Effect of increased rainfall on water dynamics of larch (*Larix cajanderi*) forest in permafrost regions, Russia: an irrigation experiment

M. L. Lopez C. · T. Shirota · G. Iwahana ·
T. Koide · T. C. Maximov · M. Fukuda · H. Saito

Abstract Sap flow measurements, from July to August 2004, were coupled with micrometeorological, soil moisture, and soil temperature measurements to analyze forest water dynamics in irrigated and undisturbed (control) larch (*Larix cajanderi*) forest plots in eastern Siberia. Plots were irrigated with 120 mm (20 mm day^{-1}) of water from 17 to 22 July. Sap flow measurements of ten trees at each plot were scaled up to daily stand canopy transpiration (E_c). Canopy transpiration at the irrigation and control plots was similar before irrigation. Forest evapotranspiration (E_a) was obtained from Ohta et al. (Agric For Meteorol 148:1941–1953, 2008) while E_a in the irrigation plot was estimated based on the E_{c_irrig}/E_{c_cont} ratio. Rainfall during July–August was 63.4 mm but, after including water from thawing soil layers, the actual water input was 109.9 and 218.5 mm in the control and irrigation plots, respectively. Despite this large difference, a corresponding difference in E_c (and E_a) was not observed [42.6 (61.5) mm and 46.4 (71.8) mm in control and irrigation plots, respectively]. Daily canopy conductance (g_c) increased as long as moisture was well supplied in the upper soil layers and evaporative demand was high. Soil moisture and rainfall contribution to E_a was 36.9 and 24.6 mm in the control plot and 34.5 and 37.3 mm in the irrigation plot, respectively. Water supply from soil thawing layers in the control plot and high runoff (105.6 mm) rates in the irrigation plot accounted for the similarity in water dynamics. Under increased precipitation, the forest used less soil water stored from previous growing seasons.

Keywords Canopy conductance · Canopy transpiration · Irrigation · Permafrost · Rainfall · Soil moisture

M. L. Lopez C. (✉)
United Graduate School of Agricultural Sciences,
Iwate University, Ueda 3, 18-8, Morioka, Iwate, Japan
e-mail: larry@iwate-u.ac.jp

T. Shirota
Faculty of Agriculture, Shinshu University, Minami-minowa,
Nagano 399-4598, Japan

G. Iwahana
Graduate School of Engineering, Hokkaido University,
N13W8, Sapporo 060-8628, Japan

T. C. Maximov
Institute of Biological Problems of Cryolithozone,
Russian Academy of Science, 41 Lenin Ave.,
Yakutsk 677891, Russia

M. Fukuda
Institute of Low Temperature Science, Hokkaido University,
N19W8, Sapporo 060-0819, Japan

T. Koide · H. Saito
Graduate School of Agriculture, Hokkaido University,
N9W9, Sapporo 060-8589, Japan

Introduction

The boreal forest in eastern Siberia, dominated by larch (*Larix cajanderii*), covers an approximately continuous permafrost area of 1.1 million km^2 (Shvidenko and Nilsson 1994). Permafrost regions occupy about 25% of the terrestrial surface in the northern hemisphere of which 60% is in Siberian Russia (Kudrjavtsev et al. 1978). The water use efficiency of larch forest during the short growing season in eastern Siberia (approximately 100 days) is influenced by the soil thawing rate (Lopez et al. 2007a), soil moisture (Sugimoto et al. 2003), and vapor pressure deficit (Dolman et al. 2004). The limited annual rainfall regime of 250 mm is unevenly distributed in summer during the growing

season, with over 40 mm of rainfall on some days. Present climate change trends indicate increases in summer precipitation for the period 1986–2004 in this region (Park et al. 2008). Changes in rainfall regime are expected to have a great impact on the water balance of the forest through its influence in the shallow active layer where the tree root system is distributed. However, there is evidence that inter-annual forest evapotranspiration and canopy transpiration does not vary in relation to large annual variation in rainfall (Dolman et al. 2004; Lopez et al. 2007a; Ohta et al. 2008). Furthermore, the modest inter-annual variation in canopy transpiration can be attributed to multiple inter-annual climatic factors that directly affect tree water use and soil thawing rate. In view of the present warming effect on permafrost regions (Fedorov and Konstantinov 2003; Jorgenson et al. 2006), this study explores the forest water dynamics via a controlled experiment where drastic increases in rainfall are simulated by irrigation. The results are compared to a control plot in order to evaluate the effect of increased rainfall under the same environmental conditions. The few studies carried out in boreal regions where irrigation and nutrients were applied have focused on tree growth (Bergh et al. 1999; Albaugh et al. 2004; Waterworth et al. 2007) and forest water relations (Cienciala et al. 1994; Ewers et al. 2001; Waterworth et al. 2007), but to our knowledge there has been no irrigation experiment focused on water dynamics of boreal forests underlain by permafrost.

Therefore, the objectives of this study are (1) to assess the effect of change in soil moisture as a result of irrigation on larch canopy transpiration and canopy conductance, and (2) to determine the water budget of the larch forest ecosystem under control (no irrigation) and increased rainfall (irrigation).

Materials and methods

Study site: control and irrigation plots

The experimental site has been thoroughly described in Ohta et al. (2001) and Lopez et al. (2007a). It is located 35 km NNW from the city of Yakutsk in eastern Siberia (62°15′N, 129°37′E, altitude 220 m) (Fig. 1). Forests in this area are exposed to dry conditions with an annual rainfall of approximately 250 mm (almost half of which occurs during the growing season). The forest is dominated by a 160-year-old *Larix cajanderi* monoculture with a tree density of 1,000 trees per ha. The sapwood basal area is 4.7 m^2 ha^{-1} and the mean height is 13 m. Larch tree root distribution shows high root concentration in the upper layers, with thicker root diameters ($d > 50$ mm) in the mineral soil. In the upper 0–10 cm soil organic layer, root
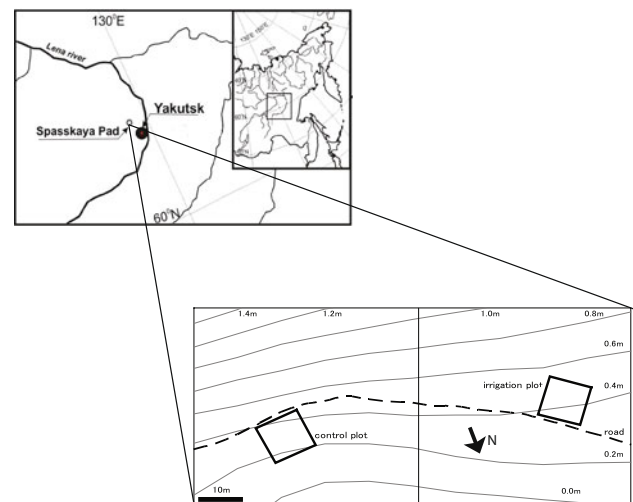

Fig. 1 Location of the study site and schematic of the control and irrigation plots and relative height of the study site

diameters ranging between $20 < d < 50$ mm are abundant whereas below 40 cm depth, root density is composed of roots with $d < 2$ mm (Kuwada et al. 2002).

In this study, two plots of 14 × 14 m (control and irrigation) were set. Irrigation was evenly applied within the plot during 6 consecutive days (20 mm per day), from 17 to 22 July in 2004 with a total of 120 mm applied through sprinklers installed around and within the site at a height of 70 cm. The irrigation occurred between 1600 and 1900 hours. The water used had an electric conductivity of 0.1 mS cm^{-1} and was carried in tanks from the Lena River. The water temperature at the moment of irrigation was around 2°C lower than air temperature. The understorey vegetation in the plots was cowberry (*Vaccinium vitis-idaea*). Both plots were at the same relative height in the west–east direction and the slope southward was 1.6%.

Weather, soil moisture and soil temperature measurements

Weather data were recorded for the period July–August 2004, representing the active phase of the growing season. The variables measured were rainfall (raingauge; Young, USA), short-wave radiation, S_r (pyranometer, CPR-PCM-01; Prede, Japan), relative humidity-air temperature, RH and T_a (HMP-35D; Vaisala, Finland) and wind speed, u (3-cup anemometer, CYG-3002; Young). These data were collected continuously every 10 min (CR10X datalogger; Campbell Scientific, UK) at the top of a 32-m-high scaffolding tower built in the larch forest by Ohta et al. (2001), located approximately 160 m SW of the control plot.

Soil moisture FDR (frequency domain reflectometry) sensors were installed at 10, 20, 30, 40, 60, and 80 cm depth (EnvironSMART; Sentek, Australia) at the center of

each plot and the results were calibrated with direct weight measurements at all depths. These data were collected continuously every 30 min in separate loggers (CR10X datalogger; Campbell). Daily soil moisture averages were calculated for the same period as above.

The soil thawing depth, represented by the 0°C isotherm was determined by soil temperature data collected from 7 May to 27 September 2004. Soil temperature was measured at 0, 10, 20, 30, 40, 60, 80, 100, 120, 140, 160, 180, and 200 cm depth (three replications) thermistors (104ET; Ishiizuka Denshi, Tokyo, Japan) in the control and irrigation plots in the spring of 2003. Thermistors were calibrated using an ice-water bath with a precision of 0.02°C at 0°C. The overall probe accuracy for the temperature range from −20 to 30°C was ±0.09°C.

Canopy transpiration (E_c)

In each plot, ten trees were chosen as a representative sample of each crown class and DBH (diameter at breast height) (Table 1). Sapwood cross-section of the trees studied and total stand sapwood were estimated from cores. The relationship between sapwood and tree diameter was used to estimate sapwood area (Lopez et al. 2007a) for each crown class at each plot. Because sap flow velocity is underestimated when part of the probe is in the non-conducting wood, individual tree sap flow values were corrected for differences in needle length and sapwood thickness (Clearwater et al. 1999).

Sap flow measurements for this study were conducted from 1 July to 31 August at each plot by the thermal dissipation technique (Granier 1987) with 20-mm-long radial sap flow sensors (UP; Umweltanalytische Produkte, Germany) installed at a height of 1.3 m in the stems. Sap flux

density (U, m^3 m^{-2} s^{-1}) was estimated by this technique. Sap flow data were collected each 10 s, and 10-min average values were stored on a CR10X datalogger. Total tree sap flow (F) was calculated as the product of U multiplied by the sapwood cross-section. Sap flow measurements carried out in individual trees were scaled up from tree to stand level using sapwood area distribution as described in Granier et al. (1996). Stand sap flow (E_c, mm day^{-1}) was calculated independently for each plot as:

$$E_c = S_T \sum p_i U_i \tag{1}$$

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. Calculations were based on 1-day interval data.

Canopy conductance (g_c)

Canopy conductance at the control (g_{c_cont}) and irrigation (g_{c_irrig}) plot was computed by the inverse form of the Penman–Monteith equation (Monteith and Unsworth 1990) assuming that stand sap flow was equal to stand transpiration (E_c, mm s^{-1}) as in Eq. 2:

$$\lambda E_c = \frac{\Delta(R_n - G) + \rho C_p D g_a}{[\Delta + \gamma(1 + (g_a + g_c))]} \tag{2}$$

where Δ is the rate of change of saturation vapour pressure (Pa C^{-1}), R_n is the net radiation (W m^{-2}), ρ is the density of dry air at constant pressure (J kg^{-1} C^{-1}), D is the vapour pressure deficit (Pa), g_a is the aerodynamic conductance (m s^{-1}), g_c is the canopy conductance (m s^{-1}), λ is the latent heat of vaporization of water (J kg^{-1}), and γ is the psychrometric constant (Pa C^{-1}). In this study, the soil heat flux (G) is taken as 10% of the R_n based on previous results (Iwahana et al. 2005). Aerodynamic conductance (g_a, m s^{-1}) was calculated as

$$g_a = \frac{k^2 u}{\left\{\ln\left[(z - d)/z_0\right]\right\}^2} \tag{3}$$

The displacement height (d) was set as 0.67 h and the roughness length (z_0) as 0.1 h, 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). In order to account for the time lag between sapflux and canopy conductance, daily values were used.

Water budget

The water budget of the forest ecosystem was estimated using the soil equivalent depth of water from July to August. Daily forest evapotranspiration (E_a) calculated from latent heat measured by the eddy covariance

Table 1 Characteristics of the ten trees selected for sapflow measurements in the control and irrigation plots

Control plot				Irrigation plot			
Tree	Class	DBH	Height	Tree	Class	DBH	Height
C-148	D	36.5	21.3	I-888	D	30.0	22.0
C-159	D	34.6	19.6	I-885	C	26.8	20.6
C-203	C	27.6	20.5	I-699	C	24.9	22.1
C-243	C	26.1	23.2	I-687	C	24.6	20.3
C-119	C	24.0	18.3	I-885	C	24.6	16.5
C-151	S	20.5	18.1	I-887	S	19.8	20.6
C-132	S	20.0	17.8	I-884	S	19.8	18.1
C-211	S	19.8	17.0	I-902	S	18.6	19.3
C-144	S	15.9	17.9	I-891	S	18.8	18.0
C-158	S	12.9	14.5	I-886	S	14.1	14.3

D Dominant, *C* codominant, *S* supressed, *DBH* diameter at breast height

method with the open-path gas analyzer for this year and location were obtained from Ohta et al. (2008). E_a in the irrigation plot was estimated based on the ratio between E_{c_irrig} and E_{c_cont}. E_a includes canopy transpiration (E_c) and evaporation from the understory vegetation (E_u), allowing us to equate the water lost as evapotranspiration with the water changes in the forest soil at each plot. In order to determine the movement of water in the upper soil profile, this was divided into the organic layer (0–10 cm), the mineral soil where the bulk of the tree roots are distributed (10–40 cm), and deeper soil layers (40–60 and 60–80 cm).

Results

Meteorological conditions, soil moisture and soil thawing depth

The year 2004 was relatively cool and dry compared to mean values for Yakutsk (Rivas-Martinez 2007). Total precipitation during the growing season from May to September was 110 mm (Lopez et al. 2007a). Air temperature in 2004 was high for a short period, from 4 to 10 July, with a maximum daily value of 30.6°C that was followed by daily T_a below 10.0°C (Fig. 2). Rainfall from 1 July until the irrigation day (17 July) was 2.9 mm, while rainfall from the day irrigation started to 31 August amounted to 60.5 mm.

Before irrigation was applied, soil moisture at the irrigation plot was higher than at the control plot (Fig. 3), which represents the micro-topographic differences that exist within the forest. After 6 days of irrigation (120 mm), soil moisture on the upper 10 cm layer increased 1.7 $m^3\ m^{-3}$, while at the 20, 30, and 40 cm depth, the increase was 2.3, 3.2, and 4.6 $m^3\ m^{-3}$, respectively. However, soil moisture at 60 and 80 cm showed the largest changes with 5.9 and 14.3 $m^3\ m^{-3}$, respectively. Meanwhile, in the control plot during this period, especially in the upper soil layers, moisture continued decreasing while in the lower layers it remained unchanged. From 26 July to 4 August, after 26.1 mm of rainfall, soil moisture in the control plot increased in the upper soil layers (0–20 cm) while no variation was observed at lower layers (30–80 cm depth). Rainfall during this period does not appear to contribute to increase soil moisture in the irrigation plot since no variation was observed at any of the measured depths, and it can be inferred that this water was lost as runoff.

On 1 July, the soil thawing depth (STD) was 55.0 and 57.0 cm in the control and irrigation plots, respectively. The first half of July was the warmest period of the growing season 2004, and accordingly the soil thawing rate
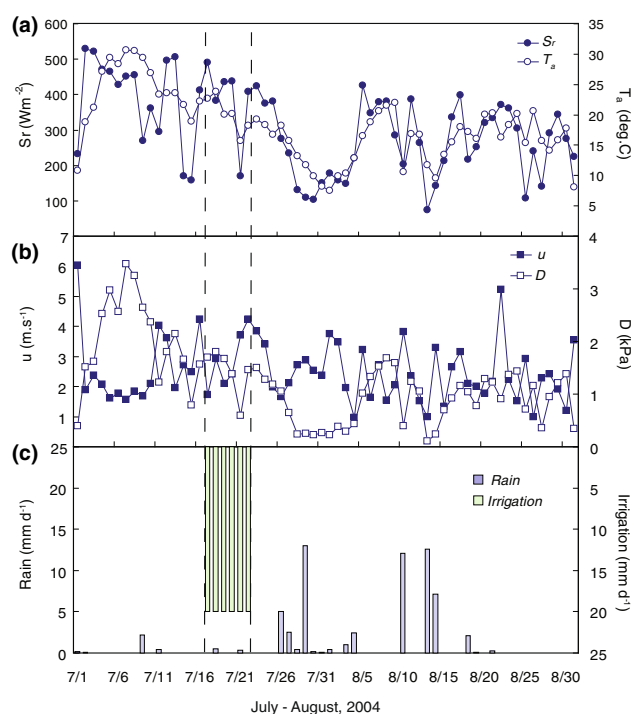
Fig. 2 Daily courses of meteorological parameters in 2004: **a** solar radiation (S_r) and air temperature (T_a); **b** wind speed (u) and vapour pressure deficit (D); **c** rain and irrigation (*upside down bars*). *Dashed lines* indicate the period when irrigation took place (17–22 July)

was the highest (1.4 cm day^{-1}). On the day irrigation began, the STD was 79.0 and 81.0 cm in the control and irrigation plots, respectively. After 6 days of irrigation, the STD increased by 5 cm (0.8 cm day^{-1}) and 17 cm (2.8 cm day^{-1}) in the control and irrigation plots, respectively, but from the time irrigation ceased and until the end of August, the soil thawing rate was 0.9 and 0.7 cm day^{-1} in the control and irrigation plots, respectively.

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

Before irrigation was applied (1–16 July), E_{c_cont} and E_{c_irrig} were on average 1.0 mm day^{-1} in each plot and the cumulative E_c during this period was 15.9 and 15.4 mm in the control and irrigation plot, respectively. Maximum E_c (1.2 mm day^{-1}) was reached on 7 July during the warmer period of the growing season. After irrigation, maximum E_{c_irrig} was 1.1 mm day^{-1} on 22 July while for the same day E_{c_cont} was 0.7 mm day^{-1} (Fig. 4a). On the days following irrigation, the difference between E_{c_irrig} and E_{c_cont} oscillated between 0.1 and 0.4 mm day^{-1} (18–69% higher). In the control plot, soil moisture appeared to recover after a period of continuous rain from 26 July to 4 August (25.1 mm). This was further accentuated after rainfall events on 13–14 August (19.1 mm) that brought
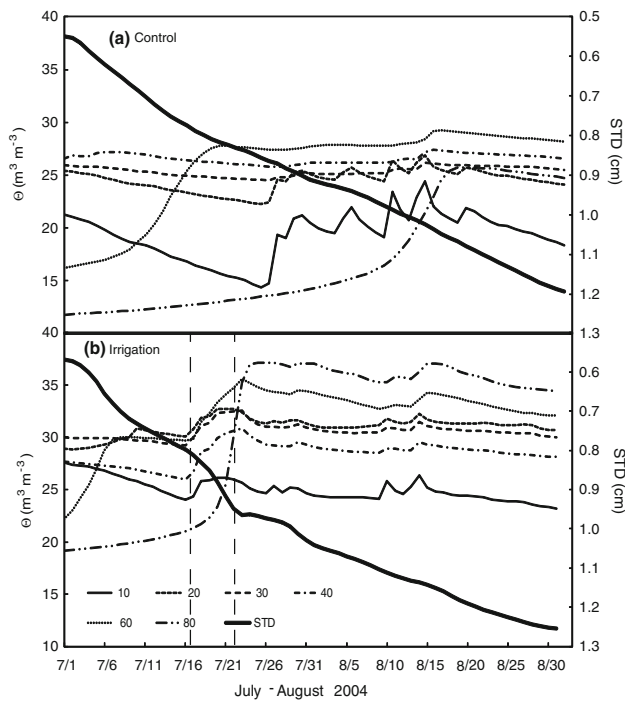
Fig. 3 Soil moisture and soil thawing depth in the **a** control and **b** irrigation plots at 10, 20, 30, 40, 60, and 80 cm. The range of soil moisture fluctuation in each of the soil layers on the *left vertical axis* and the STD on the *right one*. Soil thawing depth on 31 August was 119 cm in the control plot and 125 cm in the irrigation plot
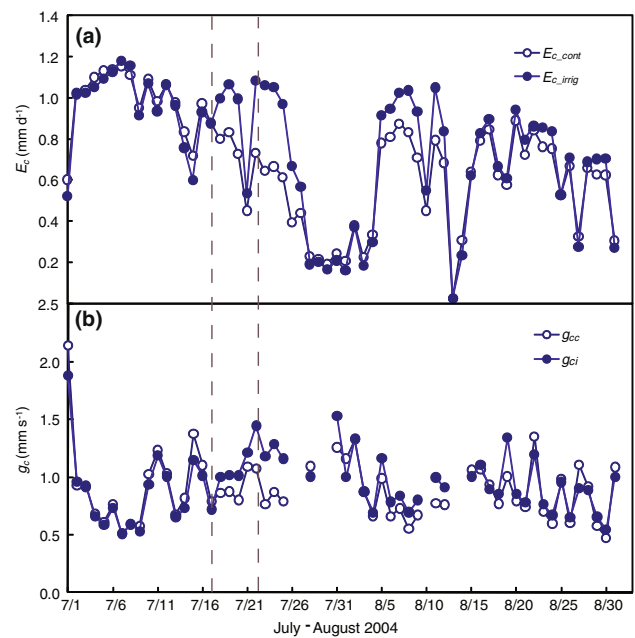

Fig. 4 a Daily courses of canopy transpiration (E_c) in the control and irrigation plots from 1 July to 31 August 2004. **b** Daily canopy conductance, calculated from sapflow measurements, in the control and irrigation plots. The *dashed lines* indicate the period when irrigation took place

E_{c_irrig} and E_{c_cont} to a similar average value of approximately 0.7 mm day^{-1}. In total, from 1 July to 31 August, E_{c_cont} was 42.5 mm and E_{c_irrig} was 46.4 mm, that is, a 9% difference, which did not correspond with the large differences in water input in the irrigation plot compared to the control plot.

Maximum g_c values in the morning were on average 2.3 and 2.4 mm s^{-1} in the irrigation and control plots, respectively before the irrigation started (Fig. 4b). From 19 to 22 July, maximum g_c, 3.9 mm s^{-1} and 3.2 mm in the irrigation and control plots, respectively. According to Cermak et al. (2007), water crown storage capacity increased considerably during periods of high soil water content and low evaporative demand, which describe the conditions in the irrigation plot in our experiment. Thus, morning g_c was driven by tree crown water storage that refilled in the previous evening (Schulze et al. 1985) under moisture saturated conditions. During irrigation and 1 week after it, g_{c_irrig} remained higher than g_{c_cont}; however, after a more modest rainfall event, by the end of July g_c reached the same values and remained stable for the rest of the growing season. This also coincided with decreasing temperatures and lower VPD. The period (during irrigation and the short time that followed) when g_c was higher,

reflects the control exerted by moisture in the upper soil layer (Lopez et al. 2007a).

Water budget in the control and irrigation plot

In the first half of July, before irrigation was applied, rainfall was 2.9 mm. During this period, in the control plot, E_a was 22.2 mm and the soil water stored in the 0–80 cm soil layer was 11.9 mm. Thus, during this period, 31.2 mm of newly available water in the forest ecosystem did not come from rainfall but from soil thawing layers. Similarly, in the irrigation plot, the contribution from thawed soils in the first half of July was 34.2 mm.

Rainfall during July–August was 63.4 mm. During this period in the control plot, rainfall contribution to soil water storage in the 0–80 cm layer was 34.5 mm while the contribution from soil thawing layers was 46.5 mm, reaching a total of 81.0 mm, of which 36.9 mm was used for E_{a_cont} (61.5 mm). Rainfall contribution to E_{a_cont} was 24.6 mm. By the end of August, the water stored in the 0–80 cm soil layer was +44.1 mm (Table 2) that remained in the soil for the next growing season. The amount of water that moved out of the 0–80 cm soil layer as runoff or to deeper layers was 4.3 mm (23–31 July).

In the irrigation plot, in addition to rainfall, 120 mm were irrigated, making a total of 183.4 mm for the period

Table 2 Water budget in the control plot

Control	July			August		Total
Date	1–16	17–22	23–31	1–16	17–31	
Rain	2.9	0.8	22.1	35.6	2.0	63.4
E_a[a]	22.2	6.5	5.5	13.4	13.9	61.5
ΔS_{0-10}[b]	−4.7	−1.8	5.5	0.8	−3.0	
ΔS_{10-40}	−4.0	−2.1	4.7	2.9	−4.6	
ΔS_{40-60}	18.8	4.4	0.2	3.0	−2.1	
ΔS_{60-80}	1.8	1.3	1.9	20.7	0.4	
E_a (from rain)	2.9	0.8	5.5	13.4	2.0	24.6
E_a (from Θ)[c]	19.3	5.7	0	0	11.9	36.9
Δ_{S0-80}	11.9	1.8	12.3	27.4	−9.3	44.1
Θ from rain	0	0	12.3	22.2	0	34.5
Θ from TSL[d]	31.2	7.5	0.0	5.2	2.6	46.5
Runoff	0	0	4.3	0	0	4.3

The + and − signs in soil storage change (ΔS) indicate the gain or loss of water from the soil layers considered in this calculation

[a] E_a Forest evapotranspiration

[b] ΔS Soil water storage change

[c] Θ Soil moisture content

[d] TSL Thawing soil layers

Table 3 Water budget in the irrigation plot

Irrigation	July			August		Total
Date	1–16	17–22	23–31	1–16	17–31	
Rain + irrigation	2.9	120.8	22.1	35.6	2.0	183.4
E_a[a]	22.2	8.2	7.5	16.7	17.2	71.8
ΔS_{0-10}[b]	−3.7	1.6	−1.0	−0.2	−1.6	
ΔS_{10-40}	−1.5	10.4	−4.2	0.0	−2.7	
ΔS_{40-60}	16.1	11.7	−2.4	−0.4	−4.2	
ΔS_{60-80}	4.0	28.5	−3.5	0.0	−5.2	
E_a (from rain + irrigation)	2.9	8.2	7.5	16.7	2.0	37.3
E_a (from Θ)[c]	19.3	0.0	0.0	0.0	15.2	34.5
ΔS_{0-80}	14.9	52.2	−11.1	−0.6	−14.3	41.1
Θ from rain	0.0	52.2	0.0	0.0	0.0	52.2
Θ from TSL[d]	34.2	0.0	0.0	0.0	0.9	35.1
Runoff	0.0	60.4	25.7	19.5	0.0	105.6

The +and − signs in soil storage change (ΔS) indicate the gain or loss of water from the soil layers considered in this calculation

[a] E_a Forest evapotranspiration

[b] ΔS Soil water storage change

[c] Θ Soil moisture content

[d] TSL Thawing soil layers

July–August. The total E_{a_irrig}, during the period July–August was 71.8 mm. During this period, rainfall and irrigation contribution to soil water storage in the 0–80 cm layer was 52.2 mm while the contribution from soil thawing layers was 35.1 mm, reaching a total of 87.3 mm of which 37.3 mm was used for E_{a_irrig}. Rainfall and irrigation contribution to E_{a_irrig} was 34.5 mm. By the end of August, the water stored in the 0–80 cm soil layer was +41.1 mm (Table 3). The amount of water that moved out of the 0–80 cm soil layer as runoff or to deeper layers was 105.7 mm. Based on the timing of irrigation and precipitation as well as on the corresponding amount of water that left the 0–80 cm soil layer, calculations show that 60.4 mm of runoff came from irrigation and 45.2 mm from rain.

In the control plot, the total amount of water available for the period July–August was 109.9 mm (rain + thawing soil layers) of which 56% was used for E_{a_cont}, 40% remained in the 0-80 cm soil layer, and 4% moved downward to deeper layers or left as runoff. Meanwhile in the irrigation plot, the total amount of water input for the same period was 218.5 mm (rain + irrigation + thawing soil layers) of which 33% was used for E_{a_irrig}, 19% remained in the soil layer, and 48% moved downward to deeper layers or left as runoff. However, if the runoff or the water that moved to deeper layers is subtracted from the total water input, the available water for the forest ecosystem was 112.9 mm, of which 64% was used for E_{a_irrig} and 36% was stored in the 0–80 cm soil layer.

Discussion

Soil moisture and soil thawing depth

Fine-weather conditions at the beginning of July favored higher rates of transpiration from larch trees that depleted soil moisture from the upper soil layers. During this period, it was the 0–20 cm layer of soil that lost more water because of higher root density in this layer (Kuwada et al. 2002). Sudden soil moisture increases were observed at 60 and 80 cm depth in the control and irrigation plots in the first half of July, associated with the thawing of soil layers, which is a common characteristic in permafrost regions (Sugimoto et al. 2003; Iwahana et al. 2005; Lopez et al. 2007b). The moisture made available by soil thawing moves upward and becomes the source for tree water uptake, although this mechanism depends strongly on the evaporative demand (Lopez et al. 2008) and the timing of the rainless span within the growing season (Hamada et al. 2004; Lopez et al. 2007a). When irrigation took place, soil moisture at the 10 cm depth did not change sharply because of the predominantly organic matter composition of this layer and the coarse texture of the mineral soil below. Irrigation replenished soil moisture in the already thawed soil profile but after saturation was reached the water is assumed to move horizontally in the form of runoff as has been previously reported in the Siberian Taiga (Ohta

et al. 2008). Soil saturation is inferred by the lack of change in moisture after continuous rainfall at the end of July.

When irrigation was applied, the heat inherent to water accelerated the soil thawing rate. However, it also caused earlier soil upward freezing in the irrigation plot because of the heat accumulation properties of saturated soil water conditions at the thawing front (Romanovsky et al. 1997; Hinkel et al. 2001). The latent heat of this saturated layer was responsible for keeping the freezing front at 0°C for a considerably longer period (Outcalt et al. 1990). A moisture-saturated layer at the boundary between the active layer and permafrost can have a positive feedback effect on permafrost stability in this region (Shur Yu 1998), since higher energy (higher air temperatures) is required to thaw this layer. The response of silty-clay soils, largely present in this region (Fedorov and Konstantinov 2003), to increases in rainfall will differ (Bernier et al. 2006; Lopez et al. 2007b), and this needs to be considered for modeling.

Canopy transpiration and canopy conductance

During the period of irrigation, E_{c_irrig} increased between 18 and 69% depending on weather conditions. After rainfall restored soil moisture availability, E_{c_irrig} remained higher than E_{c_cont}, but gradually decreased until the difference was 16% on average at the beginning of August. By the end of August, the difference was 9%, suggesting that rainfall had replenished soil moisture enough to meet forest water demand, regardless of irrigation (Bergh et al. 1999; Albaugh et al. 2004). The relatively cool conditions of the growing season in 2004 probably reduced the evaporative demand effect that could have otherwise accentuated the difference in canopy transpiration between the two plots. Higher E_{c_irrig} under non-limiting soil moisture conditions was driven by stomatal opening, which is enhanced when the upper soil layers are well supplied with moisture (Lopez et al. 2007a). Thus, the difference between E_{c_irrig} and E_{c_cont} represents the water that is not transpired by the forest ecosystem because of soil moisture deficit. The lower E_{c_cont} values observed are probably because of the presence of ABA (abscisic acid) signaling from the roots (Roberts and Dumbroff 1986) or leaf water potential, although pre-dawn water potential is a poor indicator of water deficit (Cienciala et al. 1994).

Canopy conductance increased after irrigation reaching a morning maximum that was between 15 and 30% higher than g_{c_cont}. Factors other than S_r and D have been reported to affect morning g_c in the Siberian larch forest but soil moisture was disregarded (Arneth et al. 1996), although this latter study was short-term. Ewers et al. (2001) reported increases in g_c after fertilization and irrigation accompanied by increases in LAI (leaf area index). The relationship between g_c and soil moisture was not clear

when g_c was estimated from E_a obtained by the eddy correlation technique (Ohta et al. 2001), but as reported in Lopez et al. (2007a), there was a good response to soil moisture when g_c was estimated from sap flow measurements since it better represented the local conditions. During irrigation, the upper soil layers remained well supplied with moisture which, combined with a high VPD, enhanced the stomatal opening. However, g_c at each plot reached similar values with more modest precipitation and when the evaporative demand decreased.

Water budget

The differences in water input in the control and irrigation plots were not reflected in water loss as canopy transpiration (E_c) or in forest evapotranspiration (E_a). Under normal and (simulated) extreme rainfall regimes, the contribution from thawing soil layers to E_a and the water stored in the soil at the end of the growing season in both plots was similar. Ohta et al. (2001) estimated that E_a in 1998 was 73% of the total water availability (rainfall and snow water equivalent); however, water supplied from soil thawing layers was not counted and, as seen in this study, this accounted for almost 60% of E_a in 2004. Even though irrigation water was responsible for the increase in E_c (8.4%) as well as E_a (14.3%) in the irrigation plot, the largest part of it moved to deeper soil layers or moved out of the plot soil as runoff. The lack of a strong dependency of forest E_a on rainfall (and irrigation) in this experiment confirmed the low response in inter-annual variability in canopy transpiration and forest evapotranspiration to large variations in inter-annual rainfall (Yamazaki et al. 2004; Ohta et al. 2008; Park et al. 2008). Based on the differences in soil water uptake in each plot after irrigation, it is possible to assume that the distribution of rainfall within the growing season determines the rate at which forests uptake water from the soil. The increase in extreme rainfall events and lengthening of rainless periods as a result of global warming (Karl et al. 1995) can intensify the use of water stored in the soil. Another consequence of extreme rain events is that if they occur early in the growing season, runoff will be intensified because of shallow frozen soil layers (Lopez et al. 2007b). In order to obtain more reliable results from models of the Siberian Taiga, the total contribution of water from thawing soil layers must be included rather than considering only annual precipitation.

Conclusions

1. Despite large differences in water input into the control and irrigation plot, E_c showed similar values (42.5 and

46.4 mm, respectively), during July–August 2004. This similarity can be explained by the contribution of water from stored soil moisture.

2. The effect of extreme rain on g_c was limited to a short time within the growing season, reflecting the strong upper soil moisture and evaporative demand control.

3. The water budget showed that the actual water input in the control and irrigation plot was 109.9 and 218.5 mm, respectively. Regardless of this difference, water dynamics were similar in both plots. In the irrigation plot, 105.6 mm of water moved out of the plot as runoff or to deeper layers, leaving the forest ecosystem a water availability of 112.9 mm, roughly that in the control plot.

References

Albaugh TJ, Allen HL, Dougherty PM, Johnsen KH (2004) Long term growth responses of loblolly pine to optimal nutrient and water resource availability. For Ecol Manage 192:3–19

Arneth A, Kelliher FM, Bauer G, Hollinger DY, Byers JN, Hunt JE, McSeveny TM, Ziegler W, Vygodskaya NN, Milukova I, Sogachov A, Varlagin A, Schulze ED (1996) Environmental regulation of xylem sap flow and total conductance of *Larix gmelinii* trees in eastern Siberia. Tree Physiol 16:247–255

Bergh J, Linder S, Lundmark T, Elfving B (1999) The effect of water and nutrient availability and nutrient availability on the productivity of Norway spruce in northern and southern Sweden. For Ecol Manage 119:51–62

Bernier PY, Bartlett P, Black TA, Barr A, Kljun N, McCaughey JH (2006) Drought constraints on transpiration and canopy conductance in mature aspen and jack pine stands. Agric For Meteorol 140:64–78

Brutsaert W (1982) Evaporation into the atmosphere—theory, history and applications. Riedel, Dordrecht

Cermak J, Kucera J, Baurerle WL, Phillips N, Hinckley TM (2007) Tree water storage and its diurnal dynamics related to sp flow and changes in stem volume in old-growth Douglas-fir trees. Tree Physiol 27:181–198

Cienciala E, Lindroth A, Cermak J, Hallgren JE, Kucera J (1994) The effects of water availability on transpiration, water potential and growth of *Picea abies* during a growing season. J Hydrol 155:57–71

Clearwater MJ, Meinzer FC, Andrade JL, Goldstein G, Holbrook NN (1999) Potential errors in measurement of non-uniform sap flow using heat dissipation probes. Tree Physiol 19:681–687

Dolman AJ, Maximov TC, Moors EJ, Maximov AP, Elbers JA, Kononov AV, Waterloo MJ, Van der Molen MK (2004) Net ecosystem exchange of carbon dioxide and water of far eastern Siberian larch (*Larix cajanderi*) on permafrost. Biogeosciences 1:133–146

Ewers BE, Oren R, Phillips N, Stromgren M, Linder S (2001) Mean Canopy stomatal conductance responses to water and nutrient availability in *Picea abies* and *Pinus taeda*. Tree Physiol 21:841–850

Fedorov A, Konstantinov P (2003) Observations of surface dynamics with thermokarst initiation, Yukechi site, Central Yakutia. In: Phillips, Springman, Arenson (eds) Proceedings of the eighth international conference on Permafrost. pp 239–243

Granier A (1987) Evaluation of transpiration in a Douglas-fir stand by means of Sap flow measurements. Tree Physiol 3:309–320

Granier A, Huc R, Barigah ST (1996) Transpiration of natural rain forest and its dependence on climatic factors. Agric For Meteorol 78:19–29

Hamada S, Ohta T, Hiyama T, Kuwada T, Takahashi A, Maximov TC (2004) Hydrometeorological behaviour of pine and larch forests in eastern Siberia. Hydrol Process 18:23–39

Hinkel KM, Paetzold F, Nelson FE, Bockheim JG (2001) Patterns of soil temperature and moisture in the active layer and upper permafrost at Barrow, Alaska: 1993–1999. Glob Planet Change 29:293–309

Iwahana G, Machimura T, Kobayashi Y, Fedorov AN, Konstantinov PY, Fukuda M (2005) Influence of forest clear-cutting on the thermal and hydrological regime of the active layer near Yakutsk, eastern Siberia. J Geophys Res 110:G02004. doi:10.1029/2005JG000039

Jorgenson MT, Shur YL, Pullman ER (2006) Abrupt increase in permafrost degradation in Arctic Alaska. Geophys Res Lett vol 33, L02503. doi:10.1029/2005GL024960

Karl TM, Knight RW, Plummer N (1995) Trends in high frequency climate variability in the twentieth century. Lett Nat 377:217–220

Kudrjavtsev VA, Kondratjeva KA, Romanovskii NN (1978) The zonal and regional laws of formation of cryolithozone in the USSR. Works of III International conference on permafrost studies, vol 1. Edmonton, Alberta, Canada. Ottawa, pp 419–426

Kuwada T, Kokake T, Takeuchi S, Maximov TC, Yoshikawa K (2002) Relationships among water dynamics, soil moisture and vapor pressure deficit in a *Larix gmelinii* stand, eastern boreal Siberia. J Jpn For Soc 84:246–254

Lopez CML, Saito H, Kobayashi Y, Shirota T, Iwahana G, Maximov TC, Fukuda M (2007a) Inter-annual environmental-soil thawing rate variation and its control on transpiration from *Larix cajanderi*, Central Yakutia, Eastern Siberia. J Hydrol 338:251–260

Lopez CML, Brouchkov A, Nakayama H, Takakai F, Fedorov AN, Fukuda M (2007b) Epigenetic salt accumulation and water movement in the active layer of Central Yakutia in Eastern Siberia. Hydrol Process 21:103–109

Lopez CML, Gerasimov E, Machimura T, Takakai F, Iwahana G, Fedorov AN, Fukuda M (2008) Comparison of carbon and water vapor exchange of forest and grassland in permafrost regions in Central Yakutia, Russia. Agric For Meteorol 148:1968–1977

Monteith JL, Unsworth M (1990) Principles of environmental physics, 2nd edn. Edward Arnold, London

Ohta T, Hiyama T, Tanaka H, Kuwada T, Maximov TC, Ohata T, Fukushima Y (2001) Seasonal variation in the energy and water exchanges above and below a larch forest in eastern Siberia. Hydrol Process 15:1459–1476

Ohta T, Maximov TC, Dolman AJ, NAtai T, van der Molen, Moors EJ, Tanaka H, Toba T, Yabuki H (2008) Interannual variation of water balance and summer evapotranspiration in an eastern Siberian larch forest over a 7-year period (1998–2006). Agric For Meteorol 148:1941–1953

Outcalt SI, Nelson FE, Hinkel KM (1990) The zero-curtain effect: heat and mass transfer across an isothermal region in freezing soil. Water Resour Res 26:1509–1516

Park H, Yamazaki T, Yamamoto K, Ohta T (2008) Tempo-spatial characteristics of energy budget and evapotranspiration in eastern Siberia. Agric For Meteorol 148:1990–2005

Rivas-Martinez S (2007) Global bioclimatics. Data set. Available online at http://www.-globalbioclimatics.org from Phytosociological Research Center, Madrid, Spain

Roberts DR, Dumbroff EB (1986) Relationships among drought resistance, transpiration rates and abscisic acid levels in three northern conifers. Tree Physiol 1:161–167

Romanovsky VE, Osterkamp TE, Duxbury NS (1997) An evaluation of three numerical models used in simulations of the active layer and permafrost temperatures regimes. Cold Reg Sci Technol 26:195–203

Schulze ED, Cermak J, Matyssek R, Penka M, Zimmermann R, Vasicek F, Gries W, Kucera J (1985) Canopy transpiration and water fluxes in the xylem of the trunk of Larix and Picea trees—a comparison of xylem flow, porometer and cuvette measurements. Oecologia 66:475–483

Shur Yu L (1998) The upper horizon of frozen strata and thermokarst. Nauka, Novosibirsk (in Russian)

Shvidenko A, Nilsson S (1994) What do we know about the Siberian forest? Ambio 23:389–404

Sugimoto A, Naito D, Yanagisawa N, Ichiyanagi K, Kurita N, Kubota J, Kotake T, Ohta T, Maximov TC, Fedorov AN (2003) Characteristics of soil moisture in permafrost observed in East Siberian taiga with stable isotopes of water. Hydrol Process 17:1073–1092

Waterworth R, Raison RJ, Brack C, Benson M, Khanna P, Paul K (2007) Effects of irrigation and N fertilization on growth and structure of Pinus radiata stands between 10 and 29 years of age. For Ecol Manage 239:169–181

Yamazaki T, Yabuki H, Ishii Y, Ohta T, Ohata T (2004) Water and energy exchanges at forest and a grassland in Eastern Siberia evaluated using a one-dimensional land surface model. J Hydrometeorol 5:504–515