making comparison difficult.

3.4 Scaled up transpiration (E_c) and canopy conductance (g_c)

The maximum E_c value found for 2003 and 2004 was 1.7 and 1.2 respectively. After intensive precipitation at the end of July and relatively high air temperature, transpiration steadily decreased to 0.2 mm d^{-1} because of a rainless precipitation span of almost three weeks and the limited water storage capacity of sandy soils, where saturation of soil water and ice content in the larch forest ranges from 0.27 to 0.35 g cm^{-3} (Sugimoto et al., 2003). On August 11th 2003, when E_c was 0.4 mm d^{-1}, solar radiation (around 392.7 W m^{-2}), and D (3.0 kPa) did not show different values from those found (394.7 W m^{-2} and 3.1 kPa respectively) when transpiration reached its peak values (1.6 mm d^{-1} on July 27th). From July 7th until the end of July, transpiration remained constant at an average value of 1.3 mm d^{-1} in 2003 while in 2004 the average for the same period of time was 0.9 mm d^{-1}. In August there was an increase of transpiration as a response to precipitation but its peak was much lower than the peak observed in June-July, signaling the lower transpiration capacity of larch trees at this time of the season. At the beginning of September E_c decrease is accompanied with leaf shedding, setting the end of the growing season (Fig.6). The maximum value of transpiration found in this study was 1.7 mm d^{-1} and the average during the growing season was of 0.79 mm d^{-1}.

The correlation coefficient between E_c and D was 0.05 and 0.81 in 2003 and 2004 respectively. At higher values, E_c appears to reach a plateau which is exactly the period measured in 2003 and thus the correlation appears significantly low for this year. Canopy conductance showed a strong relationship with D in 2003 and 2004 (r^2 =0.72 and 0.71 respectively). Maximum average g_c value was 3.1 mm s^{-1}

and 3.7 mm s^{-1} in 2003 and 2004 and minimum values were 0.91 and 0.84 mm s^{-1} when D was around 3.5 kPa (Fig.7). In 2003, g_c values were higher than in 2004 at the same values of D because of inter-annual differences in soil moisture. Soil moisture at 10, 20 and 30 cm depth showed a good correlation with g_c (0.68, 0.80 and 0.83 respectively) in 2003 but there was no relationship between g_c and soil moisture at the same depths in 2004 (Fig.8). The difference in slope can be interpreted as differences in root water uptake zones. Soil moisture at 10 cm is affected by rapid filtration because of the abundance of organic material and root water uptake. Soil moisture at 20 cm is predominantly affected by root water uptake and lower filtration rate because of its mineral composition.

4. Discussion

4.1 Sapflow rate and total transpiration

Higher sapflow rates corresponded to trees with bigger diameters or higher tree crown class. However, bigger trees lowered their water loss rate more than suppressed trees when soil moisture was less available, as could be observed in this study because of differences in diurnal changes in D or precipitation regimes. As expected for coniferous trees D is an important variable controlling sap flow movement and its control remains strong even at lower soil moisture values, especially in the upper soil layers. There is a seasonal and inter-annual response of tree sap flow to environmental variables and soil moisture. The maximum values of sapflow found in this study were lower than those reported by Arneth et al., (1997) probably as a result of soil texture differences (silty loam versus sandy loam in this study) in eastern Siberia and differences in precipitation regimes (702 mm) and soil texture (podsolic loam) in a European site (Schulze et al., 1985). By using the eddy covariance technique, forest evaporation was estimated as 3 mm d^{-1} (Ohta et al., 2001; Dolman et al., 2005) which, according to our results, indicates that canopy transpiration contributes to 50% of the total forest evaporation. This is in agreement with Kelliher et al. (1997, 1998), who found the same proportion for a Siberian larch and pine forest respectively. Average transpiration during the full-leaved growing season was around 1.46 mm d^{-1} (Dolman et al., 2004), which is also in agreement with the approximately 50% contribution of canopy transpiration found in this study (average value 0.79 mm d^{-1}). Furthermore, in comparison with data obtained from eddy correlation measurements in the same site in 2003

(CREST/WCNoF, 2003) and 2004 (Kuwada et al., 2004), it was found that transpiration contributed to 47 and 60 % of the total forest evapotranspiration in 2003 and 2004 respectively. This indicates that the partition of water fluxes from tree canopy and understorey has an inter-annual variation depending on the inter-annual climatic conditions. Nevertheless, these results highlight the importance of understorey transpiration in the total forest evapotranspiration.

When values obtained by Arneth et al., (1996) are used for scaling up to canopy transpiration, the maximum value is 2.3 mm d^{-1}, which according to their own conclusions, was 0.6 or 0.7 mm higher than the values reported by Kelliher et al (1997).

4.2 Soil thawing depth, soil moisture and transpiration

Canopy transpiration starts increasing from DOY 152 in 2004 when needles growth is enhanced by root activity resulting from soil thawing depth reaching 25cm depth. In the study by Dolman et al. (2004) this activity starts on DOY 150, suggesting that understorey transpiration was not detected before canopy transpiration, or that both started simultaneously. During the period of maximum transpiration, from the beginning to the end of July, the thawing depth varied from 77 to 116 cm in 2003 and from 58 to 90 cm in 2004. This is the period of maximum water uptake by roots from the soil. During this period of time deeper layers have not thawed, and consequently neither has the permafrost layer. The results found in this study contradict the findings of Sugimoto et al. (2000), who suggested that trees could use thawed permafrost water for their supply. Following this same criterion, Dolman et al (2004) suggested that in the year 2000 thawed permafrost water could maintain water supply for tree roots. However, our results suggest that their observations are probably the result of shallow active layers that kept soil moisture available for trees rather than water being supplied from lower soil layers. It is also necessary to clarify that between the active layer and the permafrost, there is a layer of soil known as the 'transient layer' or 'shielding layer' (Shur, 1988). This layer is characterized by low-ice-content as a result of deep thawing in warm years (Brouchkov et al., 2004).

It is in mid August of 2003 and 2004 that the thawing depth reached deeper layers, but by this time water demand by trees was lower than in mid July. In this study, the difference in thawing depth was 20 cm at the end of the growing season, which remained frozen in 2004 but it was part of the active layer in 2003. Soil moisture below 80 cm does not significantly contribute to tree transpiration as deduced from the lack of change in the 80cm soil moisture curve during the growing season of 2003 and 2004.

Larch tree roots need to be distributed in the upper layers to uptake water as early as possible to complete the approximately 100 days leaved growing season cycle in Siberia. Thus, the thawing of upper soil layers from mid May sets the start of larch tree activity. Soil moisture at 0-30 cm strongly controls the variation in transpiration (where the bulk of the roots distribute, Kuwada et al. (2000)). In 2004, precipitation was nearly half of that in 2003 but the difference in distribution during the growing season allowed through, more frequent but less intense precipitation to keep transpiration going at a nearly constant rate, together with shallow thawed soil layers, from June to early July. In 2003, a rainless period of nearly 20 days set the conditions for a steady decrease in transpiration. Soil moisture at 20 and 30 cm decreased proportionally and more in 2004 than in 2003, reflecting more active tree water uptake from deeper layers as a result of lower precipitation.

4.3 Canopy Transpiration, canopy conductance and environmental variables

Higher air temperature (mean daily value of 25 deg.C), higher *VPD* (mean daily value of 2 kPa) and precipitation, promoted higher transpiration rates during the growing season of 2003. As expected for coniferous trees *D* is an important variable controlling sap flow movement during fine weather days but this response decreases when soil moisture in the upper layers is low. Our results concur with Dolman et al (2004), in that years with higher soil moisture and fine weather, forest evaporation and consequently canopy transpiration is high. In August 2003, when soil moisture decreased during a rainless period, g_c was not coupled with *D*, but during the same period it was well coupled with soil moisture at 10, 20 and 30 cm. This is in contrast to the results of Ohta et al (2001), where a clear relationship between canopy conductance and soil moisture was not found because of the dual-source nature of forest evaporation and the nearly equal contribution of understorey and tree canopy. This suggests that understorey vegetation plays a higher role in the total forest evaporation than previously estimated (Ohta et al., 2001), because of the openness of larch forests in Siberia (Nikolov and Helmisaari, 1993).

5. Conclusions

1. Inter annual variation in total transpiration because of environmental conditions is influenced by larger sapflow rate variability of dominant trees. Maximum daily sapflow rate for larch trees in eastern Siberia was 42.4 kg d^{-1}.
2. The upper soil layer played an important role in the control of transpiration. Maximum canopy transpiration was 1.7 mm d^{-1} during fine weather and well watered conditions and 1.2 mm during a dry year. Results indicate that tree canopy transpiration contribution to the total forest evapotranspiration ranges between 50 to 60 % and that water flux partition between trees and understorey is affected by inter-annual climatic conditions.
3. Seasonal lower soil thawing rates set off the effect of low precipitation regimes that otherwise will lower soil moisture content by filtration in sandy loam soils. Therefore it is not only the presence of permafrost that keeps moisture in the thin active layer, but it is the soil thawing rate that plays the important role of controlling the amount of water available for trees in response to changing environmental conditions during the growing season.

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Abstract

1. Sapflow measurements were carried out in a larch forest in eastern Siberia, an area of wide permafrost distribution. Canopy transpiration and canopy conductance were scaled up from these values. The objective was to analyze the relationship between environmental variables, mainly vapour pressure deficit (D), soil moisture and soil thawing rate with canopy transpiration and canopy conductance. Maximum sapflow rate was 42.4 kg d^{-1} $tree^{-1}$ with bigger trees showing a more accentuated response to environmental changes. Canopy transpiration (E_c) showed inter-annual variability, with a maximum value of 1.7 mm d^{-1} in 2003 and 1.2 mm d^{-1} in 2004. Soil moisture was higher in 2003 because of higher precipitation (230 mm in 2003 compared to 110 mm in 2004 for the total growing season). Maximum soil thawing rate in 2003 and 2004 was 140 cm and 120 cm respectively, because of different air temperature, soil water content and precipitation regime among other factors. Canopy conductance (g_c) was positively correlated with D during fine weather and well-watered days in both years. On the other hand, canopy conductance was well correlated with soil moisture (R^2=0.83) in the upper layers (20 to 30 cm depth) during 2003 (wet

year) but not in 2004 (dry year), representing its strong but limited control over water fluxes from the forest. By comparison with other studies in this region, canopy transpiration is estimated to contribute to almost 50 % of the total forest evaporation, highlighting the important role of understorey transpiration in permafrost regions. Our results show that it is not only the impermeability of permafrost with the property of keeping soil moisture in the thin active layer but it is also the slow soil thawing rate that plays the important role of controlling the amount of water available for trees roots in the upper soil layers during dry years.

Keywords : Active layer; Canopy conductance; Canopy transpiration; Environmental control; Permafrost; Soil moisture; Soil thawing rate.

1. Introduction:

Water loss from boreal forests is of global importance because of their distribution (12.0 to 14.7 million km^2). In eastern Siberia, boreal forest grows over continuous permafrost, of which 54% is occupied by *Larix* (Shvidenko & Nilsson, 1994). Growing evidence of a higher frequency of climatic extremes as a result of global climate change (Karl et al., 1995) makes it necessary to understand the response of forest functioning to environmental as well as ground thermal conditions in permafrost regions. Forests in Siberia exist with an annual precipitation regime of 230 mm, of which half occurred during the growing season (May-September). Annual variability of precipitation in eastern Siberia during the growing season affects greatly the thin active layer (1.0 – 1.5 m depth) where the boreal forest stands. Precipitated water in autumn becomes a water reservoir for the next growing season (Sugimoto et al., 2003) and changes the rate of soil thawing, which is a function of the thermal parameters of soil thermal conductivity and latent heat of the soil moisture (Romanovsky et al., 1997). According to recent studies, active layer depth is increasing due to climatic warming (Osterkamp and Romanovsky, 1999; Fedorov and Konstantinov, 2003; Jorgenson et al., 2006) and this can have a great effect on the soil water supply for *Larix* forests. It has been suggested that during dry years, thawed permafrost, caused by active layer thickness increase, can supply water for trees to keep the forest functioning (Sugimoto et al., 2002).

In eastern Siberia, forest evaporation (Kelliher et al., 1997, Ohta et al., 2001; Dolman et al., 2004) and canopy transpiration have been estimated by different methods. However, measurements have been short-term (Arneth, 1996) or the number of trees necessary for scaling up to canopy transpiration (Cermak et al., 1995) has been insufficient (Kuwada et al., 2000). Long-term measurements and scaling up methods are important when modeling canopy conductance (g_c) because of the large control it exerts on transpiration from coniferous forests in boreal regions (Jarvis and McNaughton, 1986). Under given concentrations of nitrogen in the soil, g_c is mostly limited by a vapour pressure deficit, by soil water deficit or by a combination of both factors (Cienciala et al., 1997). The active layer response to environmental conditions and its relationship with soil moisture and canopy transpiration still needs to be studied in permafrost regions.

The objectives of this study are: 1. to elucidate the relationship between canopy transpiration and the environmental parameters under two different precipitation regimes; 2. to determine the role of soil thawing depth on soil moisture availability and its relation with canopy transpiration; 3. to determine the relationship between g_c-D and g_c - soil moisture.

2. Materials and Methods

2.1 Study site

The site, Spasskaya Pad, is located at 35 km NNW from the city of Yakutsk in eastern Siberia (62°15'N, 129°37'E, altitude 220m). The climate in this area is dry, with annual precipitation of approximately 230 mm and mean annual air temperature of -10°C. The content of the soil upper layers is sandy loam whereas soil horizons in deeper layers are silty loam. The forest is dominated by a 160 year-old *Larix cajanderi* monoculture. Tree density is 1000 trees per ha. The sapwood basal area is 4.7 $m^2 ha^{-1}$ and the mean height is 13 m height. The frequency diameter at breast height (dbh) and tree characteristics are described in Fig 1. The understorey vegetation is mainly composed of *Vaccinium vitis-idaea and Arctous erythrocarpus* Small. According to Ohta et al (2001) the plant area index (PAI) for the fully leaved season is 3.7.

2.2 Measurements

Weather conditions during the period July 7th -September 30th, 2003 – May 20th - September 27th 2004 were recorded continuously every ten minutes (CR10X datalogger, Campbell) at the top of a 32 m height scaffolding tower built by Ohta et al (2001). The variables measured were rainfall (Young Inc., USA), solar radiation (Pyranometer, CPR-PCM-01, Prede, Japan), relative humidity -air temperature (HMP-35D, Vaisala, Finland) and wind speed (Young Inc., USA).

Soil temperature moisture and measurements started on June 7th 2003 (one month before the installation of instruments in the meteorological tower and the sapflow sensors) and May 7th in 2004. Soil temperatures were measured at depths of 0.01, 0.1, 0.2, 0.3, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, and 2.0 m using calibrated thermistors (104ET, Ishizuka Denshi, Tokyo, Japan). Soil temperature probes were calibrated with an ice-water bath. Soil moisture was measured by the FDR method (EnviroSMART, Sentek Pty Ltd, Australia) at depths of 0.1, 0.2, 0.3, 0.4, 0.6, and 0.8 m. Calibrations for FDR sensors were conducted separately for the depth of 0.1

m (the boundary between organic mat layer and mineral soil layer) and the depth below 0.2 m (mineral soil layer). Eleven in-situ soil samples in various moisture conditions were taken and the volumetric water content was determined gravimetrically to construct the calibration curve.

The soil temperature measurements were conducted every 30 sec and stored every 30 minutes as averages. Soil moisture measurements were conducted every 30 minutes and recorded. All data were logged using a CR10X datalogger (Campbell Scientific, Inc.).

2.3 Sap flow and canopy transpiration

Sap flow was measured continuously during the two growing seasons by the thermal dissipation technique (Granier, 1985, 1987) with 20 mm long radial sap flow meters (UP Umweltanalytische Produkte, Germany) installed at a height of 1.3 m in the stems. Sap flow sensors in each crown class were installed following the dbh distribution (Fig.1). Sap flux density (U, m^3 m^{-2} s^{-1}) was estimated by this technique. Measurements of sap flow was operated each 10 s and 10-minute average values were stored on a CR10X Campbell Scientific (Shepshed, UK) datalogger. Total tree sap flow F was calculated as the product of U by the sapwood cross-section. Sapwood cross-section of the studied trees and total stand sapwood were estimated from cores. Sapwood thickness was manually measured, since it is easy to distinguish the difference in color between sapwood and heartwood, due to differences in water content. The relationship between sapwood and tree diameter (Fig.2) was used to estimate sapwood area for each crown class. Individual tree sap flow values (Granier *et al.*, 1987) were corrected (Clearwater *et al.*, 2001) for differences in needle length (20 mm) and sapwood thickness. Sapflow measurements carried out throughout the two growing seasons in individual trees were scaled up to stand level using sapwood area distribution as described in Granier et al. (1996). Stand sap flow E_c was calculated as:

$$E_c = S_T \sum p_i U_i$$

where S_T is the stand sapwood area per unit of ground area ($m^2\ m^{-2}$), p_i is the proportion of sapwood in the class i and U_i is the average sap flux density in the class i. To avoid short-time lags between courses of sap flow and transpiration, calculations were based on 1 day interval data.

2.4 Canopy conductance

Canopy conductance was derived from the Penman-Monteith equation assuming that stand sap flow E_c was equal to tree transpiration:

$$E_c = \frac{\Delta(Rn - G) + \rho C_p D g_a}{\lambda\left[\Delta + \gamma(1 + {g_a}/{g_c}\right]}$$

where Δ is the rate of change of saturation vapour pressure (PaC^{-1}), R_n is the net radiation above stand (Wm^{-2}), G is the rate of change of sensible heat in the biomass plus heat flux in the soil (Wm^{-2}), ρ is the density of dry air at constant pressure (Jkg^{-1}C^{-1}), D is the vapour pressure deficit (Pa), g_a is the aerodynamic conductance (ms-1), gc is the canopy conductance (ms^{-1}), λ is the latent heat of vaporization of water (Jkg^{-1}), and γ is the psychrometric constant (PaC^{-1}). In this study heat flow in the soil was neglected due to the low incoming energy. Net radiation (R_n) was derived from solar radiation measurements as R_n=a_1+$a_2 R_s$. The coefficients a_1 and a_2 were determined from hourly daytime values of net and solar radiation measured at a nearby meteorological station. Aerodynamic conductance (g_a, ms^{-1}) was calculated as

$$g_a = \frac{k^2 u}{\left\{\ln\left[{(z-d)}/{z_0}\right]\right\}^2}$$

The displacement height (d) was set as 0.67h and the roughness length as 0.1h, where h is stand height, k is von Karman's constant (0.40) and u is wind speed at height z above the canopy (Brutsaert, 1982). The acceptability of the accuracy of this equation relies on the importance of g_c in equation 2 since $g_c << g_a$.

3. Results

3.1 Meteorological conditions

Inter-annual variation of climate in Siberia is one of the most important characteristics affecting the growing season in the forest. The year 2003 was characterized as rainy (total precipitation from May to September was 230 mm, rainfall data for May 2003 was obtained from a station 8 km away from Spasskaya Pad) and daily average temperatures remained above 20 deg.C during summer. In contrast, 2004 was characterized by lower precipitation (for the same period 110 mm) and lower air temperatures, with few days with daily values higher than 20 deg.C. Wind speed was similar for both years except for some windy days in 2004 when mean daily value reached 7 m s^{-1}. Solar radiation from July to the end of the season was similar in 2003 and 2004 (Fig. 3).

3.2 Soil Moisture and soil temperature

Soil moisture in the upper 10 cm of the active layer experiences the largest variations after rainfall events (reaching a maximum of 34 m^3m^{-3}) followed by smaller increases in soil moisture in deeper layers. Soil moisture increased after precipitation (July 24th), but then decreased steadily reaching a minimum value of 14 m^3m^{-3} in mid August, after a three-week rainless period in 2003. In 2004, the sensor at 20 cm malfunctioned and therefore data for this depth was extrapolated. Soil moisture at the soil surface showed a steady decrease from the beginning of the season (33 m^3m^{-3}, after snow melting) until mid July (13 m^3m^{-3}), when after a total of 19 mm of three continuous days precipitation, it increased again to 21 m^3m^{-3}. A rainless period of two weeks July 7th-23rd was selected for both years to observe how soil moisture was used at different soil depths under to different precipitation regimes. During the rainy year (2003) soil moisture at 10 cm decreased significantly partly as tree water uptake and partly lost to deeper layers by filtration (40.5 %). In contrast in 2004, soil moisture decreased 22.7 % at the same depth. At the same time the change in soil moisture at 20 cm was only 4.7 % in 2003 and 12.0 % in 2004. At 30 cm, soil moisture decreased 3.6 and 4.3 % for the same period of time in 2003 and 2004 respectively. These results reveal a different use of soil moisture by trees when adjusting to water availability in the soil.

Soil moisture shows its actual value after soil thaws, since the sensor is not able to measure accurately moisture when the soil is frozen. In 2003, soil at 80 cm depth thawed approximately on July 20th whereas in 2004, soil at 80 cm thawed approximately on August 16th, almost one month later than in 2003. In 2003, measurements started when the soil thawing depth had reached 37 cm, on June 7th. In 2004, on the same day, the thawing depth was 30 cm. On July 1st the thawing depth reached 76 cm and 56 cm in 2003 and 2004 respectively and on August 15th, the thawing depth was 134 and 107 cm in 2003 and 2004 respectively. Soil thawing, as mentioned above, occurred at a higher rate in 2003 than in 2004 and consequently the thawing depth at the end of the growing season reached approximately 140 cm depth on September 17th in 2003, whereas in 2004 the thawing depth was approximately 120 cm on September 20th (Fig.4). It is important to mention that despite lower precipitation the layer of soil containing high water (and ice) content beneath 120 cm was not made available for tree use during this year and which according to Sugimoto et al. (2003) ranges annually between 0.4 to 0.7 g cm^{-3}.

3.3 Tree Sap flow and soil moisture availability

Maximum values of sapflow of individual trees were higher in 2003 than 2004. Dominant trees (C-159 and C-148) reached values between 2.5 and 3.0 kg h^{-1} respectively on July 14th and 15th and decrease to an average 2.2 kg h^{-1} in response to increases in diurnal *D*. Meanwhile, codominant (C-151, C-203) trees showed lower sapflow rates that ranged between 1.6 to 2.0 kg h^{-1} without any apparent effect caused by changes in diurnal *D* on July 16th. Suppressed trees values ranged from 0.8 to 1.0 kg hr^{-1} showing the same behavior toward *D* as the codominant trees. In contrast, in 2004, the differences among the three different crown classes narrowed. Maximum values for the dominant trees were between 1.4 and 1.7 kg h^{-1}, codominant ranged between 1.2 to 1.4 kg h^{-1} and suppressed trees ranged from 0.3 to 0.4 kg h^{-1} from July 6th to 8th (Fig.5a). Light trapping ability by taller tree canopies made dominant trees start transpiring earlier than smaller trees (between 1 or 2 hours earlier) due to induced stomata opening. The response of tree sapflow to diurnal changes in *D* (Fig. 5b) appears to diminish when soil moisture decrease below 20 m^3 m^{-3} in the upper layers.

The maximum sapflow rate of 42.4 and 26.5 kg h^{-1} corresponded to dominant trees on July 27th 2003 and June 28th in 2004 respectively. In general, daily sapflow rates were lower in 2004. Following the diurnal change in 2003, bigger and high transpiring dominant trees showed larger values than codominant and suppressed trees. In 2004, sapflow from dominant trees decreased, bringing them closer to the codominant trees sapflow rates. The maximum value of sap flow found in this study was lower than the maximum value (67 kg h^{-1}) found by Arneth et al. (1996) for *Larix gmelinii* in another location in eastern Siberia or by Schulze et al. (1985) in Europe, where the value reached 74.4 kg h^{-1} for *Larix* sp. In the study carried out by Kuwada et al (2002), only sapflow total average values were presented and not individual tree values, making comparison difficult.

3.4 Scaled up transpiration (E_c) and canopy conductance (g_c)

The maximum E_c value found for 2003 and 2004 was 1.7 and 1.2 respectively. After intensive precipitation at the end of July and relatively high air temperature, transpiration steadily decreased to 0.2 mm d^{-1} because of a rainless precipitation span of almost three weeks and the limited water storage capacity of sandy soils, where saturation of soil water and ice content in the larch forest ranges from 0.27 to 0.35 g cm^{-3} (Sugimoto et al., 2003). On August 11th 2003, when E_c was 0.4 mm d^{-1}, solar radiation (around 392.7 W m^{-2}), and D (3.0 kPa) did not show different values from those found (394.7 W m^{-2} and 3.1 kPa respectively) when transpiration reached its peak values (1.6 mm d^{-1} on July 27th). From July 7th until the end of July, transpiration remained constant at an average value of 1.3 mm d^{-1} in 2003 while in 2004 the average for the same period of time was 0.9 mm d^{-1}. In August there was an increase of transpiration as a response to precipitation but its peak was much lower than the peak observed in June-July, signaling the lower transpiration capacity of larch trees at this time of the season. At the beginning of September E_c decrease is accompanied with leaf shedding, setting the end of the growing season (Fig.6). The maximum value of transpiration found in this study was 1.7 mm d^{-1} and the average during the growing season was of 0.79 mm d^{-1}.

The correlation coefficient between E_c and D was 0.05 and 0.81 in 2003 and 2004 respectively. At higher values, E_c appears to reach a plateau which is exactly the period measured in 2003 and thus the correlation appears significantly low for this year. Canopy conductance showed a strong relationship with D in 2003 and 2004 (r^2 =0.72 and 0.71 respectively). Maximum average g_c value was 3.1 mm s^{-1}

and 3.7 mm s^{-1} in 2003 and 2004 and minimum values were 0.91 and 0.84 mm s^{-1} when D was around 3.5 kPa (Fig.7). In 2003, g_c values were higher than in 2004 at the same values of D because of inter-annual differences in soil moisture. Soil moisture at 10, 20 and 30 cm depth showed a good correlation with g_c (0.68, 0.80 and 0.83 respectively) in 2003 but there was no relationship between g_c and soil moisture at the same depths in 2004 (Fig.8). The difference in slope can be interpreted as differences in root water uptake zones. Soil moisture at 10 cm is affected by rapid filtration because of the abundance of organic material and root water uptake. Soil moisture at 20 cm is predominantly affected by root water uptake and lower filtration rate because of its mineral composition.

4. Discussion

4.1 Sapflow rate and total transpiration

Higher sapflow rates corresponded to trees with bigger diameters or higher tree crown class. However, bigger trees lowered their water loss rate more than suppressed trees when soil moisture was less available, as could be observed in this study because of differences in diurnal changes in D or precipitation regimes. As expected for coniferous trees D is an important variable controlling sap flow movement and its control remains strong even at lower soil moisture values, especially in the upper soil layers. There is a seasonal and inter-annual response of tree sap flow to environmental variables and soil moisture. The maximum values of sapflow found in this study were lower than those reported by Arneth et al., (1997) probably as a result of soil texture differences (silty loam versus sandy loam in this study) in eastern Siberia and differences in precipitation regimes (702 mm) and soil texture (podsolic loam) in a European site (Schulze et al., 1985). By using the eddy covariance technique, forest evaporation was estimated as 3 mm d^{-1} (Ohta et al., 2001; Dolman et al., 2005) which, according to our results, indicates that canopy transpiration contributes to 50% of the total forest evaporation. This is in agreement with Kelliher et al. (1997, 1998), who found the same proportion for a Siberian larch and pine forest respectively. Average transpiration during the full-leaved growing season was around 1.46 mm d^{-1} (Dolman et al., 2004), which is also in agreement with the approximately 50% contribution of canopy transpiration found in this study (average value 0.79 mm d^{-1}). Furthermore, in comparison with data obtained from eddy correlation measurements in the same site in 2003

(CREST/WCNoF, 2003) and 2004 (Kuwada et al., 2004), it was found that transpiration contributed to 47 and 60 % of the total forest evapotranspiration in 2003 and 2004 respectively. This indicates that the partition of water fluxes from tree canopy and understorey has an inter-annual variation depending on the inter-annual climatic conditions. Nevertheless, these results highlight the importance of understorey transpiration in the total forest evapotranspiration.

When values obtained by Arneth et al., (1996) are used for scaling up to canopy transpiration, the maximum value is 2.3 mm d^{-1}, which according to their own conclusions, was 0.6 or 0.7 mm higher than the values reported by Kelliher et al (1997).

4.2 Soil thawing depth, soil moisture and transpiration

Canopy transpiration starts increasing from DOY 152 in 2004 when needles growth is enhanced by root activity resulting from soil thawing depth reaching 25cm depth. In the study by Dolman et al. (2004) this activity starts on DOY 150, suggesting that understorey transpiration was not detected before canopy transpiration, or that both started simultaneously. During the period of maximum transpiration, from the beginning to the end of July, the thawing depth varied from 77 to 116 cm in 2003 and from 58 to 90 cm in 2004. This is the period of maximum water uptake by roots from the soil. During this period of time deeper layers have not thawed, and consequently neither has the permafrost layer. The results found in this study contradict the findings of Sugimoto et al. (2000), who suggested that trees could use thawed permafrost water for their supply. Following this same criterion, Dolman et al (2004) suggested that in the year 2000 thawed permafrost water could maintain water supply for tree roots. However, our results suggest that their observations are probably the result of shallow active layers that kept soil moisture available for trees rather than water being supplied from lower soil layers. It is also necessary to clarify that between the active layer and the permafrost, there is a layer of soil known as the 'transient layer' or 'shielding layer' (Shur, 1988). This layer is characterized by low-ice-content as a result of deep thawing in warm years (Brouchkov et al., 2004).

It is in mid August of 2003 and 2004 that the thawing depth reached deeper layers, but by this time water demand by trees was lower than in mid July. In this study, the difference in thawing depth was 20 cm at the end of the growing season, which remained frozen in 2004 but it was part of the active layer in 2003. Soil moisture below 80 cm does not significantly contribute to tree transpiration as deduced from the lack of change in the 80cm soil moisture curve during the growing season of 2003 and 2004.

Larch tree roots need to be distributed in the upper layers to uptake water as early as possible to complete the approximately 100 days leaved growing season cycle in Siberia. Thus, the thawing of upper soil layers from mid May sets the start of larch tree activity. Soil moisture at 0-30 cm strongly controls the variation in transpiration (where the bulk of the roots distribute, Kuwada et al. (2000)). In 2004, precipitation was nearly half of that in 2003 but the difference in distribution during the growing season allowed through, more frequent but less intense precipitation to keep transpiration going at a nearly constant rate, together with shallow thawed soil layers, from June to early July. In 2003, a rainless period of nearly 20 days set the conditions for a steady decrease in transpiration. Soil moisture at 20 and 30 cm decreased proportionally and more in 2004 than in 2003, reflecting more active tree water uptake from deeper layers as a result of lower precipitation.

4.3 Canopy Transpiration, canopy conductance and environmental variables

Higher air temperature (mean daily value of 25 deg.C), higher *VPD* (mean daily value of 2 kPa) and precipitation, promoted higher transpiration rates during the growing season of 2003. As expected for coniferous trees *D* is an important variable controlling sap flow movement during fine weather days but this response decreases when soil moisture in the upper layers is low. Our results concur with Dolman et al (2004), in that years with higher soil moisture and fine weather, forest evaporation and consequently canopy transpiration is high. In August 2003, when soil moisture decreased during a rainless period, g_c was not coupled with *D*, but during the same period it was well coupled with soil moisture at 10, 20 and 30 cm. This is in contrast to the results of Ohta et al (2001), where a clear relationship between canopy conductance and soil moisture was not found because of the dual-source nature of forest evaporation and the nearly equal contribution of understorey and tree canopy. This suggests that understorey vegetation plays a higher role in the total forest evaporation than previously estimated (Ohta et al., 2001), because of the openness of larch forests in Siberia (Nikolov and Helmisaari, 1993).

5. Conclusions

1. Inter annual variation in total transpiration because of environmental conditions is influenced by larger sapflow rate variability of dominant trees. Maximum daily sapflow rate for larch trees in eastern Siberia was 42.4 kg d^{-1}.
2. The upper soil layer played an important role in the control of transpiration. Maximum canopy transpiration was 1.7 mm d^{-1} during fine weather and well watered conditions and 1.2 mm during a dry year. Results indicate that tree canopy transpiration contribution to the total forest evapotranspiration ranges between 50 to 60 % and that water flux partition between trees and understorey is affected by inter-annual climatic conditions.
3. Seasonal lower soil thawing rates set off the effect of low precipitation regimes that otherwise will lower soil moisture content by filtration in sandy loam soils. Therefore it is not only the presence of permafrost that keeps moisture in the thin active layer, but it is the soil thawing rate that plays the important role of controlling the amount of water available for trees in response to changing environmental conditions during the growing season.

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Figures captions

Fig1. Diameter at breast height (dbh) distribution of the studied stand *(above)*. Characteristics of the sampled trees for sapflow measurements at the experimental site.

Fig2. Relationship between tree diameter (at breast height) and sapwood thickness measured on cores. The number of trees selected was 26.

Fig3. Meteorological conditions in 2003 and 2004 at Spasskaya.

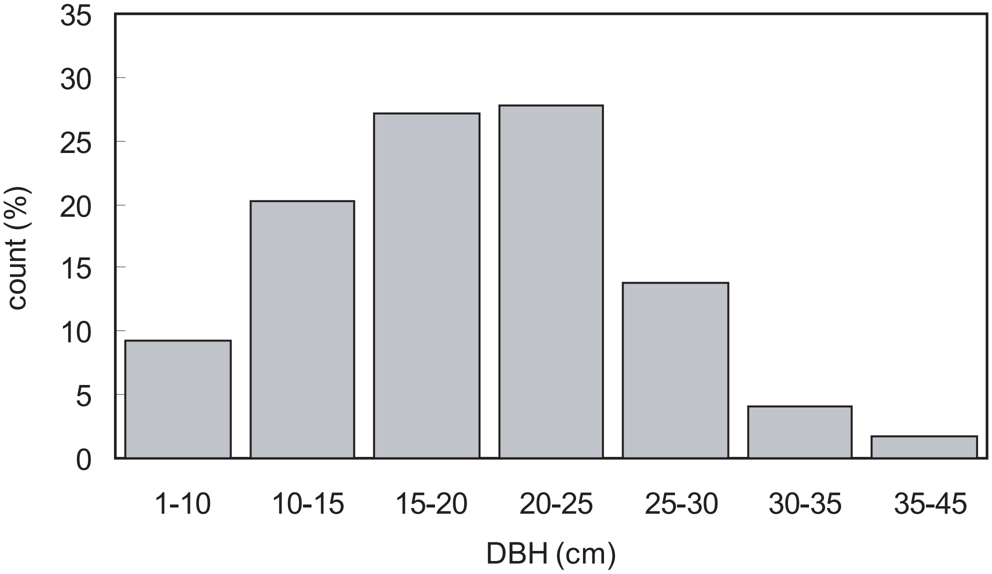
Fig4. Soil moisture in 2003 (June 6 – Sept 30) and 2004 (May 7th – Sept 27th) at the experimental site. Soil thawing depth (STD) is represented by the '0' isotherm measured simultaneously with soil moisture. Maximum soil thawing depth in 2003 was 140 cm on Sep 17th and 120 cm on Sep 20th 2004.

Fig5. Half-hourly averages of sapflow rates, during a 3-day measurement period in 2003 (July 14-15th) and in 2004 (July 6-7th): dominant trees, codominant tree and suppressed trees (a) and half-hourly averages of solar radiation (S_r) and vapor pressure deficit (D)(b). The labels in the right upper side of the above graph indicate the tree crown class as specified in Fig.1

Fig6. Canopy transpiration (E_c) in 2003 (July 7th – Sept. 30th) and 2004 (May 20th – Sept 27th). Maximum E_c value in 2003 was 1.7 mm d^{-1} on July 10th and 1.2 mm d^{-1} on July 7th in 2004

Fig7. (a) Relationship between E_c and D in 2003 (filled circles) and 2004 (open circles). There was no response of E_c to D in 2003 but the longer period of measurement in 2004 showed a much stronger response of E_c to D (R^2=0.81). (b) Relationship between g_c and D in 2003 (filled circles) and 2004 (open circles). The correlation for both years is the same (0.72 and 0.71 respectively). These data correspond to fine weather and well watered days.

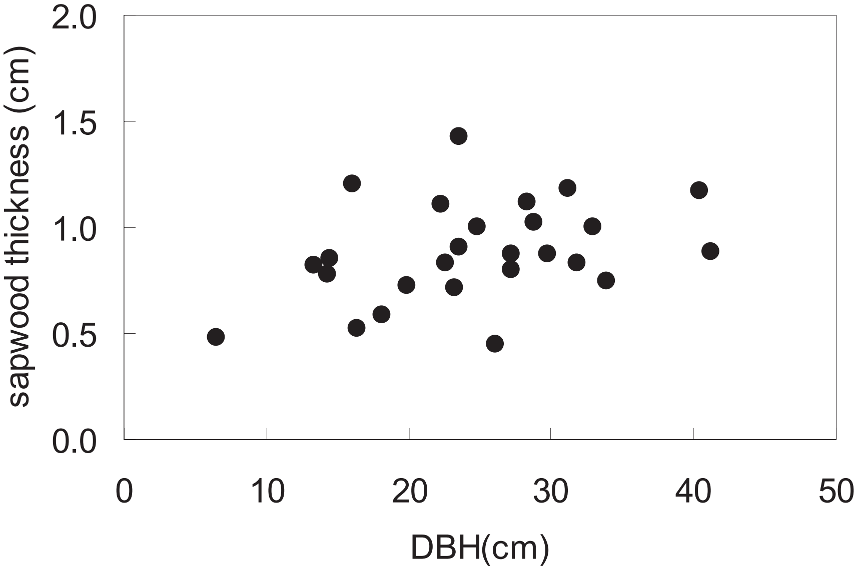
Fig8. (a) Relationship between g_c and soil moisture at 10 cm (x), 20 cm (+) and 30 cm (-) in 2003 and (b) 2004.



Crown class	Tree	DBH (cm)	Height (m)	SW_{thick} (cm)	SW_{area} (cm^2)	a (%)	b (%)	PCA (m^2)
D	C-148	36.5	21.3	0.95	92.0	0.47	0.53	27.7
D	C-159	34.6	19.6	0.92	87.0	0.46	0.54	28.8
C	C-203	27.6	20.5	0.54	68.6	0.27	0.73	10.6
C	C-243	26.1	23.2	0.51	64.6	0.25	0.75	14.2
C	C-119	24.0	18.3	0.71	59.1	0.36	0.64	14.6
C	C-151	20.5	18.1	0.67	49.9	0.33	0.67	14.7
S	C-132	20.0	17.8	0.89	48.6	0.44	0.56	8.3
S	C-211	19.8	17.0	0.58	48.1	0.29	0.71	11.0
S	C-144	15.9	17.9	1.07	37.8	0.54	0.46	10.6
S	C-158	12.9	14.5	1.07	29.9	0.54	0.46	12.1

Fig.1 Lopez et al.

Figure



Figures 2 Lopez et al.

Figure

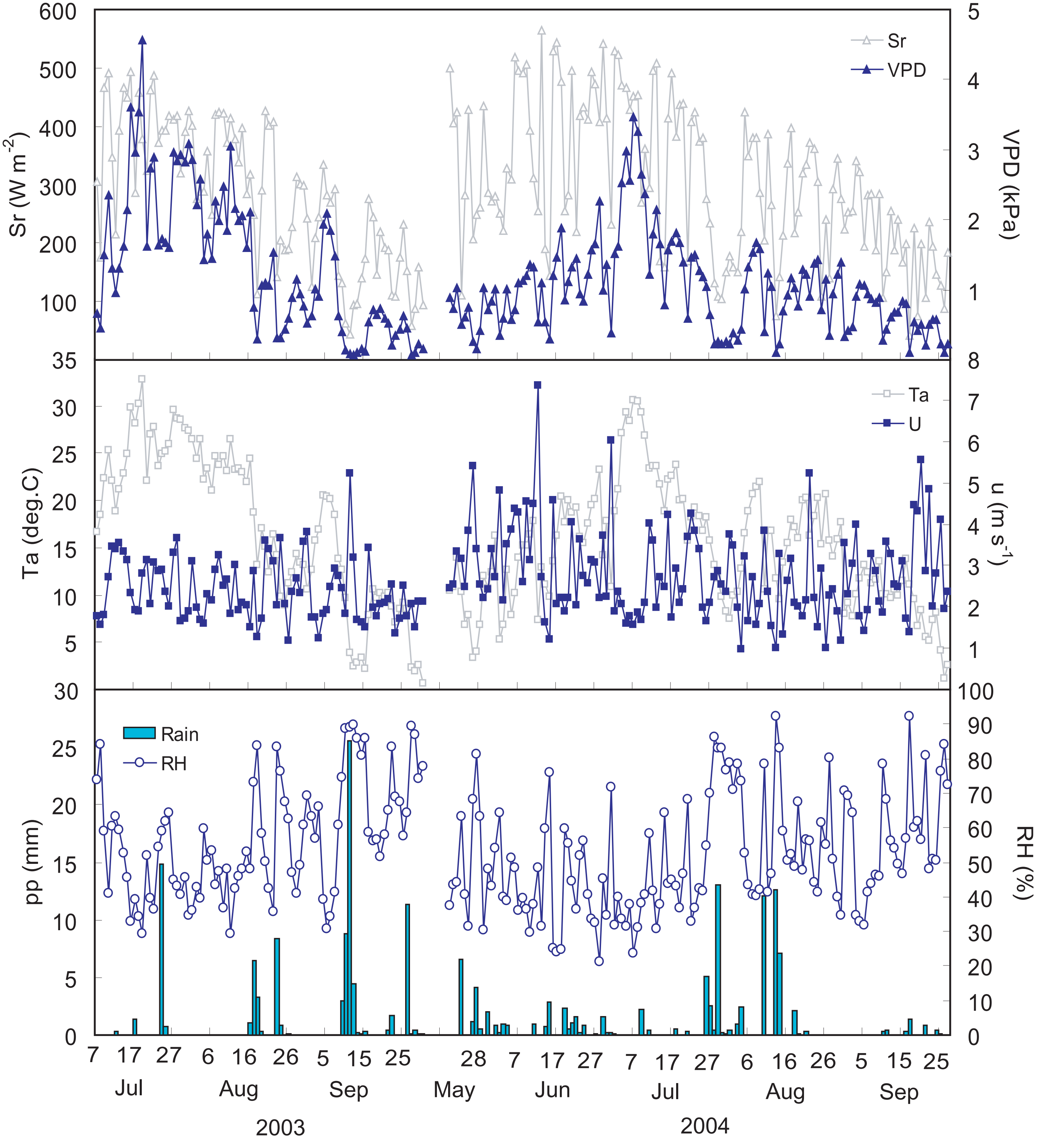


Fig.3 Lopez et al.

Figure

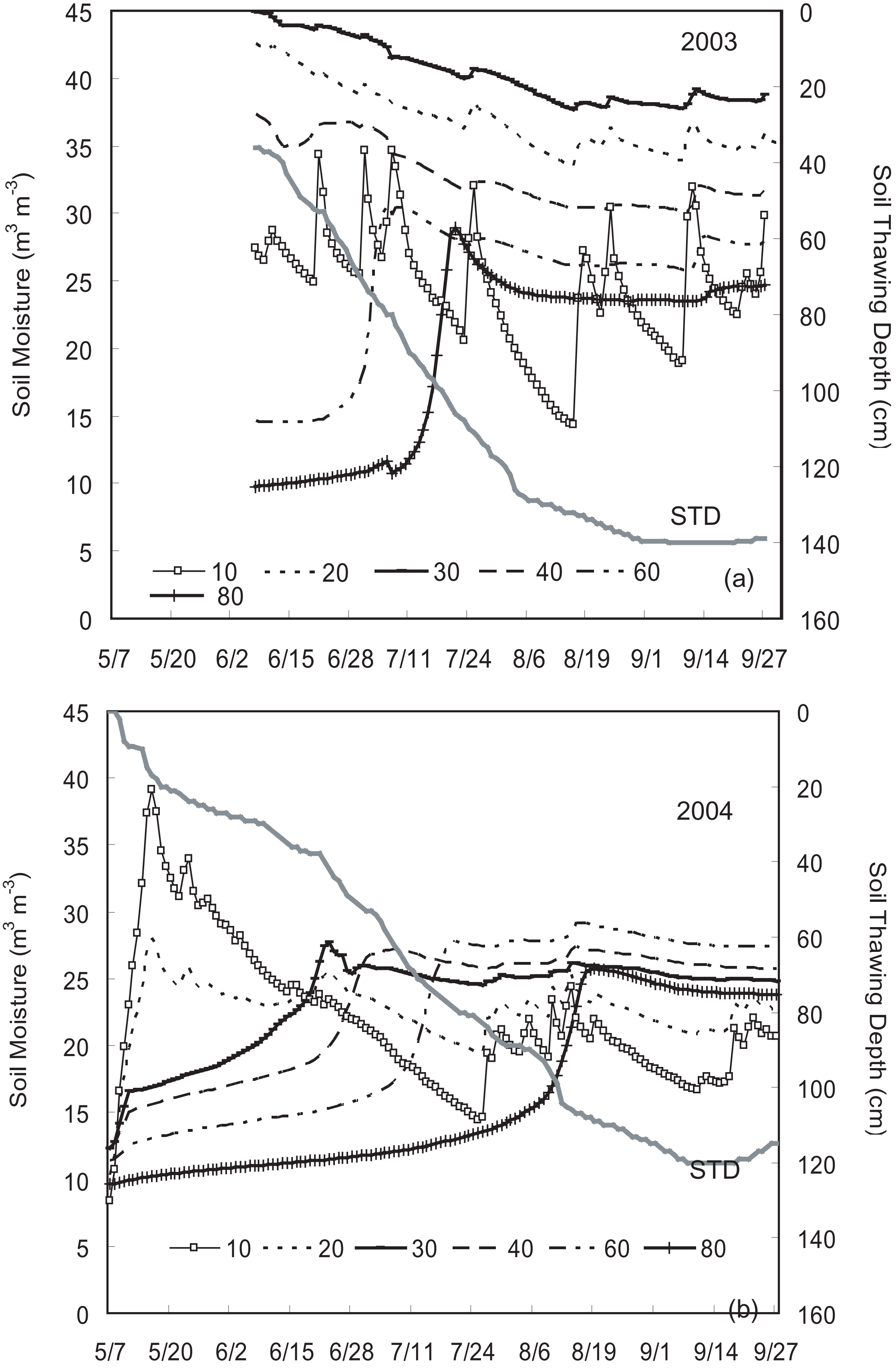


Fig. 4 Lopez et al.

Figure

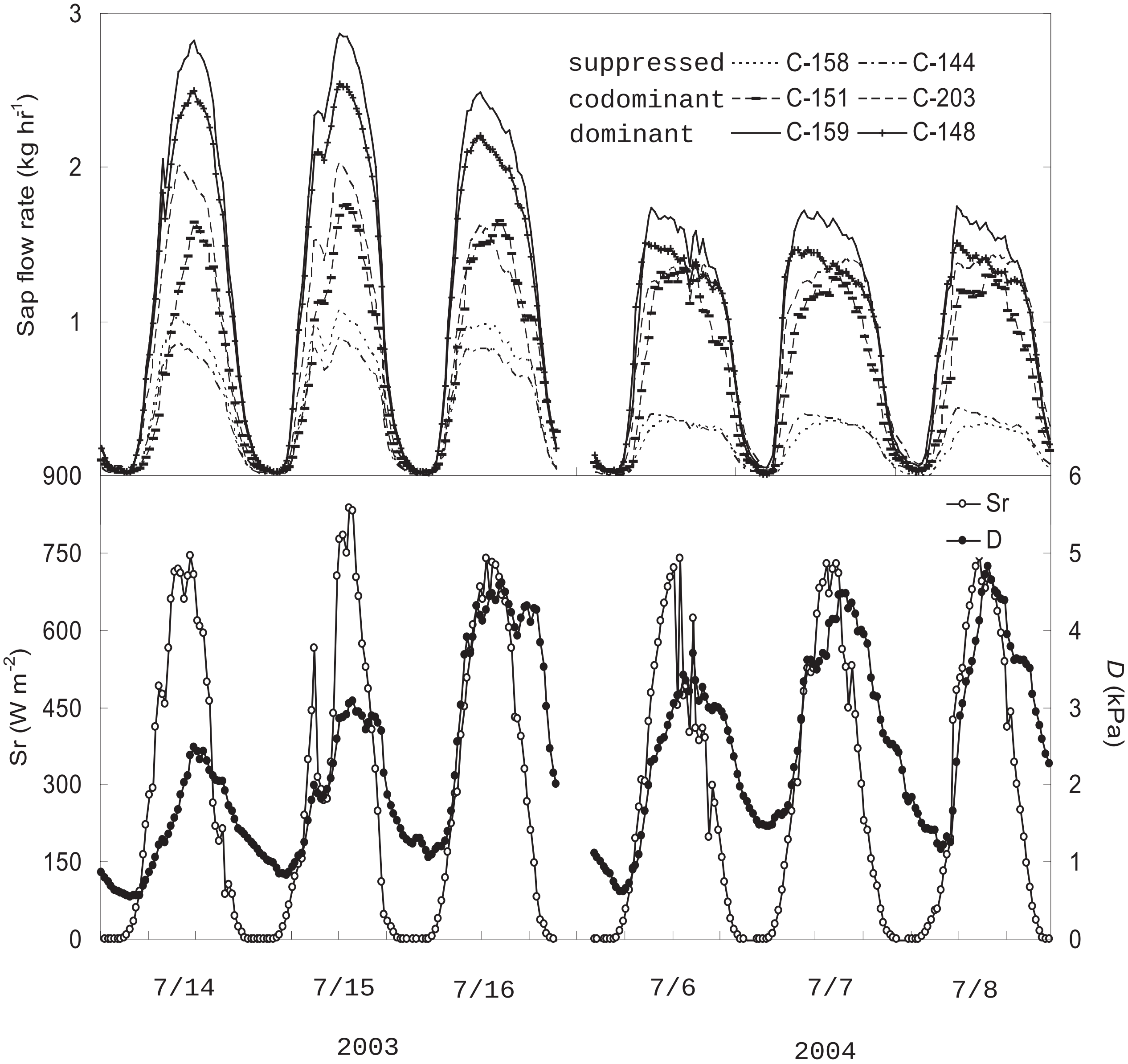
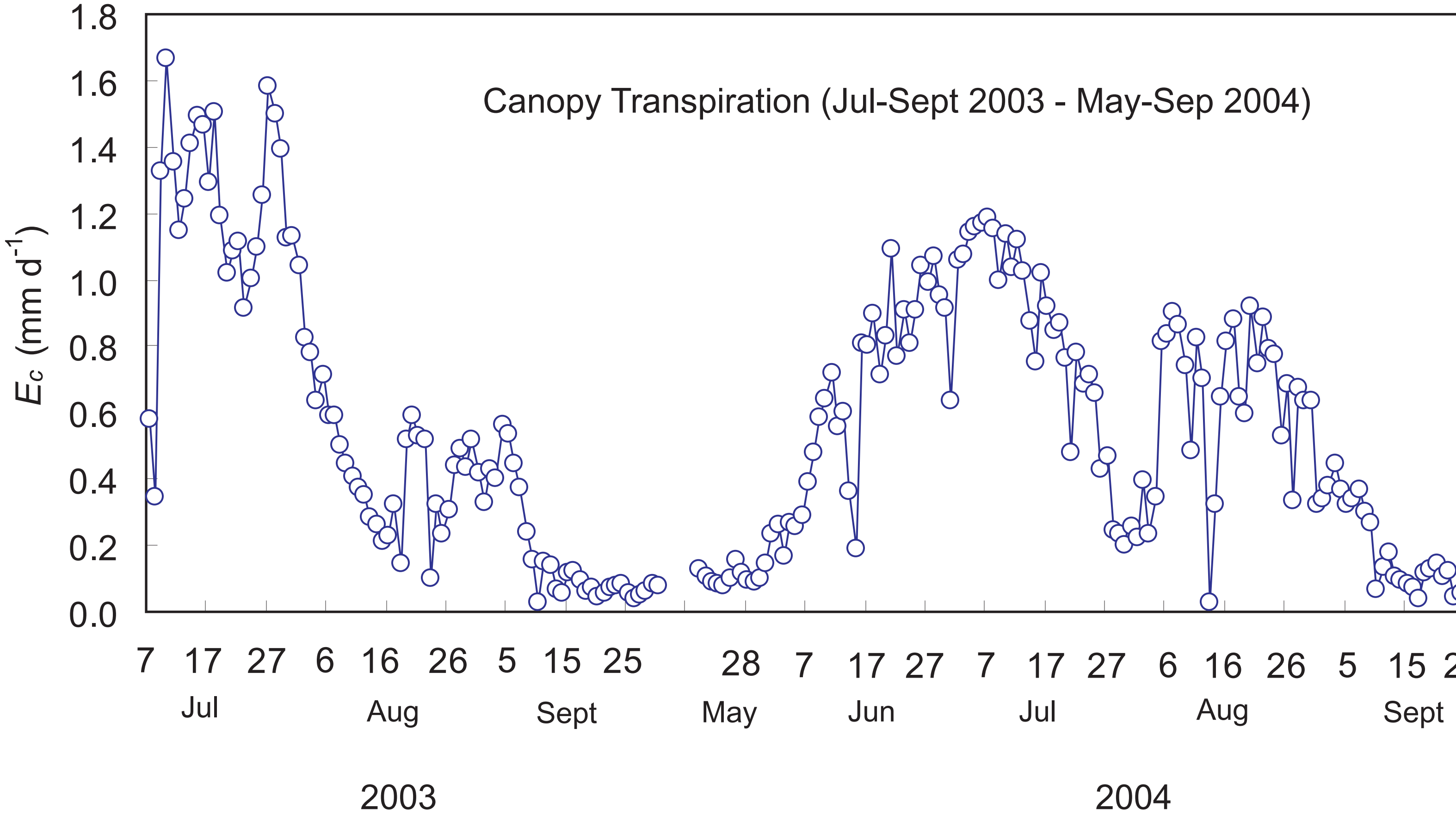


Fig. 5 Lopez et al.

Figure



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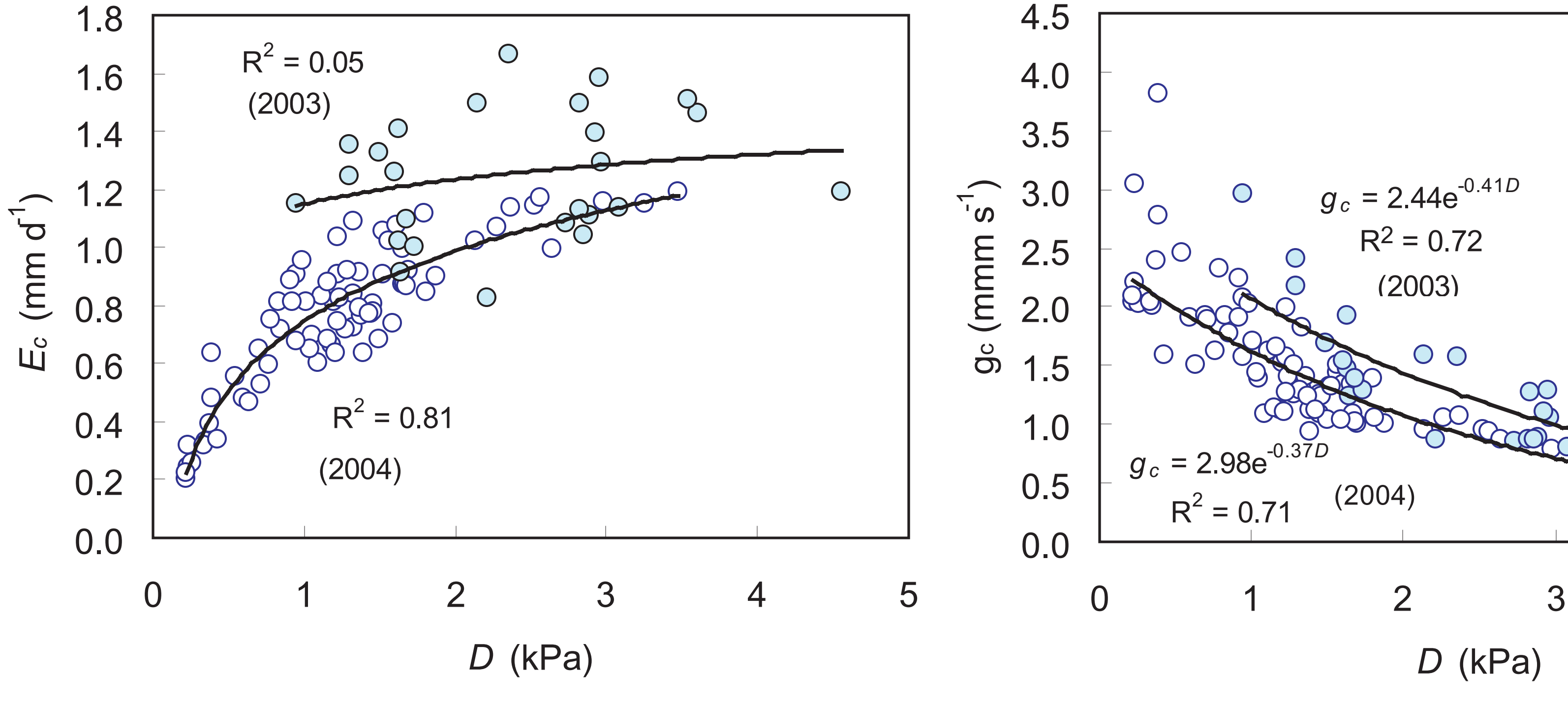

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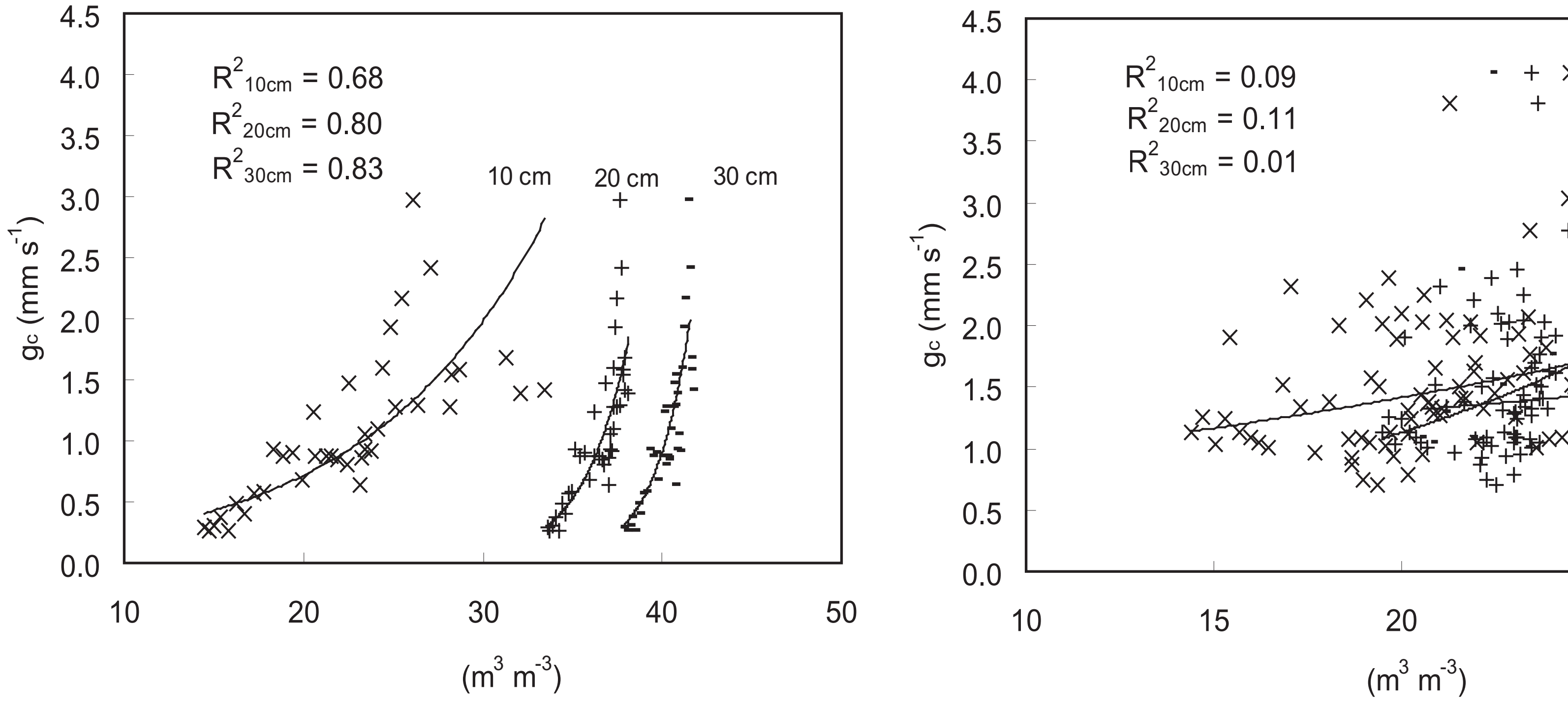

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