Forest Ecology and Management 256 (2008) 1055–1063

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Effects of moisture limitation on tree growth in upland and floodplain forest ecosystems in interior Alaska

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ARTICLE INFO

Article history:
Received 17 January 2008
Received in revised form 4 June 2008
Accepted 6 June 2008

Keywords:
Boreal forest
Summer drought
Tree growth
Upland
Floodplain
Picea glauca
Betula neoalaskana
Populus tremuloides
P. balsamifera

ABSTRACT

The objective of this study was to examine the impact of summer throughfall on the growth of trees, at upland and floodplain locations, in the vicinity of Fairbanks, Alaska. Corrugated clear plastic covers were installed under the canopy of floodplain balsam poplar/white spruce stands and upland hardwood/white spruce stands to control soil moisture recharge as a result of summer precipitation. The covers were installed in 1989 and tree growth measurements were conducted through 2005. Soil moisture dynamics were measured using TDR techniques. Tree basal area growth at dbh in the control plots was approximately twice as high on the floodplain compared to the upland. Summer throughfall exclusion significantly decreased white spruce growth on the floodplain sites but not in the upland sites. In upland sites the melting snow pack is a major moisture resource for tree growth although it is not clear if moisture limitation occurs during the summer in the control plots. However in the floodplain stands white spruce growth was highly dependent on seasonal throughfall even though the ground water table was within the rooting zone and the soils were supplied with a spring recharge due to snowmelt. A number of factors were suggested as a foundation for this strong relationship. These include rooting distribution, soil texture, and the electrical conductivity of the ground water.

1. Introduction

The inter- and intra-seasonal relationships between rainfall and evaporation, which are linked to summer air and soil temperature dynamics, and strongly influence nutrient availability and tree growth in boreal forests are unclear (Gower et al., 2001). For interior Alaska there are three primary seasonal time periods related to soil moisture dynamics, spring soil moisture recharge resulting from snowmelt, summer rainfall and evapotranspiration dynamics and fall recharge after the growing season prior to winter snow accumulation. The potential for soil moisture recharge due to rainfall taking place after the growing season prior to freezing temperatures in the fall and recharge that may occur during the spring snowmelt period has not been adequately investigated. Drought stress may accompany wanner air temperatures in tree line sites in interior Alaska thus reducing tree growth (Lloyd and Fastie, 2002). Spring soil moisture was proposed as an important factor that controls the functioning of boreal forests at a southern BOREAS field site (Jarvis and Linder, 2000) located in central Saskatchewan, Canada. Evapotranspiration rates from a boreal forest coniferous canopy can be in the range of 2.5 mm day^{-1} which could represent between 25 and 75% of the equilibrium evaporation (Baldocchi et al., 2000). A potential rate of evapotranspiration of 6 mm day^{-1} was estimated for aspen stands. Modeled climatic change scenarios were shown to decrease soil moisture in both southern and northern Finland Scots pine *(Pinus sylvestris* L.) forests (Kellornaki and Vaisanen, 1996). The decrease did not affect current tree growth but it may have an effect on regeneration and young tree growth following harvest or disturbance. Sites in the forest-tundra zone in the Siberian subarctic were actually shown to have reduced growth due to higher snow pack and later snow pack melting (Vaganov et al., 1999).

Tree growth limitations related to water, nutrient availability and soil temperature dynamics have been investigated for Norway spruce *(Picea abies* (L.) Karst) in Scandinavian boreal forests (Bergh and Under, 1999; Bergh et al., 1999). In southern stands a direct control of tree growth from both moisture and nutrient limitations was observed. In a northern stand the moisture limitation was not observed. It was impossible to separate the influence of soil temperature increases from changes in available nutrients. In addition they found that raising soil temperature without a direct connection to potential increases in air temperature resulted in very little change in photosynthetic response (Bergh and Linder, 1999). A clear distinction between the three potential growth-limiting factors was not totally identified.

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0378-1127/$ – see front matter © 2008 Published by Elsevier B.V.
doi:10.1016/j.foreco.2008.06.022

Water infiltration rates and depth are reduced in frozen soils due to the presence of ice in the soil pores. As a result the potential infiltration of snowmelt in the spring will be dependent on the amount of ice present in the soil pore volume (Kane and Stein. 1983a.c). Dry frozen soils have the potential to behave as an unfrozen soil during spring soil moisture recharge periods. However the water movement may be restricted with the development of seasonal ice in the available pore space limiting the potential spring moisture recharge. Kane and Stein (1983a) have suggested that most of the groundwater recharge does occur during the spring snowmelt period. Early summer recharge will then be limited by the timing and intensity of precipitation events and evapotranspiration dynamics. Significant soil moisture recharge may also occur in the fall after leaf senescence, prior to the start of snowfall events, but this will be dependent on rainfall dynamics at that time period.

The objective of this study was to determine the importance of summer through fall on the growth of trees in both upland and floodplain locations in interior Alaska. The initial hypotheses were: (1) forest growth in upland birch/aspen *(Betula neoalaskana* Sarg./*Populus tremuloides* Michx.) stands is strongly controlled by summer throughfall, and (2) forest growth in floodplain balsam poplar/white spruce *(Populus balsamifera* L./*Picea glauca* (Moench) Voss) ecosystems will show no relationship to summer throughfall due to the influence of ground water, linked to river flow dynamics, on soil moisture recharge.

2. Methods

2.1. Field methods

Plot locations selected for the moisture limitation study were in the hardwood/conifer turning point (Van Cleve et al., 1996) in both upland and floodplain physiographic settings in interior Alaska. The mid-successional turning point in each landscape location was defined as the change from a deciduous early successional forest to a coniferous forest. In both the upland and floodplain locations the forest is composed of older deciduous trees that occupy the overstory with coniferous trees in the understory at the intermediate or codorninate crown class level. These sites were part of the Bonanza Creek (BNZ) Long-Term Ecological Research (LTER) program. The average distance between upland and floodplain site locations is approximately 7 km. Replicates within each landscape position occurred over 2 km in upland locations and over 4.5 km on the floodplain.

The upland and floodplain landscape positions were replicated three times. The replicates were identified with the letters A, Band C at the end of the site designation. The upland sites are designated as UP2 sites. The UP2A and B sites are dense mixed stands of paper birch, aspen, white spruce and balsam poplar. Deciduous species dominate the tree canopy but white spruce is beginning to replace the deciduous species as succession proceeds. The UP2C site is a dense mixed stand of aspen and white spruce. Aspen dominates the tree canopy and white spruce has a relatively low canopy cover. Maximum age forthe hardwoods found across all replicates was 82 years while the maximum age for the white spruce was 50 years (Table 1). Tree age estimates were determined at the beginning of the study in 1989.

The floodplain landscape locations are designated as FP3 sites. All three replications (A, B, and C) represent a mixed balsam poplar and white spruce forest type that is transitional between the deciduous balsam poplar stage and the conifer white spruce stage. In this stand, 50-year old balsam poplar is dominant. Maximum age was 95 years for balsam poplar. Mortality of balsam poplar is common. There is a well-developed understory of young white spruce, maximum age of 80 years, beginning to reach into the

Table 1
Average tree age, number of stems and aboveground tree biomass at the upland and floodplain control and moisture limitation research sites during the fall of 1989

Item	Treatment	Species	Floodplain: Balsam Poplar/ White Spruce Sites	Upland: Hardwood/ White Spruce Sites
Tree age (years)	Control and drought plots	Aspen		66 (82)
		Birch		60 (78)
		Poplar	60 (96)[a]	53 (69)
		W. Spruce	41 (80)	46 (60)
Tree density (stems/ha)	Control	Alder	933	22
		Aspen		778
		Birch		1178
		Poplar	467	289
		W. Spruce	2133	1378
		Total	3533	3645
	Drought	Alder	755	44
		Aspen		600
		Birch		1311
		Poplar	378	378
		W. Spruce	2289	1044
		Total	3422	3377
Aboveground biomass (mg/ha)	Control	Alder	1	1
		Aspen		58
		Birch		34
		Poplar	96	27
		W. Spruce	68	30
		Total	165	150
	Drought	Alder	1	
		Aspen		57
		Birch		56
		Poplar	47	36
		W. Spruce	105	23
		Total	153	172

[a] The value in parenthesis is the maximum age found in the set of sample trees.

canopy (Table 1). Tree age estimates were determined at the beginning of the study in 1989.

The soils at each site have been described in detail by Van Cleve et al., (1996). Soils on the floodplain sites were identified as Typic Cryofluvents. Alfic Cryochrepts occurred on the upland sites. The average forest floor depth on the upland sites was 6 cm, and the average depth on the floodplain sites was 10 cm. The soil texture on the upland sites is a silt loam (Table 2) with an average pH of 5.4 in the surface soil.increasing to 6.6 in the lowest layer. The FP3A and FP3B sites, on the floodplain, also have a silt loam texture but the proportion of sand increases lower in the profile. The amount of sand present on the FP3C site was higher than on the A and B replicates. If the texture was averaged across all layers a sandy loam soil would be present (Table 2). Actually, the texture changes from a silt loam in the top layer to a sandy loam in the remaining four horizons.

Within each of the three FP3 and UP2 sites a 10m x 15 m control and drought plot was established. Clear PVC greenhouse panels were used to construct a cover under the overstory canopy in each replicate UP2 and FP3 drought site. The covers (Fig. 1) were designed to prevent summer throughfall from entering the soil and recharging soil water during the growing season. The covers, designed to drain throughfall off the plot, were placed on wooden framing. On the floodplain sites the high end of the cover was at approximately 2 m and the low end at 1 m above the ground. On the upland sites the covers were parallel to the sloping surface of the plot. A hole in the cover was placed at the location of each tree and a dam was placed up-slope from each tree on the cover to force drainage of water around the tree and off of the treatment area (Fig. 1). The covers were assembled in late May of each year and taken down before the first snowfall in early September.

Plastic sheeting (6 mil thickness) was installed vertically in the soil to a depth of 75 cm, around each plot, to prevent belowground lateral flow and root growth into and out of the drought plots. The physical location of each upland location was close to the top of the slope; as a result there was very little potential upslope source (less than 50 m for each replicate) for soil moisture movement into the plot below the depth of the vertical plastic sheeting. No plastic sheeting was installed under each plot parallel to the ground surface to allow vertical soil water movement at each site. Ground water was not a factor on the upland sites however on the floodplain ground water was hypothesized to play a major role in tree moisture dynamics (Viereck et al., 1993). The covers have been in place since 1990.

Soil moisture has been measured with the use of TDR techniques starting in 1993. A four depth horizontal profile of Campbell Scientific 30 cm 3-rod TDR probes was replicated twice in replications A and C in both the upland and floodplain locations. The TDR probes were placed horizontally at depths of 5, 10, 20 and 50 cm below the organic matter/mineral soil interface. Soil moisture was determined using a Tektronic 1502 B Cable tester and the readings were recorded on a Campbell CR10x data logger. During the winter prior to installation the probes were calibrated in the lab with a standard silt loam soil collected from the vicinity of the research plots. It was found that the standard calibration curves that were supplied with the equipment were satisfactory for measuring volumetric water content in the soils typical of the research sites. Volumetric soil moisture estimates from each depth were averaged for replicate sensors within sites at weekly time intervals. From 1996 through 2000 hourly estimates of volumetric soil moisture were recorded using a second TDR instrument on the UP2A site. The hourly recording instrument was moved to the FP3A site in the summer of 2001. In the replicate sites that were not being continuously recorded, weekly measurements of soil moisture were accomplished with the use of a second TDR instrument. The database consists of a combination of seasonal hourly recordings of soil moisture at one site and weekly measurements made at the remaining sites for the entire study period. Weekly readings from the recorded site were used to complete the weekly dataset for all sites.

Soil temperature was measured at the same depths as soil moisture at the site that had a recording TDR instrument. The soil temperature dynamics were recorded on the Campbell CRl0x data logger. These measurements would give us an indication if changes in soil moisture content were having an effect on soil temperature dynamics.

Weekly measurements of the depth to ground water were performed on the FP3 sites. A set of four ground water wells were installed at each site using 10.2 cm diameter perforated PVC pipe covered with Dupont Typar cloth to prevent the well from filling in with silt. The cloth did allow free movement of water into and out of the well. The depth of water in the well was measured to the nearest centimeter on a weekly basis using a dip stick and then the vertical depth to the surface of the ground water from the soil

Table 2
Average values for layer depth, %sand, %silt, %clay, pH and the potential value for the saturated water content based on soil texture for the upland and floodplain research sites

Layer	Average depth (cm)	%Sand	%Silt	%Clay	pH	Potential saturated soil water content (m^3/m^3)
FP3A and FP3B Profile Averages						
1	12	16.43	78.70	4.87	6.91	0.7486
2	12	36.73	59.15	4.12	7.62	0.5491
3	29	47.76	48.75	3.50	7.87	0.5077
4	27	60.17	36.96	2.87	8.03	0.4869
5	22	47.49	49.52	2.99	8.17	0.5322
FP3C Profile Averages						
1	8	39.60	56.48	3.92	6.24	0.6821
2	13	51.30	45.33	3.37	7.37	0.5686
3	12	68.10	29.35	2.55	7.84	0.5358
4	51	70.80	27.95	1.25	7.97	0.4849
5	43	92.60	6.05	1.35	7.93	0.4906
UP Profile Averages						
1	5	13.43	75.30	11.27	5.36	0.7872
2	15	12.33	74.20	13.47	5.87	0.5988
3	16	14.43	73.43	12.14	6.19	0.5693
4	31	17.83	73.73	8.44	6.51	0.5348
5	39	16.93	75.63	7.44	6.64	0.5230

The values represent averages for 4 soil profiles around each replicate site for each distinct soil horizon starting at the surface (layer 1) and progressing to the deepest layer (5).

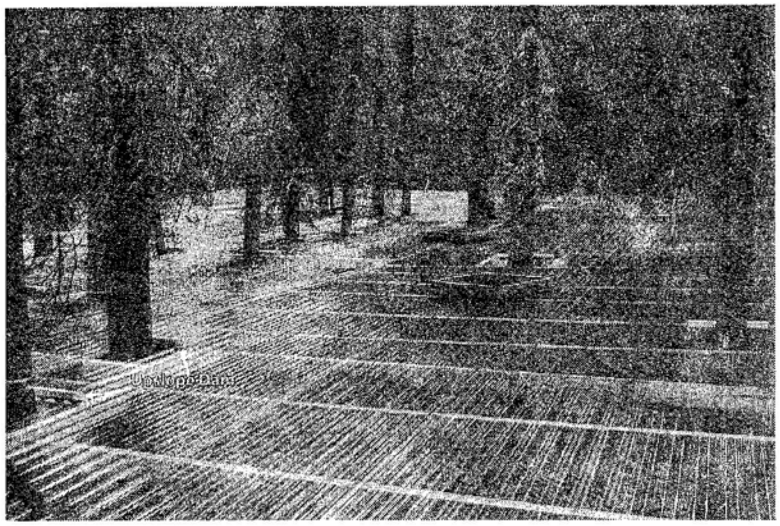

Fig. 1. Summer drought cover on the FP3A site. The cover is sloped downhill and a dam is positioned at the upper side of the trees to prevent water from draining into the opening. Litterfall collection traps are in place on top of the cover during the summer and on the forest floor during the winter after the cover is removed.

surface was calculated. Ground water was not monitored in the upland site because it was well below the rooting zone and of no consequence to soil moisture relations.

The surface elevation of the Tanana River was monitored at a downstream location from the FP3 sites. The level was monitored on a continuous basis with the use of a Druck pressure transducer placed in a perforated PVC drain pipe wrapped in Typar cloth. The river surface elevation is approximately 1 m lower at the gauge than at the replicate floodplain site with the greatest horizontal distance (2.5 km straight line) from the river level sensor. Due to the physical structure of the river at these locations the height dynamics of the river surface at both locations will follow the same pattern of changes during the year. Monitoring of the river level produced a good estimate of the depth to ground water on the floodplain sites.

Daily precipitation was measured at the two primary LTER climate stations. One station was in an upland location and the other was in a floodplain location (Hollingsworth, 2000). The climate stations were within 2 km of the research sites in both landscape locations. Due to problems with data recorders a long-term consistent record for the LTER climate stations is not available. Precipitation measurements for Fairbanks from the NOAA climate station at the Fairbanks airport are also included (Table 3). The airport climate station is approximately 25 km from the research sites. The year was divided into two seasons, the growing season (16 May through 9 September) when the throughfall cover was in place and the dormant season (10 September through 15 May the following year). The dormant season represented the time period for soil moisture recharge between growing seasons.

Due to the slow growth of boreal trees in the Fairbanks area diameter growth on all trees greater than 2.54 cm at breast height (1.37 m above the ground) was measured on a 5-year interval. The initial, time zero measurement, was preformed in the spring of 1989 prior to that year's growth and then repeated at the same position on the tree in the fall (after growth has stopped) in 1993, 1998 and 2003.

Table 3
Seasonal precipitation quantities (mm) during the study period for upland (LTER1), floodplain (LTER2) and a nearby standard NOAA climate station (Fairbanks Airport)

Year	Non-growing season (9/10–5/15) (mm)			Growing season (5/16–9/9) (mm)			Percentage of total year precipitation occurring in the summer (%)		
	LTER1	LTER2	Airport	LTER1	LTER2	Airport	LTER1	LTER2	Airport
1990	161		126	418		296	72		70
1991	295		230			89			28
1992	185		162	152		132	45		45
1993	191		198	127		104	40		34
1994	161		126	136		136	46		52
1995	158		105	199		161	56		60
1996	120	118	96	208	130	142	63	52	60
1997	133	128	105	143	98	99	52	44	48
1998	61	85	63	296		214	83		77
1999		100	71	194	137	150		58	68
2000	189	185	144	218	171	161	54	48	53
2001	133	110	115	141	123	138	51	53	54
2002			132	220	212	174			57
2003			94			231			71
2004			134	106	83	80			38
2005			148	218	185	169			53
2006	130	75	112	183	130	135	58	63	55
Average	153	114	127	197	141	154	56	53	54

The total year used for the percentage value runs from 9/10 the previous year to 9/9 the current year.

2.2. Statistical analysis

The comparison of individual tree basal area growth between the drought and control treatments on the FP3 and UP2 sites was tested for significant differences on a periodic (5-year) basis. The SAS MIXED procedure was used with a repeated ANOVA to calculate significant differences (alpha ≤ 0.05) in the mean basal area growth using an estimate statement with an error type of AR(1) across individual species in each landscape location (floodplain or upland). The data set used was the periodic 5-year measurement of all trees greater than 5 cm at dbh within each plot.

3. Results

3.1. Seasonal dynamics in precipitation and ground water

The total precipitation for the growing season months (gs) at the upland (LTER1) and floodplain (LTER2) sites averaged 197 and 142 mm/gs. respectively, over the study period. The airport site which is situated close to the Tanana River floodplain, approximately 25 km straight line distance from the research sites, averaged 154 mm/gs. The seasonal dynamics were consistent between the two sites but the monthly averages were lower on the floodplain site compared to the upland site. The total annual precipitation was approximately 61-94mm higher in the upland (LTER1) compared to the floodplain (LTER2) depending on the time period used Crable 3). Based on the average precipitation characteristics during the study period, the summer throughfall exclusion reduced the annual inputs, on average, by 55% with a range from 28 to 83% (Table 3).

Measurements of the Tanana River stage (or level) and depth to ground water under the floodplain sites is well correlated (Fig. 2). The correlation between the river level and the depth to ground water during 1995 at the white spruce site was 0.92. The correlation of the ground water levels between the white spruce site and the FP3A site was 0.89, and the correlation between the FP3A ground water and the river level at the white spruce site was 0.98. These correlation levels were consistent with all other years of measurement.

3.2. Moistule dynamics in the UP2 sites

In the upland locations soil water content declined from peak values at the individual depths in May, immediately after soil thaw, to about 0.1 m^3/m^3 in late June and early July. Recharge occurred following mid- to late summer throughfall in the control plots (Fig 3). The soil water trends in the drought plots were similar to the control plots during the first half of the growing season. However the drought treatment restricted soil moisture recharge in the second half of the growing season. Distinct differences in the summer rainfall can be seen between years 1997 and 1998 where the rainfall totals, measured at the research sites, were 151 and 315 mm, respectively. As a result of these rainfall quantities, differences were seen in the soil moisture status between the 2 years (Fig. 3). The control plots showed a reduction in soil moisture throughout the entire 1997 growing season. Only small amounts of recharge occurred at shallow depths during late July and into the fall. The drought plots showed a downward trend across all measurement depths throughout the growing season in all measurement years. The general differences between the control and treatment plots were seen during the fall and were dependent on the quantity of rainfall that was occurring.

The influence of late season rainfall and spring snowmelt is visible in both the control and drought plots. In both years there is a substantial recharge of soil moisture in the spring (Fig. 3). Precipitation that occurred during the non-cover period (approximately from 9/10 in the fall till 5/15 in the following spring) was 133 mm in 1997 and 61 mm in 1998 (Table 3).

3.3. Soil moisture trends in the floodplain (FP3) sites

Spring seasonal recharge, due to through fall after the covers were removed and snow melt, was present in almost all years of measurement in both the control and drought treatments, especially at the 5 cm depth in the floodplain sites. The average TDR values for the control and drought treatments were 0.55 and 0.33 m^3/m^3 for week 18 (approximately the middle of May) at 5 cm, respectively and 0.14 and 0,16 m^3/m^3 at 20 cm, respectively, at the same time period. In general the highest water content values for shallow depths were present after soil thawing in the spring. An example of this trend is visible for 1997 at the 20 cm depth (Fig. 4). Across all years of measurement, moisture levels on the FP3 control plots tended to be the lowest at the 5 cm level (Fig. 4). The FP3A site had higher silt content at the 20 cm depth than the FP3C site (Table 2). This resulted in the higher moisture content values at the 20 cm depth compared to the 50 cm depth. However due to the sand in the soil profile soil water content values were lower in the FP3C site (Fig. 4). Considering all years of measurement, there was not a clear trend in annual dynamics of moisture content at depths below 20 cm in the soil profile on the control plots.

In the drought plots the 5 cm layer showed the lowest water content values with a general decline throughout the summer. This trend indicates an effective throughfall barrier had been established with the plot covers. Soil moisture recharge was not occurring from the surface when throughfall was adding moisture to the control plots later in the growing season. Recharge of soil moisture due to throughfall occurred during the fall on the

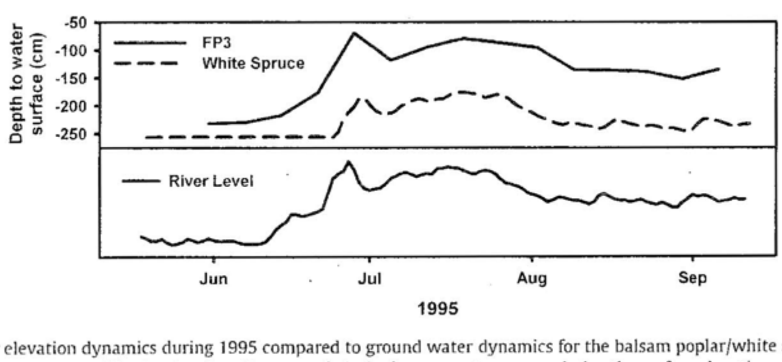

Fig. 2. An example of Tanana River elevation dynamics during 1995 compared to ground water dynamics for the balsam poplar/white spruce site (FP3) and an old growth white spruce site. A vertical scale is not presented for the river level because of a lack of an accurate survey relating the surface elevation of the ground water wells to the river level sampling location. The flat line at the beginning of the season for the white spruce site indicates that the water level was below the total depth of the ground water well.

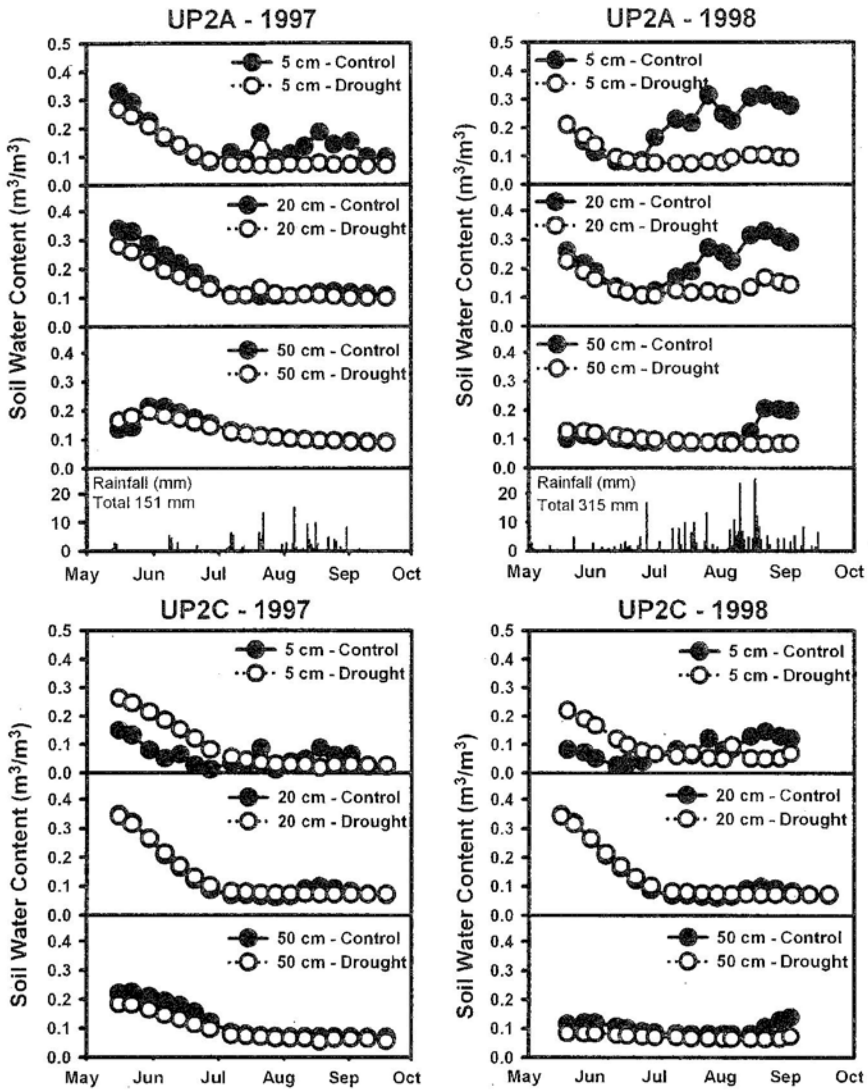

Fig. 3. Soil water content and rainfall dynamics for two upland sites that show examples for a low (1997) and a high (1998) rainfall summer. TDR measurements were made at 5, 20 and 50 cm below the interface of the forest floor and the mineral soil.

floodplain control plots (Fig. 4). This is evident during the August time period at the 5 cm soil depth. This trend was also present at the 10 cm depth which is not reported. If the recharge was directly connected with rising river levels, then increasing soil moisture val ues should have progressed upward from the 50 cm layer to the 20 cm layer, etc.; and an identical trend would have been present in both the control and drought treatments.

3.4. Soil temperature dynamics

Soil temperature was recorded on both the drought and control plots in the UP2A and FP3A sites in conjunction with the recording TDR instrument. For the upland site soil temperature was higher in the drought than the control plots at the 50 cm depth (Fig. 5). In the floodplain site the 50 cm temperature was slightly lower in the drought treatment. At 5 cm early to mid-season temperatures were higher in the upland drought plots while no differences were found on the floodplain. Daily temperature variation was generally highest for the 5 cm depth. It would be expected that temporal variation in temperature will be greater as the heat capacity of soil decreased as a result of drying. This was obvious in the upland sites more than the floodplain sites and could be associated with the moisture dynamics and the different topographic settings at the two sites.

3.5. Tree diameter growth

When the experiment was designed it was hypothesized that the throughfall deficit treatments would result in a decrease in tree growth in the upland sites, but due to the proximity of ground water and the capillary rise of water to the rooting zone on the floodplain there would be no change in tree growth. In fact the opposite trend was present in tree growth (Table 4). Summer throughfall elimination from the upland sites did not result in a statistically significant decrease in the growth of all species in the 5-year time intervals and the total 15-year measurement period. However on the floodplain white spruce growth was significantly decreased in all of the 5-year measurement periods and the total 15-year time frame. There was no significant decrease in the growth of balsam poplar (Table 4).

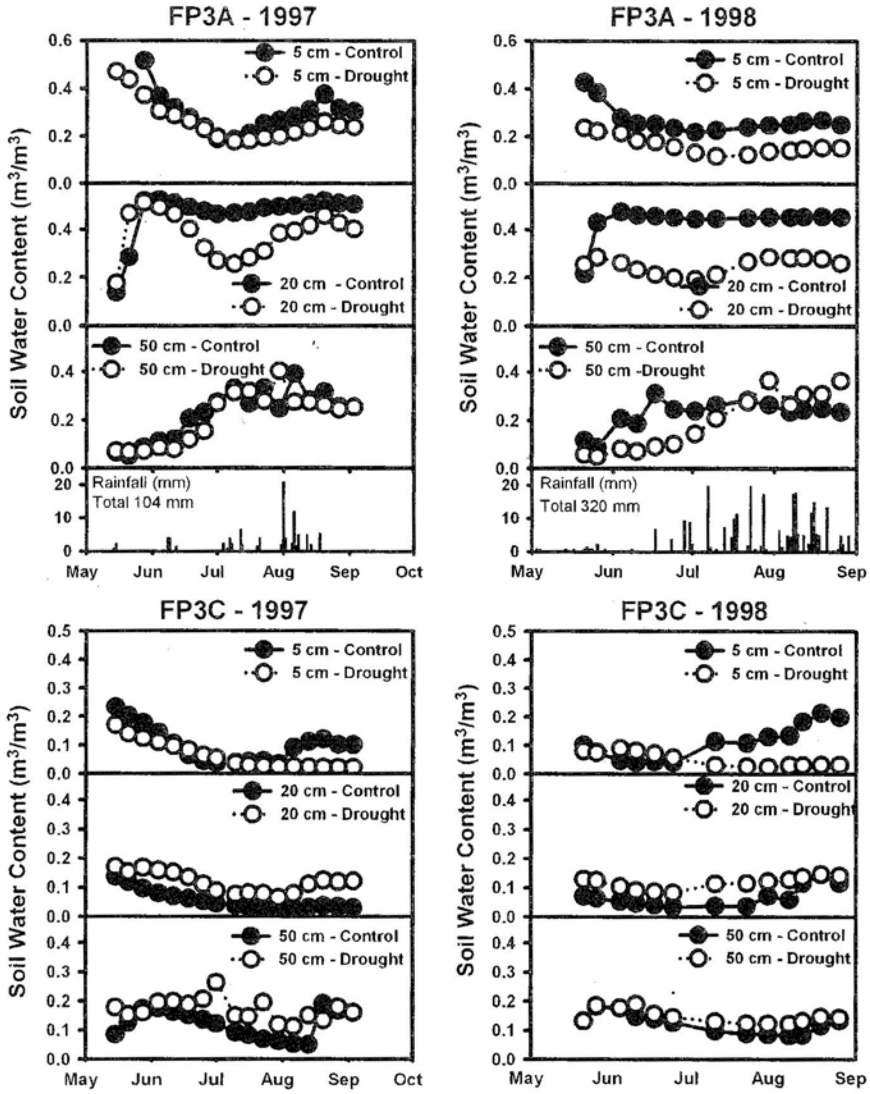

Fig. 4. Soil water content and rainfall dynamics for two floodplain sites that show examples of a low (1997) and high (1998) rainfall summer. TDR measurements were made at 5, 20 and 50 cm below the interface of the forest floor and the mineral soil.

4. Discussion

The hypothesis that launched this study was that summer throughfall played a key role in controlling the growth of upland forests while growing season river levels, through their effect on soil water supply from shallow ground water played a fundamental role in promoting growth offorests on the floodplain. Based on 15 years of the summer moisture limitation study, opposite results were found. Upland stands showed no effect of summer throughfall limitation and the growth of floodplain white spruce decreased due to summer throughfall limitation.

The cambial growth of boreal species is limited by a short growing season. White spruce displays most of its cambial development within 45 days after growth starts (Gregory and Wilson, 1968). Diameter growth usually begins about the end of May in interior Alaska. Similar results were found in an earlier study that observed diameter growth for white spruce, birch and aspen (Downing, 1960). In this case all three species were found to start radial growth in early June and it ended in mid-July, approximately a 45-day period.

For the upland stands there are two potential explanations for a lack of growth reduction. First, moisture recharge from the melting snow pack supplies the soil with sufficient moisture to accommodate plant growth during dry summer months. This condition would depend on the size of the winter snow pack, the melt characteristics during the spring, and the water holding properties of the soil. Second, both the upland drought and control sites displayed a significant soil moisture reduction during the early part of the growing season (May and June) that limited growth in the same manner prior to the start of precipitation induced moisture recharge in July and extending through the fall (Fig. 4). Late season (mid-July and August) throughfall events did not play a key role in stimulating tree diameter growth because the majority of tree growth occurred earlier in the season (May and June). Past studies of the seasonal dynamics of tree growth in interior Alaska have shown that the major portion of all diameter growth occurs early in the growing season (Downing, 1960; Gregory and Wilson, 1968). If this is the case then removal of spring snowmelt should cause a significant reduction in tree growth depending on the spring throughfall characteristics. In this study the winter

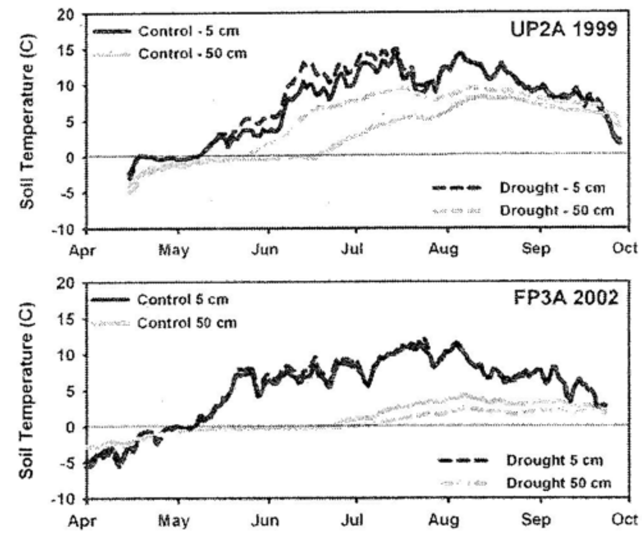

Fig. 5. Soil temperature observed at the UP2A and FP3A drought and control plots during the summer of 1999 and 2002, respectively, at the 5 and 50 cm soil depths.

snowpack had completely melted prior to placement of the throughfall covers.

Second, the upland control plots were themselves water-limited throughout the study period. It is assumed that snowfall recharges soil moisture as a result of spring snowmelt. Twenty-eight to 72% of the yearly precipitation (Table 3) occurs as snowfall. However a number of losses are possible to the snow pack prior to and during the snowmelt period (Kane and Stein, 1983b). Prior to snowmelt, water can be lost to sublimation. This was measured to be in the range of 30-70 mm of the snowpack water at Palmer, Alaska (Branton et al., 1971) and simulated at 21% of the precipitation input in Arctic Alaska (Liston and Sturm, 2002). During the snowmelt period the infiltration of water into the surface soil will be controlled by the quantity of ice in the profile (Kane and Stein, 1983a,c; Gray et al., 2001: Zhao et al., 2002), Kane and Stein (1983a) found that soil moisture formed an ice lens close to the soil surface during winter that limited water infiltration. In addition (Zhao et al., 2002) suggested that with most soil textures, water infiltration during snow-melt was limited to the top 10 cm of soil even if ice lenses are not present. The limitation for the upland sites was closer to the 20 cm depth based on soil moisture content estimates. The maximum spring soil water content for the upland sites was close to 0.3 m^3/m^3 in the spring at the 5, 10 and 20 cm measurement depths. The consistent soil water content values between the fall of 1997 and the spring of 1998 indicate that soil moisture recharge as a result of snowmelt did not reach the 50 cm depth (Fig. 3). This potential lack of recharge during the spring snowmelt period is usually followed by summer rainfall quantities that fall well short of potential evaporation (~385 mm) (Gieck and Kane,1986; Hinzman et al., (1997) resulting in a potentially significant low soil moisture status early in the growing season.

For the floodplain sites the growth of white spruce was significantly decreased as a result of the throughfall exclusion treatment. In this case there are three driving mechanisms that affect soil water utilization: (1) evapotranspiration, (2) capillary effects, and (3) osmotic effects due to the salt concentrations in the soil solution. Evapotranspiration dynamics during the growing season will decrease soil moisture within the rooting zone and potential evapotranspiration is higher than the average precipitation. The extent of capillary rise from the water table could have been insufficient to supply water to the rooting zone during the growing season. This factor would have been complemented by a shallow rooting distribution. The majority of roots that playa role in moisture uptake could have been located at shallow depths in the soil profile. Ruess et al. (2006) indicate that 75% of white spruce fine root production occurs within 20 cm of the ground surface and 85% of balsam poplar fine root production occurs within 30 cm of the ground surface in floodplain ecosystems. Then as a result of the lower throughfall and coarse textured soils water utilization will occur at a faster rate on the floodplain. Ion concentrations of the ground water were sufficiently high (Yarie et al., 1993) to limit water uptake by the root systems (Rowell. 1988). Rowell indicated that an electrical conductivity (EC) value of 4 dS/m or greater will indicate sufficient salt content in the soil solution to have a detrimental effect on salt sensitive plants. Measured values for EC in floodplain soil solution were in the range of 0.7-2.0 dS/m in higher elevation, mature white spruce, terraces at a soil depth of 50 cm and from 1.0 to 3.6 dS/m in lower elevation, alder-young balsam poplar, terraces at the 20 cm depth in the mineral soil (Yarie et al., 1993). The FP3 sites have a terrace elevation between the two sites with the reported EC values. By limiting aboveground water recharge the EC values of all soil water in the drought treatments may be higher, resulting in a potential reduction in water uptake and the growth of trees in the drought treatment on the floodplain.

Both balsam poplar and white spruce displayed higher growth rates on floodplain compared to upland control sites. It was expected that the higher growth rates observed on the floodplain would indicate that moisture limitation was less, due to the combination of natural throughfall and capillary rise of soil water related to the proximity of ground water. Balsam poplar exhibited 42% greater growth on the floodplain when compared to the uplands for the total growth over the 15 year measurement period (Table 4). White spruce displayed 85% greater total growth on the floodplain compared to the upland (Table 4). These growth differences occurred despite the fact that upland sites received 40% more summer precipitation than floodplain sites (Table 3). Soil

Table 4
Average 5-year tree basal area growth (cm^2) by species in both the UP2 and FP3 site in interior Alaska

Time period[a]	Upland Sites (UP2)								Floodplain Sites (FP3)			
	Aspen		Birch		Balsam Poplar		White Spruce		Balsam Poplar		White Spruce	
	Control	Drought	Control	Drought	Control	Drought	Control	Drought	Control	Drought	Control	Drought
1	23.1 (3.82)	24.4 (4.52)	8.5 (1.03)	6.6 (0.75)	15.6 (1.78)	13.5 (1.97)	10.9 (1.98)	10.3 (1.24)	14.5 (2.66)	10.0 (2,54)	**16.8* (2.84)**	**14.6* (1.86)**
2	14.6 (2.47)	19.8 (3,63)	5.8 (0.80)	5.2 (0.99)	11.8 (1.92)	10.3 (2.35)	9.3 (1.78)	9.2 (1.14)	20.2 (7.86)	10.2 (4.51)	**19.7* (4.70)**	**12.1* (2.08)**
3	14.4 (2.93)	12.6 (5.58)	5.5 (1.04)	4.6 (1.02)	8.3 (2.36)	5.3 (1.02)	10.4 (2.09)	10.2 (1.39)	16.2 (7.66)	6.5 (1.30)	**19.8* (4.20)**	**10.6* (1.23)**

The data presented represent total growth in a 5-year period for all individuals greater than 5 cm dbh present on the treatment and control plots. Significant differences between the control and drought plots for individual species are indicated with a bold font and symbol "*".
[a] The time periods represent 5 growing seasons in the following years (1) 1989–1993, (2) 1994–1998, and (3) 1999–2003.

water availability was apparently greater on the floodplain due to the presence of shallow ground water and the capillary movement of soil water. It was initially thought that the moisture requirements For tree growth on the floodplain were primarily controlled by the ground water proximity to the rooting system which would result in reciuced dependence on growing season precipitation to satisfy moisture requirements. However the results of this study indicate that higher levels of growth are a result of both the ground water and summer precipitation sources of moisture. The relative importance of these sources is not clear. Further work using an isotope ratio method is strongly suggested to delineate the actual source of water for tree growth on the floodplain. Unpublished data indicate that local rainfall has an ^{18}O value of -15.06‰, the river water has a value of -21.93‰, and ground water sampled at the sites has a value of -20.68‰.

What are the implications of this study to analysis of future growth of forests in interior Alaska in the context of climate change? It appears there will be a substantial increase in temperature especially during the winter months and the length of the growing season seems to be increasing (Keyser et al., 2000). However, over the past 20 years there has been no clear change in the quantity of summer precipitation (Juday et al., 2003). For the present we will assume that precipitation quantity and distribution will remain constant. Then, two scenarios can be derived from this research. The first for upland sites would indicate that there will be very little or no change in tree growth dynamics. The soil water will be replenished on a yearly basis from the spring snowmelt and seasonal distribution and quantity of summer throughfall. Floodplain sites will also experience a recharge of the soil water from spring snow melt and seasonal distribution and quantity of summer throughfall, but it will last for a smaller portion of the growing season due to the higher sand content found in the soil profile. It has been shown that a silt texture soil will have a volumetric wetness (m^3/m^3) of 0.275 while a sandy soil will have a value of 0.175 after 2 days of drainage starting at a saturated water content (Hillel, 2004). Tree growth on the floodplain will then have a greater dependence on throughfall events assuming no change in the soil water capillary dynamics. If the growing season continues to lengthen the duration of a potential moisture deficit will lengthen and the growth capability on the floodplain sites will decrease. At this time these scenarios are only hypothesized outcomes of the potential warming and precipitation dynamics that could result from climate change.

Acknowledgements

I am grateful for the assistance of Lola Oliver, Tim Quintel, Jason Downing, Jessica Garron, and Roy Erickson for a tremendous amount of help in establishing and maintaining the research sites. Dr. Keith Van Cleve for help and encouragement in designing and maintaining the experiment. Drs. David Valentine and Larry Hinzman for comments on an earlier draft of the manuscript. Dr. Keith Van Cleve for many comments on the current version of the manuscript. Funding for the work was provided through the Bonanza Creek LTER (Long-Term Ecological Research) program (funded jointly by NSF grant DEB-0423442 and USDA Forest Service, Pacific Northwest Research Station grant PNW01-JVl1261952-231). Additional funding was supplied through the McIntyre-Stennis research program at the School of Natural Resources and Agricultural Sciences (SNRAS), University of Alaska Fairbanks. This is publication number 2005-005 through SNRAS/AFES at the University of Alaska Fairbanks.

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