Karl Berglund

SVERIGES LANTBRUKSUNIVERSITET

Lic. EXAMEN exempel

RADIAL STEM GROWTH AND TRANSPIRATION OF NORWAY SPRUCE IN RELATION TO SOIL WATER AVAILABILITY

Granens tillväxt och transpiration i relation till markvattnets tillgänglighet

Ghasem Alavi

Licenciatavhandling

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Sveriges Lantbruksuniversitet
Institutionen för markvetenskap
Avdelningen för lantbrukets hydroteknik
Box 7014
750 07 UPPSALA

Tel. 018-67 11 85, 67 11 86

Swedish University of Agricultural Sciences
Department of Soil Sciences
Division of Agricultural Hydrotechnics
P.O. Box 7014
S-750 07 UPPSALA, SWEDEN

Tel. +46-(18) 67 11 85, +46-(18) 67 11 86

Till Ingmar
Från Ghasem

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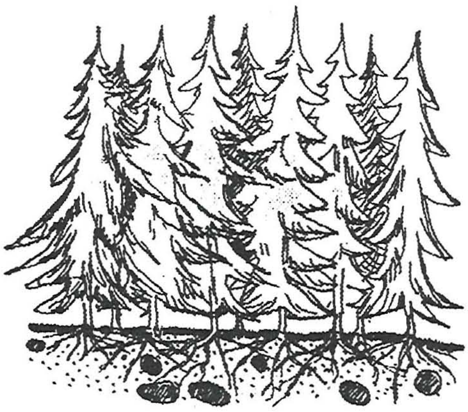

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PREFACE

This report is a thesis for the degree of "Filosofie licentiat". This degree is an autonomous part of a doctoral programme, consisting of 80 credit points, which is equivalent to two years of full time study beyond the degree of M.Sc.. It is awarded on the basis of both course work and a dissertation. Two papers are presented:

I. Alavi, G. & Jansson, P.-E. 1995. Transpiration and soil moisture dynamics for spruce stands of different canopy densities and water availability. In Mathy P. & Nilsson L-O (Ed). Nutrient Uptake and Cycling in Forest Ecosystem. *Ecosystem research report 13.* In press.

II. Alavi, G. 1995. Radial stem growth of Norway spruce in relation to spatial variation in soil moisture conditions. Submitted to *Scandinavian Journal of Forest Research.*

A general introduction about the relation between water deficit and forest decline in Sweden and summaries of the papers are given in Swedish.

Financial supports by the National Swedish Environmental Protection Agency and Swedish University of Agricultural Sciences are thankfully acknowledged. I want to thank my supervisor, Prof. Per-Erik Jansson for planning this investigation and his valuable advice and comments concerning my work. Special thanks to Dr. Henrik Eckersten for commenting on manuscripts. I am also grateful to my colleagues and others at the Department of Soil Sciences.

The front page illustration was drawn by Hans Persson.

Uppsala, Mars 1995
Ghasem Alavi

INNEHÅLLSFÖRTECKNING

INLEDNING

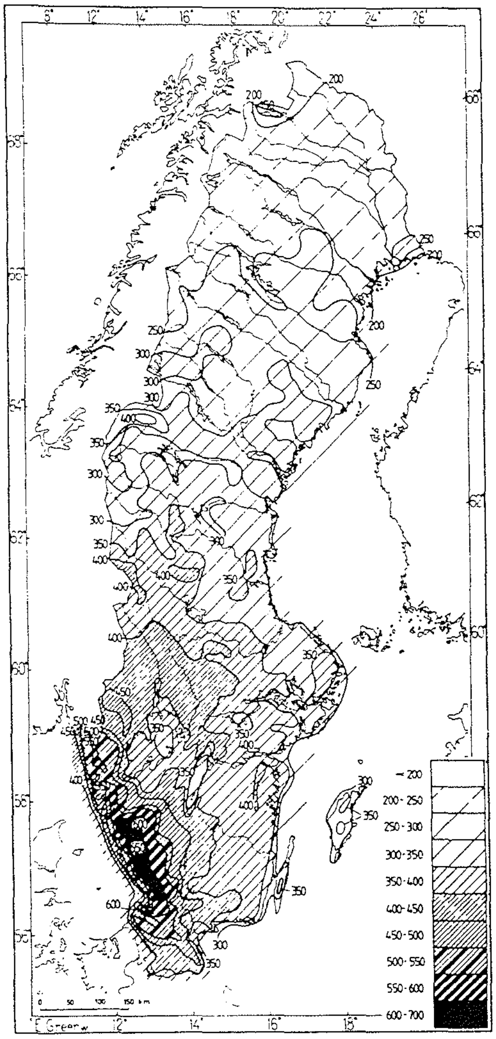
Skogsskador i Sverige - Vart tog vattnet vägen ?

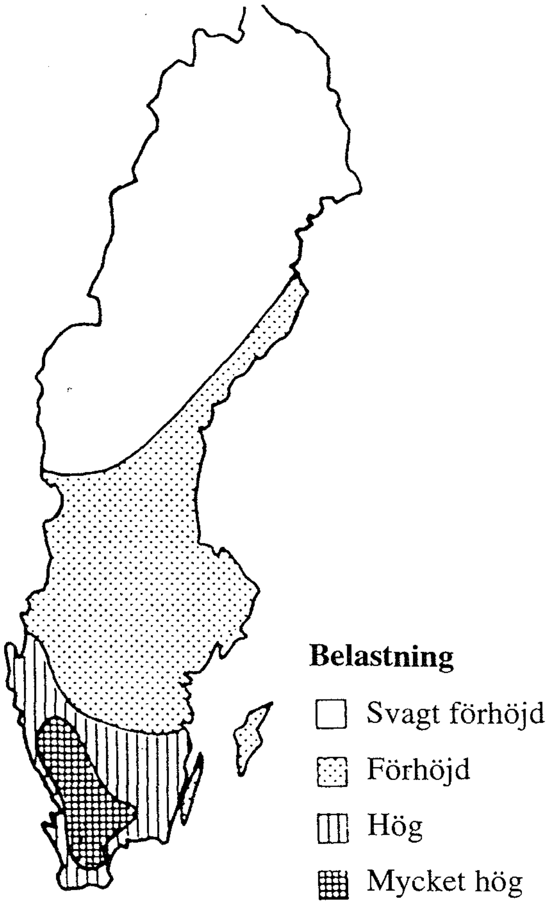
Rapporter om skogsskador i mellaneuropa och Sverige i slutet av 70- och början av 80- talet (Ulrich, 1981, Bauch, 1983, Rehfuess, 1981, Aronsson et al., 1978, Barklund, 1983) väckte stor uppmärksamhet och en debatt om orsakerna inleddes. Det var främst luftföroreningar och försurning som sattes i samband med de observerade skadorna. Sensommaren 1983 kom rapporter från södra Sverige att gran och tall uppvisade den typ av kronutglesning som beskrivs från mellaneuropa (Jfr Andersson 1985). Detta var orsaken till att man bestämde sig för kontinuerlig skogsinventering av skadesitutionen med början 1984. Sedan dess har orsaker till skadorna varit i fokus bland skogsforskare.

I debatten utpekas ofta luftföroreningarna som den främsta orsaken till skadorna. Flera forskare har dock påpekat att vi inte varit tillräckligt uppmärksamma på andra orsaker till skadorna (Jfr Barklund, 1994, Innes, 1993, Skelly, 1992, Kohh, 1985). En sådan orsak som inte har fått berättigad uppmärksamhet är vattenbrist som enskild faktor och som kopplad till andra faktorer som luftföroreningar. Detta trots att man ser klara samband mellan ökningen av skogsskaderapportering och torra somrar i södra Sverige. En möjlig orsak till att vattenbrist ej beaktas är att de nederbördsrikaste regionerna också är de som hårdast drabbats av försurning och luftföroreningar (Fig 1&2).

Faktum är att det i södra Sverige i slutet av 1960-talet och under 70-talet förekom anmärkningsvärt många somrar i följd med mindre nederbörd än normalt (Eriksson, 1986). Samma undersökning visar att årtal för torraste sommar mellan 1883 - 1983 i de flesta delar av Götaland är 1969, 1976 och 1983, även 1982 hade en torr sommar. I resultatet av riksskogstaxeringar för barrträd t.o.m. 1992 i Götaland minskade utglesningen i mitten av 80-talet efter en följd av år med betydligt gynnsammare väderbetingelser för skogen än de torra somrar som rådde innan dess, för att i slutet av 80- talet öka i den äldre skogen och förbli på en nivå i paritet med 1984 (Wijk et al., 1993). Man kan förvänta sig en ny ökning av skador pga de torra somrar som har inträffat efter 1989. Tre varma och torra vegetationsperioder har inträffat i en följd. Maj och juni 1992 var mycket varma och torra och det blev värmerekord i många delar av landet, men redan året därpå blev rekordet slaget i delar av Götaland och Östra Svealand (Anonym, 1992 & 1993). Århundradets april- och majvärme inträffade 1993 som dessutom blev rekordtorr i Sydvästra Götaland och Östra Svealand (Anonym, 1993). Slutligen år 1994 fick man ett nytt rekord på många platser i södra och mellersta Sverige med århundradets varmaste juli samtidig som det blev rekordtorka i delar av Götaland (Anonym, 1994).

I början av 90- talet konstaterades en ny och tidigare okänd typ av skada i granskog kallad Hallandssjukan, eftersom den först upptäcktes i Halland. Skadorna yttrar sig i form av onormala kådflöden hos till synes i övrigt friska träd. Många forskare antog att huvudorsaken till dessa skador var försurning och luftföroreningar i kombination med det faktum att Halland ligger på gränsen av granens egentliga utbredningsområde. Sedan hösten 1994 har likadana skador upptäckts på platser långt från Halland ända upp i Norrland. Det finns nästan ingen säker kunskap om orsakerna men i ett försöksområde vid Skogaby i Halland förekommer ett mönster med en högre frekvens av drabbade träd i torkbehandlade ytor.





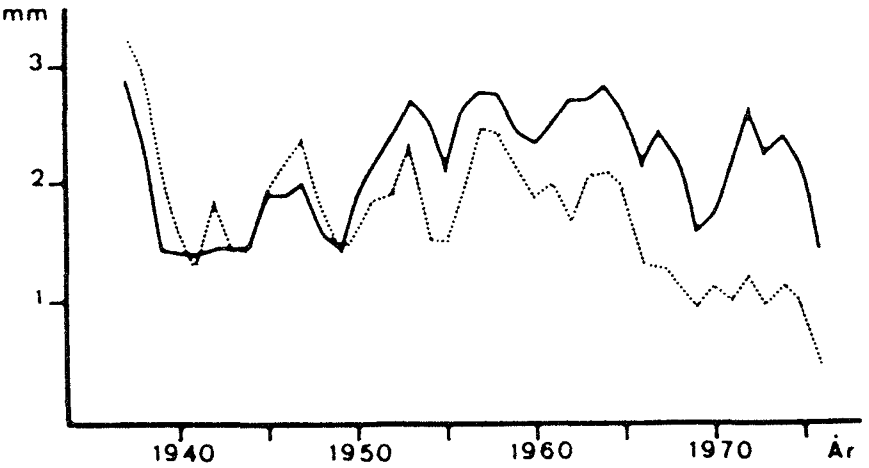
Figur 1. Nederbörden i mm (medelvärde 1951-80) under vegetationsperioden. Okorrigerade värden. (Efter Eriksson, 1986).

Figure 1. *Precipitation amount during the vegetation period. Uncorrected values. From: Eriksson (1986).*

Figur 2. Fördelning av det våta nedfallet av luftföroreningar mellan olika områden i Sverige. (Efter Rune, 1990).

Figure 2. *Distribution pattern for wet deposition of air pollutants in Sweden. From: Rune (1990).*

Sedan länge har vi en allmän kunskap som visar att trädens klyvöppningar stänger då markvattenhalten kommer under en viss nivå. Detta leder till att både transpiration och fotosyntesen och följaktligen trädens tillväxt minskar (Jfr Zahner, 1968, Kozlowski, 1982). Markfukten reglerar även tillväxten genom sin effekt på mineraliseringen av olika näringsämnen (McMurtrie et al., 1990, Powers, 1990). Runt om i världen har man i olika fältförsök visat att vattenstress kan begränsa skogsproduktionen (Benson et al., 1992, Cole et al. 1990, Linder, 1987, Myers & Talsma, 1992, Nambiar, 1991, Snowdon & Benson, 1992, Yarie et al., 1990).

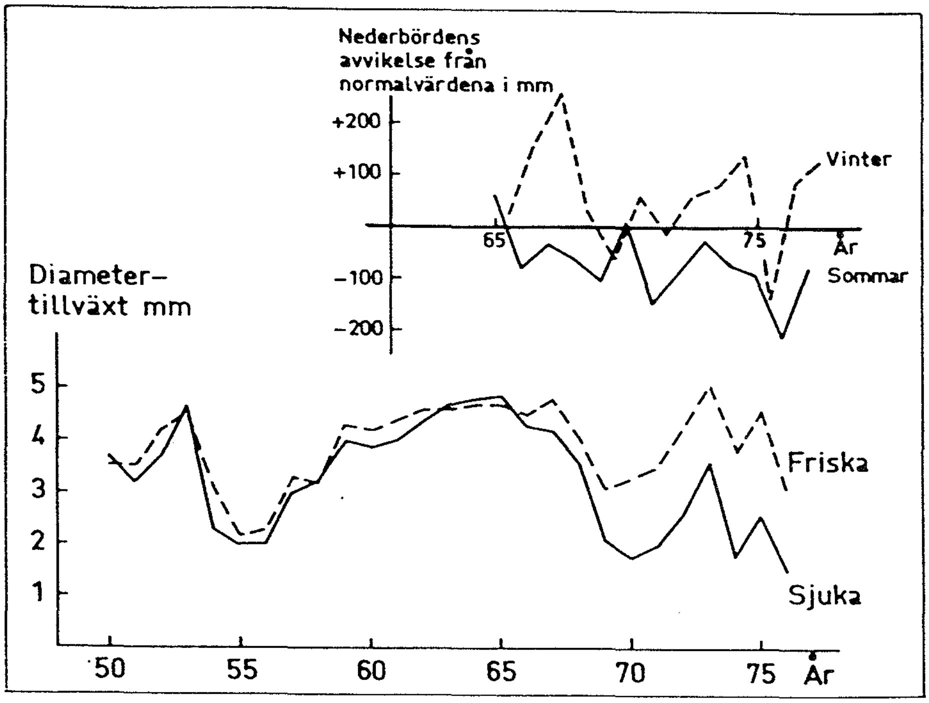


Figur 3. Årsringstillväxten i brösthöjd hos skadade (..........)respektive friska (▬▬▬) träd under perioden 1937 - 1976. (Efter Aronsson et al., 1978).

Figure 3. *Annual ring growth at breast height for symptomatic (..........) and asymptomatic (▬▬▬) spruce trees during 1937 - 1976. From: Aronsson et al. (1978).*

I den första riksinventeringen av skogsskador konstaterades att skadefrekvensen, speciellt i de högre skadeklasserna, är störst på torra marker (Bengtsson, 1985). Aronsson et al. (1978) studerade diametertillväxten hos skadad och oskadad gran i Västmanland och hittade en lägre diametertillväxt hos skadade träd jämfört med oskadade för de sista 25 åren som föregick undersökningen (Fig 3). Samma mönster har man konstaterat i norra Halland, norra Skåne och Blekinge (Barklund, 1983, Björkdahl & Eriksson, 1989) (Fig 4). Figur 4 visar att gapet mellan friska och sjuka träd i diametertillväxten är relaterad till underskott av nederbörden under sommarhalvåret. En analys av tillväxt i olika skadeklasser baserad på omfattande datamaterial från inventeringar mellan 1984 och 1990 (32 000 träd) visar att reducering av tillväxt hos enskilda träd ökade med graden av skada (Söderberg, 1993). Resultatet visar att tillväxten för gran i Götaland var lika till mitten av 70- talet för att senare bli mindre och mindre för skadade träd. I Figur 5 kan man tydlig se att skillnaderna förstärktes under torra år som 1976 och 1983. Motsvarande undersökningar av tillväxt hos gran och tall i de av luftföroreningarna drabbade områdena i nordöstra USA tyder på samma tendens. Torka och efter varandra följande torra somrar nämns som huvudorsaken till tillväxtminskningen (Johnsson et al., 1983).

I två uppsatser (I och II) belyses sambandet mellan markfukt och grundytetillväxt i Skogaby i Halland. Datamaterialet bestod huvudsakligen av mätningar av markvattenpotentialen under fem vegetationsperioder från 1988 t o m 1992.

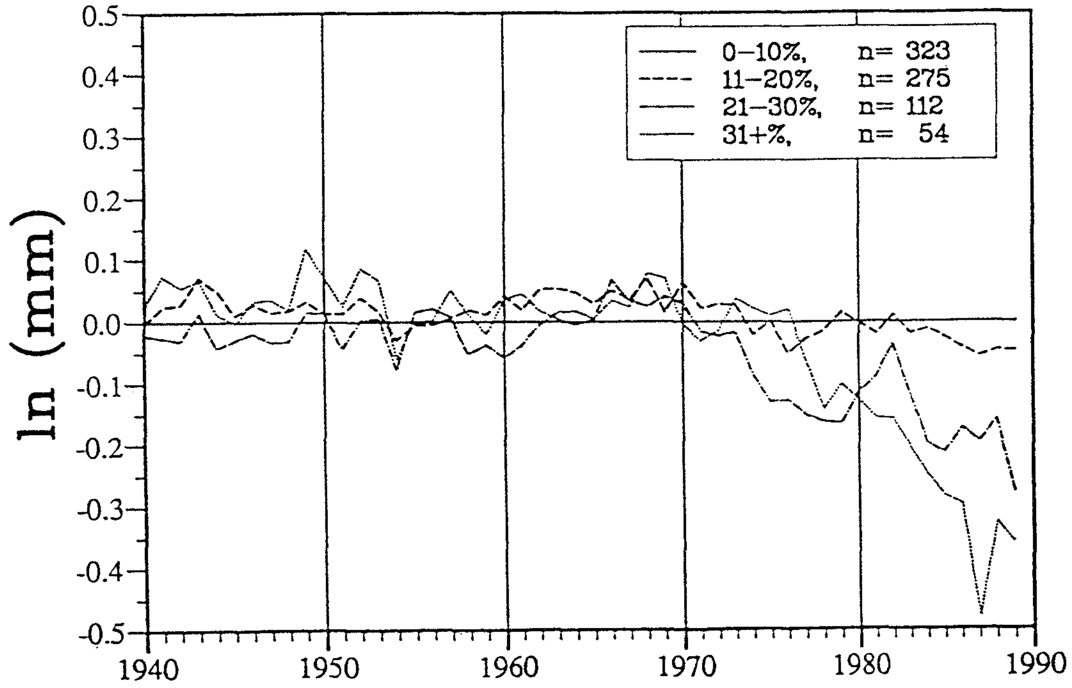


Figur 4. Årliga diametertillväxten, i äldre bestånd, i 29 friska granar (medeldiameter 31,3 cm) och 21 svårt skadade granar (medeldiameter 31,6 cm) i diameterintervallet 26 - 35 cm, 60-årigt bestånd i Gällared (Halland). Nederbörden i mm för sommar- och vinterhalvår vid SMHI:s station i Fagered 14 km NNV Gällared. (Efter Barklund, 1983).

Figure 4. *Annual diameter increment of 29 healthy spruce, mean diameter 31.3 cm (dashed line) and 21 severely damaged spruce, mean diameter 31.6 cm (solid line) at the diameter interval 26-35 cm, 60-year-old stand at Gällared in southwestern Sweden. Upper diagram shows departure from the normal values of six months-precipitation for summer- (solid line) and winter (dashed line) in mm at Fagered 14 km northwest of Gällared. From: Barklund (1983).*

Undersökta ytor i (I) representerade olikheter i grundyta och experimentella behandlingar, nämligen: bevattning, näringsbevattning och kontroll. För att normalisera mätvärdena från ytor med olika vattentillförsel användes en fysikalisk baserad matematisk modell, SOIL. Resultaten visade att de ytor som hade en större grundyta också hade högre markvattentensioner dvs "torrare marker". Slutsatsen var att tätare bestånd orsakar högre interceptionsavdunstning och transpiration. Modell användes också för att simulera hela vattenbalansen. Resultaten visade stora mellanårsvariationer i transpiration mellan bevattnade och icke bevattnade bestånd. Under en regnig sommar var skillnaden bara 4% högre avdunstning för bevattnade bestånd, 1991, medan skillnaden ökade till hela 56% under en torr sommar, 1992. En känslighetsanalys av den markvattentension där reduktion av vattenupptagningen börjar, ψ_c , utfördes med hjälp av modellen. Den relativa ökningen av simulerad transpiration för bevattning visade den största likhet med motsvarande ökning av grundytetillväxt när man använde ett värde av 150 cm vp för ψ_c . Detta indikerade att grundytetillväxten reduceras relativt ofta eftersom markvattentensionen ofta överskrider det värdet även i delar av landet med hög nederbörd.

Undersökta ytor i (II) bestod av ytor med olika näringsbehandling men med samma vattentillförsel (naturlig nederbörd). Grundytans variation mellan olika ytor relaterades till markvattentensionen. Resultaten visade ett klart samband mellan grundytetillväxt och markfuktighet. Lägre grundytetillväxt förekom på ytor med högre markvattentension. Detta tyder på att markfukten har bestämt stamtillväxten under många år och att stamtillväxten i regel reduceras på ytor med tunna marktäcken i den del av Sverige trots den höga årsnederbörden (1100 mm). En analys av två kontrollytor och två kväve-behandlade ytor med olika markfuktsförhållanden tydde på att träden inte kunde dra nytta av tillgänglig näring då brist på vatten uppträdde.



Figur 5. Skillnader i årsringstillväxt i olika kronutglesningsklasser jämförd med tillväxt för träd i kronutglesningsklass 0 -10% för 50-70 år gamla granar i Götaland. (Efter Söderberg, 1993).

Figure 5. *The difference in diameter increment for different defoliation classes compared to the increment of trees in defoliation class 0-10% of Norway spruce with age 50-70 years in southern Sweden. From: Söderberg (1993).*

Trots att nederbörden var klart högre än avdunstningen under vegetationsperioderna förekom torra perioder, speciallt under försommrar, som ledde till betydande markvattendeficit (Tab 3 (I), Fig 2 (II)). Detta betyder att total nederbörd under vegetationsperioden inte är en ändamålsenlig indikator på vattentillgängligheten. För att kunna göra en någorlunda korrekt beräkning av vattentillgången måste fördelningen av nederbörden och avdunstningen i tid och rum beaktas. Topografiska förhållanden och markens förmåga att lagra vatten spelar här avgörande roller. Ett större markvattenmagasin ger en längre varaktighet av potentiell transpiration och torra perioder med reducerad transpiration blir kortare. Högre total transpiration ger också en högre tillväxt. Sammanfattningsvis konstaterades att:
Produktiva granbestånd lider av vattenbrist trots att de befinner sig i en humid region med stort nederbördsöverskott under vegetationsperioden.

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SOIL MOISTURE DYNAMICS AND TRANSPIRATION FOR SPRUCE STANDS OF DIFFERENT CANOPY DENSITIES AND WATER AVAILABILITY

G. Alavi and P-E. Jansson
Dept of Soil Sciences, Swedish University of Agricultural Sciences
P.O. Box 7014, S - 750 07 Uppsala, Sweden

SUMMARY - Soil water tension was measured during five growing seasons in closed stands of Norway spruce (Picea abies (L.) Karst.) in southern Sweden, subjected to different water and nutrient regimes. The aim of this paper was to present comparisons of soil water tension for different plots representing different above-ground biomass, and to interpret the results in terms of evaporation rate. A physically based mathematical model, SOIL, was used as a tool to identify differences in evaporation properties between plots and to estimate stand evaporation. Differences between plots due to differences in water additions was eliminated with a normalisation procedure. The result of five years of investigation showed that plots with higher basal area had higher rates of transpiration and interception losses. The non-irrigated stands suffered from water stress, even though a yearly excess of water was found for all years. Trees that suffered during very dry conditions, compensated with higher transpiration after rewetting of the soil, thus at this stage a higher rate of water uptake was found for the non-irrigated treatment than for the irrigated treatment.

1. INTRODUCTION

High frequency of spruce damage in south Sweden has caused increasing interest in the possible synergistic effects of air pollutants and climatic extremes [13,17]. Andersson [1] made a time series analysis (1883-1987) using a conceptual soil moisture model and detected a trend towards higher summer soil moisture deficits for coniferous forests in south-central Sweden. A major problem for hydrologists and ecologists has been estimation of evaporation losses from forests and the role of water for growth and vitality. In spite of a number of investigations, knowledge of forest water use is still incomplete. To understand and overcome these difficulties the Skogaby Project was started in 1988. The general objective was to find out which climatic and nutritional conditions result in positive or negative effects of air pollutants on spruce forest growth and vitality [8]. Studies on the water relations of spruce were carried out as an integrated part of the research programme.

The two most important processes that make up forest evaporation are water losses from the intercepted water on the tree canopy and transpiration through the needles of the trees. The interception process is influenced by a certain group of meteorological factors and a relatively good physical understanding of it has been obtained [22]. In contrast, the transpiration component of evaporation is influenced by many other factors; forest age, species, leaf area index, stomatal conductance and soil-moisture conditions producing large variations in forest transpiration. Consequently, it is much more difficult to obtain sufficient information about forest transpiration [21]. In spite of this, Nordén [19] estimated transpiration of a Norway spruce stand in southeast Sweden and found it about 400 mm $year^{-1}$ during three consecutive years. Also, Stålfelt [23] measured transpiration of a spruce stand in southern Sweden (Skåne) and found 378 mm transpiration during the growing season.

Briefly, the two important resistances regulating vapour fluxes are the surface resistance, which is the sum of all stomatal resistances of all needles, and the aerodynamical resistance between vegetation and atmosphere. The rate of transpiration is particularly sensitive to saturation vapour deficit and canopy resistance [12,14].

2. OBJECTIVE

In the present paper, the following hypotheses are tested concerning water use for a Norway spruce stand (Picea abies): Higher rate of above-ground biomass, represented by stem basal area, in a highly productive stand will cause higher interception evaporation and transpiration rates leading to drier soil moisture conditions. Measured values of soil water tension,ψ, for different plots, representing different stem basal area and production levels, are used together with a physically-based soil water model.

3. MATERIAL AND METHODS

3.1 Site description and experimental set-up

A detailed description of the site is given by Bergholm et al. [2] and thus in the present paper the description will be restricted to the most important characteristics . The site is located in southwest Sweden, 30 km southeast of Halmstad (56°33.5'N,13°13.5'E) at an altitude of approximately 100 m. The bedrock is covered by a layer of till more than 2 m thick, the average thickness of the humus layer was 6.7 cm and that of the leached layer was 2.1 cm [2]. The sandy till soil has a pH of around 4.0 which increases to about 4.5 in the subsoil. The climate is characterised by a high precipitation of around 1100 mm. The mean annual air temperature (1931-1960) is about 7° C.

The Norway spruce [Picea abies (L.) Karst.] monoculture stand was planted in 1966 as the second generation of coniferous forest. The basic stand characteristics for the studied plots in 1987 were: Mean height 12.5 m, diameter breast height 11 cm and tree density 2360 trees ha^{-1} (Table 1). The rate and development of basal area ha^{-1}, BA, during 1987-1992 are shown in Figure 1, which shows a higher growth of BA in I and especially IF relative to C. The present stands contained no other tree species and no understory.

The site was surveyed and the field plots were selected during 1987. The area of each plot is about 2000 m^2. The treatments started during the growing season of 1988. Irrigation was done using a sprinkler technique which gives an even distribution of water on the soil surface. The amount of water was adjusted to avoid any soil moisture deficits exceeding 20 mm of water in the 50 cm upper zone during the growing season both in the treatment with irrigation only (I) and with irrigation together with liquid fertilizers (IF). No treatment was applied in the control (C).

In the present study, the plots were split into 3 blocks on the basis of soil moisture condition (Table 1). Three plots were studied during all five years of investigation, namely 22IF, 24C and 25I. Three plots, 12I, 15C and 26IF, were studied during 1988-1989 and 1992 while 3C was studied during 1989-1991, and 4I and 9IF were studied during 1990-1991.

3.2 Model Description

The main part of the SOIL model consists of the partial differential equation describing heat and water transport in a soil profile. The profile is divided into a number of layers with user-specified thickness and soil properties in order to solve the flow equations with a finite difference technique. Appropriate boundary conditions are supplied by submodels of interception, evapotranspiration, snow dynamics and net horizontal ground water flow. Driving variables used in this study were daily sum of precipitation, daily averages of air temperature, air humidity, wind speed and global radiation.

A detailed description of the model is given by Jansson and Halldin [11] and Jansson [9,10]. The water balance equation gives the changes in the water content profile and is combined by the Darcy equation [20]:

$$\frac{\partial\theta}{\partial t} = -\frac{\partial}{\partial z}\left(k_w\left(\frac{\partial\psi}{\partial z} + 1\right)\right) + s_w \qquad (1)$$

Where θ is the volumetric water content ($m^3\,m^{-3}$), t is the time (day), k_w is the unsaturated hydraulic conductivity (m day^{-1}), ψ is the soil water tension (m water), z is depth (m) and s_w is water sink/source (day^{-1}).

The soil water retention curve and the unsaturated conductivity function are based on the expressions of Brooks and Corey [3] and Muelem [16] but modified to explicitly account for the influence of macro pores. Transpiration is defined as potential rate when neither soil water deficits nor soil temperatures influence the water loss. Unless given directly as a driving variable, daily potential transpiration, E_{tp}, is calculated from Penman´s combination equation in the form given by Monteith [15].

3.3 Method of identifying effects of treatments

Direct comparison between the measured ψ in irrigated and non-irrigated plots will not reveal differences in forest evapotranspiration properties because irrigation causes wetter soil conditions. Comparison between the soil tension of I and IF may also be doubtful because these plots were not always irrigated simultaneously. *SOIL* was used to transform the measured values from different treatments into comparable indicators. By calibrating the model to the control, it was used as a mould to identify differences in the soil moisture conditions which could be the results of changed evaporation properties. The procedure was:

Step 1. The model was parameterized with help of the measured values of ψ in C for growing seasons in 1990 and 1991.

Step 2. Without changing any of the parameter values, the model was run for the irrigated plots using the same driving variables as for the C treatment but adding the applied irrigation.

Step 3. The measured values of ψ were compared with the simulated values and a regression line was made for each plot with the simulated values as independent variable.

Step 4. Differences between plots with different treatments were found by comparing the predicted values at a logarithmic value of simulated ψ (cm water) equal to 2.25, pF = 2.25, using the two obtained regression equations.

This difference, $\Delta\psi$, is a function of the stands and therefore an indicator that shows the differences between plots in Water Uptake and Interception Capacity (WUIC).

3.4 Measurements and parameterization of the model

Air temperature, air humidity, wind speed, solar radiation and precipitation were measured at intervals of 60 minutes in an open area (50 by 50m, surrounded by forest). To estimate the wind speed at the top of canopy, the measured values were multiplied by a correction factor of 2.9. This factor was obtained by comparing the measured values with the measurement of wind speed at the top of the canopy in the summer of 1991.

Soil cores (diameter 7 cm) taken from four different pits were used to determine soil water retention characteristics. A special investigation of stones larger than 20 mm (Johan Bergholm, pers. comm. 1992) was used to adjust the porosity obtained from the soil cores to the porosity of the field soil.

Conventional tensiometers (Soil moisture equipment) were used during a 5-year period to measure ψ during the growing season in the studied plots at depths of 15, 30, 45 and 60 cm. They were read manually once a week. Because of the shallow root zone, most of the tensiometers were installed at 15 and 30 cm depths. The average numbers of tensiometers per year were 22, 14, 5 and 4 for 15, 30, 45 and 60 cm depths, respectively. The total number of tensiometers generally increased during the 5-year period. During the three last years 13, 19 and 41 tensiometers were connected to a data logger, respectively. The valid range for all tensiometer measurements was restricted to between 0 and - 650 cm water.

The critical soil water tension, ψ_c, where reduction of the actual water uptake begins, was chosen to 1000 cm water [24]. The deepest level with roots was chosen to 100 cm (Majdi, H., pers. comm., 1992), and an exponential decrease of the root density from soil surface to the root depth was estimated according to an investigation made by Hans Persson et al. (pers. comm., 1992). Leaf area index was estimated according to seasonal development of LAI in C during 1991 (Nilsson and Wiklund, pers. comm., 1992). To estimate hydraulic conductivities of the soil layers, measured ψ were used for calibration during periods with low evapotranspiration rates (Fig. 2). The output of the model showed the best agreement with measured ψ for the control plots during the years 1990 and 1991 when using a value of 1.5 for the ratio between the distance from displacement height to the reference height and the roughness length in the calculation of the aerodynamic resistance and a value of 60 sm^{-1} for the surface resistance during the summer. The same values were used for all years and no efforts were made to calibrate the model for other years.

4. RESULTS

Regression analysis was used to quantify the agreements between the simulated and the average value of measured ψ for each plot. To use R^2 as a sensitive indicator of model performance, the measuring periods were split into different subperiods. In general, R^2 was about 0.8 for the entire 5-year period simulated (Table 2). The simulated dynamics agreed well with the measurements. Deviations between simulated and measured ψ occurred during periods when soil water tension was above the capacity of tensiometers, like during early summer droughts (Fig. 3). The best agreement was obtained for the 15 and 30 cm depths in 1990 and 1991. This may have been the result of using these years for calibration of the model. Also the other years were similar and there were no differences in agreement for the different depths.

Table 1. Basic stand characteristics for the studied plots in 1987.

Block	Plot	Mean diameter breast height (cm)	Stem basal area (m^2 ha^{-1})	Number of Trees (trees ha^{-1})
1	9IF	11.6	19.2	1793
	24C	12.2	30.1	2459
	25I	12.1	31.6	2469
	26IF	11.1	26.8	2622
2	12I	9.9	29	3269
	15C	12.6	24.8	2133
	22IF	12.6	29.4	2242
3	3C	10.7	21.5	2020
	4I	10	22.5	2212

Table 2. Minimum, maximum and mean values of coefficient of determination (R^2) and number of performed regression lines (n) between simulated and measured ψ (whole periods and subperiods).

Depth (cm)	Indicator		Year 1988	1989	1990	1991	1992
15	n		6	8	27	21	29
	R^2	Min	0.66	0.65	0.656	0.47	0.3
		Max	0.928	0.928	0.999	0.999	0.999
		Mean	0.76	0.78	0.84	0.88	0.71
30	n		6	7	21	18	25
	R^2	Min	0.62	0.66	0.48	0.6	0.38
		Max	0.934	0.814	0.994	0.999	0.999
		Mean	0.74	0.74	0.86	0.9	0.79
45	n			5	9	14	9
	R^2	Min		0.57	0.61	0.51	0.59
		Max		0.894	0.94	0.999	0.999
		Mean		0.71	0.67	0.85	0.85
60	n			2	8	6	16
	R^2	Min		0.575	0.73	0.61	0.47
		Max		0.583	0.998	0.998	0.999
		Mean		0.58	0.91	0.82	0.89

The amount of irrigation was negligible in 1988, and therefore no differences in water balance were simulated between C and I (Table 3). During the other years, simulated transpiration increased 24%, 14%, 4%, 56% for I compared with C during the growing seasons of 1989 to 1992, respectively (Table 3). The mean daily transpiration, during April through October, was 1.6 mm for C and 2 mm for I.

Table 3. The simulated water balance components for the control and for the irrigated treatments assuming the same stand properties as for the control treatment, from 1 April to 31 October.

Year	1988		1989		1990		1991		1992	
Treatment	C	I	C	I	C	I	C	I	C	I
Precipitation	743		659		800		775		704	
Irrigation		6		127		118		203		322
Transpiration	387	387	342	424	370	422	381	397	276	430
Evaporation from intercepted water	201		182		211		200		137	
Evaporation from soil surface	23	23	22	23	19	21	19	20	10	12
Total runoff and drainage from soil	156	161	97	145	197	262	179	362	228	394
Change in soil water storage	-24	-23	16	12	3	2	-4	-1	53	53

A number of widely different values of ψ_c have been suggested in the literature [cf. 6]. Jansson [7] found this value about 150 cm water in a mainly spruce forest while Calder [4] found a value about 6000 cm water for a Norway spruce forest. To test the sensitivity of the increased simulated transpiration for I compared to C, four-year simulations were performed using a wide range of ψ_c values (Fig. 4). The sensitivity for ψ_c was quite different for the different years because of differences in the duration and frequency of drying periods. Annual increases of simulated transpiration for I relative to C showed the most similarity with the corresponding increases of basal area growth when using a value about 150 cm water for ψ_c (Fig. 4).

To find relationships between BA and WUIC, $\Delta\psi$ was obtained by subtraction of ψ in a plot with relatively low BA from ψ in a plot with relatively high BA, both between plots in the same block, and between plots belonging to different blocks, which gave the difference between plots in WUIC (Tables 4-6). Generally, plots with high BA were also high in WUIC. An exception occurred after the long dry period in 1992. A substantial negative effect of irrigation on WUIC was observed in comparison of irrigated with non-irrigated plots during the later period of growing season in 1992. All comparisons indicate a higher WUIC in C than in I and IF in September (Table 7).

5. DISCUSSION

The results showed that plots with higher BA had higher WUIC, $\Delta\psi > 0$ (Tables 4-6). However, the subperiods were almost exclusively within July 1 - Sep. 31. It means that these results are not valid for the early summers. This indicated that increased above-ground biomass increased the demand of soil water because of an increased rate of transpiration and interception evaporation.

The differences between C and I in transpiration indicated that the non-irrigated stands were suffering from water deficit almost during all years investigated (1988 excluded), especially during 1989 and 1992 in which simulated transpiration increased by about 25% and more than 40% for irrigation relative to control. Annual increases of basal area growth for I

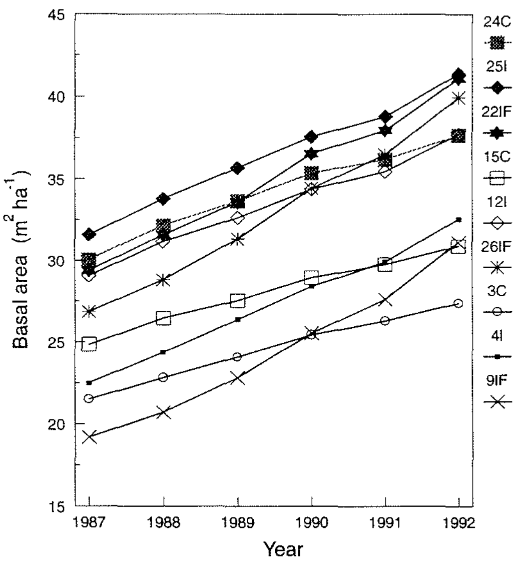

Fig. 1. Basal area in the studied plots during 1987-92, (data of Nilsson & Wiklund, 1993).

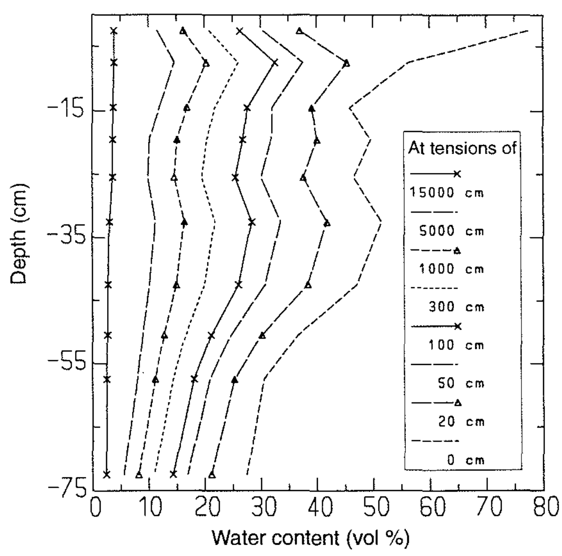

Fig. 2. Water content at different tension for a representative soil profile. Hydraulic conductivity was obtained by comparing measured and simulated tension.

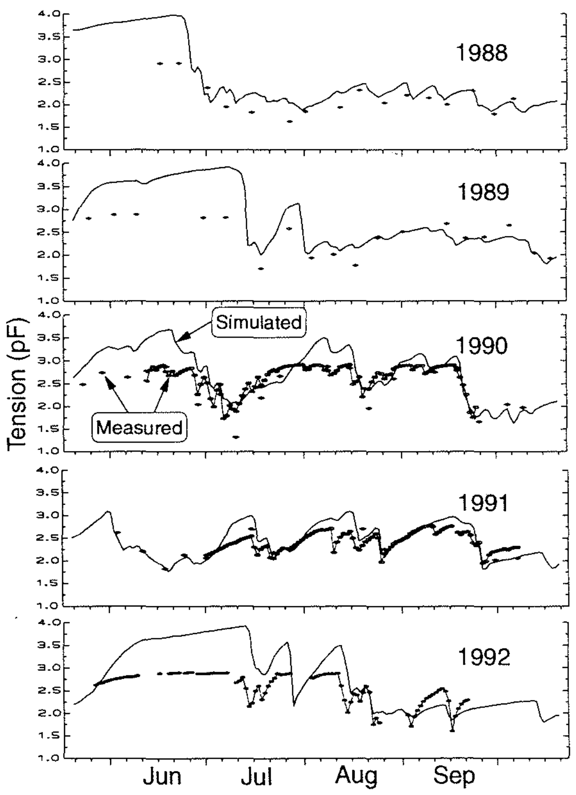

Fig. 3. Simulated and measured values of soil water tension ψ at 15 cm depth in a control plot, 24C. The solid symbols represent weekly values from the tensiometers, whereas the open symbols connected with a dashed line represent tensiometers connected to a data logger with hourly registrations.

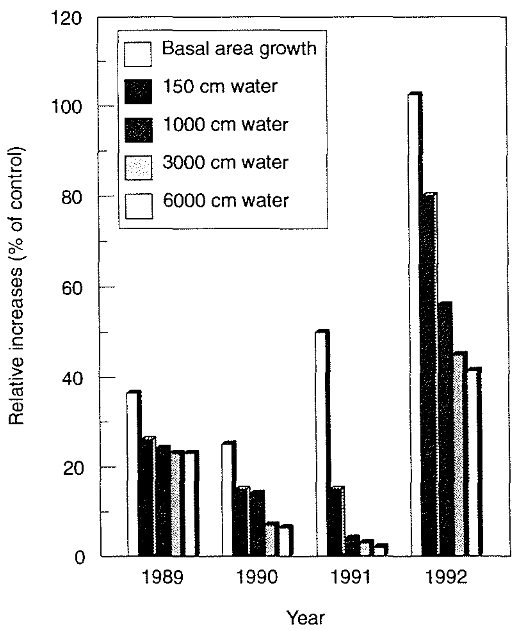

Fig. 4. Annual increases of basal area growth and increases of simulated transpiration for the irrigation treatment relative to the control (0). The simulated values represent different values of critical soil water tension, (Basal area growth from Nilsson & Wiklund, 1993).

Table 4. Differences between plots in the same block in tension, $\Delta\psi$, during 1988-92.

Block	Plot	Depth (cm)	Year				
			1988	1989	1990	1991	1992
1	25I-24C	15	-36	43	58	25	122
		30	-51	27	33	8	-17
		45				14	
		60			70		
	24C-26IF	15	25	-44			
		30	26	-39			
	26IF-24C	15					-80
		30					0
	25I-26IF	15	-11	13			93
		30	-25	0			92
		45		0			
	25I-9IF	15			95	53	
		30			96	127	
		60			115	100	
	24C-9IF	15			52	75	
		30			60	98	
		60			97	60	
2	22IF-15C	15	8	0			72
		30	0	0			86
	12I-15C	15	0	0			0
		30	28	34			47
		45					
		60					-102
	22IF-12I	15	11	0			55
		30	-29	-38			57
		45		-11			66
		60					11
3	4I-3C	15			20	0	
		30				0	
		45			29	-56	

Table 5. Differences between plots belonging to different blocks in tension, $\Delta\psi$, during 1988-92.

Plot	Depth (cm)	Year				
		1988	1989	1990	1991	1992
25I-22IF	15		49	71		14
	30			67	38	55
	45		10	70	51	
25I-15C	15					65
	30					114
25I-12I	15					60
	30					76
25I-3C	15		43	80	25	
	30		26			
	45		14	125		
25I-4I	15			60	46	
	30			33	50	
26IF-15C	15		34			
24C-15C	15	5				
	30	25				
24C-3C	15			26		
24C-4I	15				42	
12I-3C	15		44			
	30		68			
	45		15			
26IF-3C	15		44			
	30		38			
	45		20			
15C-3C	15		20			
	30		34			

Table 6. Statistical analysis of $\Delta\psi$ (cm water) in 15 and 30 cm depths.

Indicator	Year				
	1988	1989	1990	1991	1992
Mean	-1.7	18	57.8	45	50.6
Median	2.5	26.5	60	42	58.5
Confidence Level (95%)	13.3	12.6	13.4	20.3	23.4
Count	14	22	13	13	18

Table 7. Statistical analysis of differences between non-irrigated and irrigated plots in tension (15 and 30 cm depths) during Sep. 2, 1992 - Sep. 21, 1992.

Indicator	$\Delta\psi_{(non\text{-}irrigated - irrigated)}$ (cm water)
Mean	106
Median	107.5
Confidence Level (95%)	40.8
Number of comparisons	16

relative to C were proportional to corresponding increases of simulated transpiration during the four years simulated, with the exception of 1991 (Fig. 4). Also, Nilsson and Wiklund [18] studied the effect of various treatments on Norway spruce production at Skogaby during 1988-1991 and found that the trees were suffering from temporary water stress during all the investigated years. The yearly sum of precipitation in 1989 was 974 mm, which is about 200 mm lower than for the other four years, and the summer of 1992 was the driest for many years, with almost no precipitation between May 12 and July 10.

The small differences between the transpiration rates in I for all five years of investigation indicated an annual transpiration of about 400 mm when soil water deficit is avoided. Cienciala et al. [5] estimated the sum of transpiration during the 1990 growing season (April 13, 1990 - Oct.19, 1990) for an irrigated stand in Skogaby to be 392 mm, based on measurement of sap-flow rate. For the same period, we found the sum of transpiration in I to be 411 mm. The estimated seasonal transpiration rates here, both for I and C, with the exception of C in 1992, are fairly close to estimated transpiration rates according to Nordén [19] and Stålfelt [23] (see Introduction), but are higher than the average annual transpiration rate of 333 mm estimated for northwest Europe [21].

Finally, trees that suffered from water stress during the early summer of 1992 had more efficient transpiration ability than irrigated stands after the soil had been rewetted to favourable conditions (Table 7). Also the measurements of LAI in 1992 (Nilsson and Wiklund, pers. comm., 1993) showed an increase for C in September compared with August, but a decrease for IF and I.

6. CONCLUSIONS

It demonstrated that a model can be used not only to estimate the water balance components but even to normalise experimental data from different treatments to screen out differences between stand properties.

Higher rates of above-ground biomass in a highly productive stand will cause higher interception evaporation and transpiration rates, leading to drier soil moisture conditions.

The Norway spruce stand at Skogaby was suffering from water stress to quite different degrees depending on the chosen value for critical soil water tension, where reduction of the actual water uptake begins. The most similar between-year pattern in the irrigation effect, expressed as increased transpiration, was obtained when a low value of critical soil water tension around 150 cm water was used.

In future investigations, it would be an advantage to simultaneously measure soil water tension, sap-flow rate, stomatal conductance and leaf area index.

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Radial stem growth of Norway spruce in relation to spatial variation in soil moisture conditions

Ghasem Alavi
Dept of Soil Sciences, Swedish University of Agricultural Sciences
P.O. Box 7014, S - 750 07 Uppsala, Sweden

SUMMARY - Soil water tension was measured for five years (1988-1992) in different plots established in a 26-year-old stand of Norway spruce in southern Sweden. The plots were subjected to different nutrient regimes but having the same precipitation input. Content of stone and gravel varied between plots. Stem growth, estimated as basal area increment, varied between plots. This variation was related to soil water tension to evaluate the role of soil moisture in regulating stem growth. An annual increase in basal area equivalent to 2.1 m^2 ha^{-1} was estimated for trees growing on soils without a water deficit. Lower rates of stem growth were found on soils with higher soil water tensions. The result showed that soil moisture has been a major factor limiting stem growth for many years and that stem growth is generally hampered on shallow soils despite an annual precipitation of around 1100 mm in this part of Sweden. Analysis of two control plots (C) and two ammonium sulphate-treated plots (N) showing within-treatment differences in soil moisture conditions revealed two different trends: The ratio of the annual basal area growth on the plot on the wet soil to that of the plot on the drier soil was 50% higher for the N-fertilized plots compared with control plots. Thus it seems as though trees were unable to fully utilise available nutrients in the absence of adequate water.

Key words: basal area growth, evapotranspiration, Norway spruce, soil water deficit, soil water tension.

Introduction

Since the 1970s, decline in Norway spruce has been frequently observed in the southern part of Sweden. However, the cause(s) of this decline has been a matter of controversy. Although the common view has been that air pollunts have contributed most to the onset of forest decline, recent reviews attest to the importance of the direct and indirect effects of water stress (Innes, 1993, Skelly, 1992, Barklund, 1994). Manion (1991) suggested that climate change and low soil moisture holding capacity are major predisposing, or inciting, factors in forest decline. Aronsson et al. (1978) showed that the soil water deficit during the growing season was the primary cause of forest damage in southern Sweden. Prior to the appearance of damage, reduced diameter growth was detected. The same tendency was detected by Johnsson et al., (1983) in the northeastern United States. Both Aronsson et al. and Johnsson et al. concluded that the low level of precipitation during several successive years was the principal factor responsible. In a comprehensive investigation of forest damage in Sweden, Bengtsson (1985) concluded that the frequency of damage was highest on shallow soils, and that trees on hills or on upper parts of slopes were damaged more severely than trees on level areas.

The growth of forest varies widely, even within a relatively small area. Differences in the growth of trees, that have developed under apparently similar environmental conditions indicate that productivity is determined by differences in the availability of soil resources (water and nutrients) (Nambiar 1990/91). Zahner (1968), who made extensive studies of the effects of water deficit on tree growth, showed that water stress is an important factor restricting the growth of annual rings. Soil playes an important role in plant growth by supplying and transmiting water toward the roots at a rate sufficient to meet transpiration requirements. Generally, an increase in soil water tension from field capacity to wiltpoint is associated with reduced rates of photosynthesis and growth. In particular, water uptake by forest trees is commonly limited by high soil water tensions (Item, 1974).

An interesting challenge for forest researchers is to understand how moisture and nutrients interact in their influence on tree growth and forest productivity. Nitrogen fertilization has been shown to inhance forest production (Tamm, 1991). It has been speculated that the rise in nitrogen deposition in southern Sweden may increase drought sensitivity (Lindroth, 1989). A larger leaf area in a denser stand leads to a larger interceptive and transpirative surface and this, in turn, leads to drier soil moisture conditions. Alavi & Jansson (1995) found "drier" soil moisture conditions for Norway spruce stands with higher basal area. Since the studied stands had been subjected to different water regims, a mathematical model was used to identify differences between irrigated and non-irrigated stands. In the present study the relationship between soil moisture conditions and stem growth has been further explored using stands subjected to different nutrient regims but having the same precipitation input. The aims were to determine whether soil moisture has determined stem growth in Norway spruce stands at Skogaby in southwestern Sweden and to evaluate the importance of water availability as a factor limiting tree growth in Norway spruce stands in a humid region of Sweden.

Material and methods

Site description and experimental setup

The Skogaby study site is located in the southwestern part of Sweden, 30 km southeast of Halmstad (56°33.5' N, 13°13.5' E), about 16 km from the coast and at an altitude of approximately 100 m. The climate is characterised by a mean annual precipitation of around 1100 mm and an annual mean air temperature of about 7 °C. The mean soil pH in 1987 was 4.3.

The parent material at Skogaby, which is derived from gneiss, is poor in base minerals and is covered by a more than 2-m-thick till layer. The soil type is a poorly developed podzol (Haplic podsol according to FAO) with a sandy loamy till texture and a humus layer (O) and leached layer (E) with average thicknesses of about 6.7 cm and about 2.1 cm, respectivily (Bergholm et al., 1994). There is a wide spatial variation in the content of stones larger than 20 mm in the Skogaby experimental field (Bergholm, 1995). The volumetric stone content (computed as a percentage of the total volume of the soil) varied between 6 and 52% for 0 to 50 cm depth and between 17 and 65% for 50 to 100 cm depth.

The site was surveyed and the field plots were established in 1987. The experimental design was a randomised block design with four replicates. The blocks were created on the basis of the basal area ha^{-1} (BA) of the different plots in the autumn of 1987. The treatments (Table 1) started during the 1988 growing season. There are 30 plots, each with an area of 2000 m^2 (Fig. 1).

Air temperature, air humidity, wind speed, solar radiation and precipitation were measured hourly in a 50 × 50 m gap.

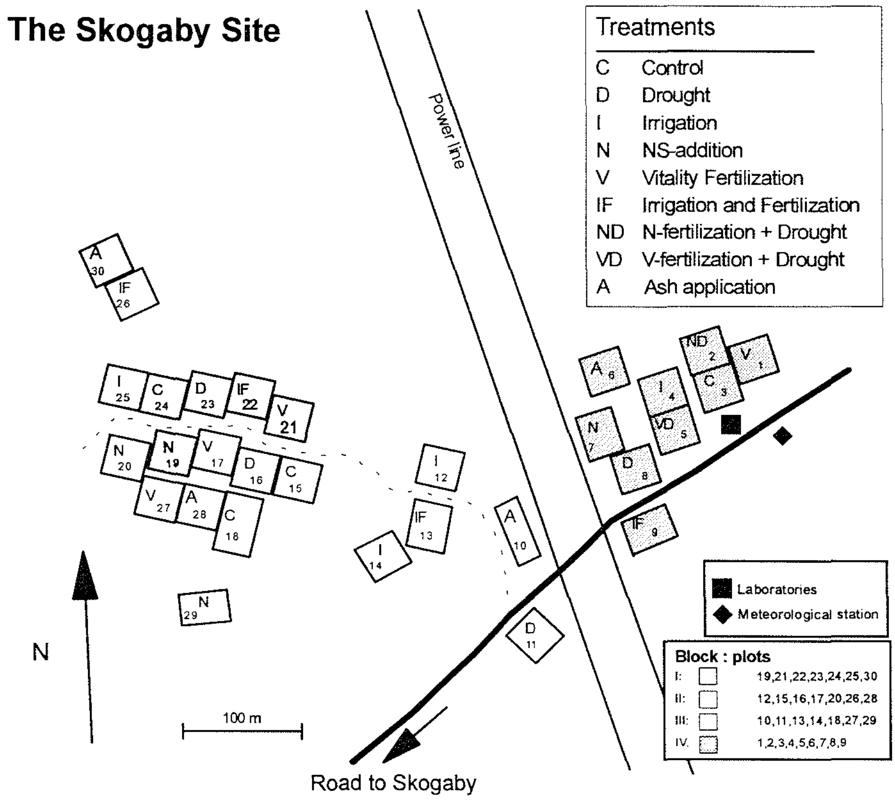

Fig. 1 The experimental area.

Table 1. Descriptions of treatments within the Skogaby Project during 1988-1992.

Symbol		Treatment	Description
C		Control	No treatment
D	D1	Drought 1988-89	A roof prevents 2/3 of the throughfall from reaching the ground in half the plot during April to September. During winter all precipitation is allowed to infiltrate into the soil profile.
	D2	Drought 1990-92	As D1 with the exception of year.
N		NS-addition	Ammonium sulphate is added manually three times a year (100 kg nitrogen and 114 kg sulphur per ha and year).
V		Vitality fertilization	500 kg per ha of the fertilizer "Skog-vital" was added in solid phase once a year during a period of two years (1988-89). "Skog-vital" is a commercial fertilizer without any nitrogen but including other elements supposed to be of importance for high forest vitality.
ND		NS-fertilization followed by drought	Like N but followed by drought identical to D in 1992.
VD		Vitality fertilization followed by drought	Like V but followed by drought identical to D in 1992.

Stand description

The area was planted in 1966 with two provenances of Norway spruce (Picea abies L. Karst.), replacing the first generation of Scots pine (Pinus sylvestris L.) planted in 1913. The two spruce provenances are Istebna (I) originating from southern Poland (lat. 49°34', long18°56', 5-700 m elev.) in plots 11-27 and 29, and Augustow (A) from northern Poland (lat. 54°, long 23°, 2-300 m elev.) in plots 1-5 and 7-9. The mean breast height diameter before starting the experiment in 1987/88 was 11.3 cm. The basal area of the entire experimental site was 24.4 m^2 ha^{-1} in 1987, while the basal area for the studied plots varied between 18.5 to 32.7 m^2 ha^{-1}. However, plots consisting entirely of provenance A were less productive than plots consisting of provenance I (Nilsson & Wiklund 1992). Diameters at breast height were measured annually at the end of the growing season. Diameters were converted to basal area on a per-hectare basis to representant stem growth in each plot (Nilsson & Wiklund 1992).

Soil moisture

Conventional tensiometers installed vertically (Soil moisture equipment, size of porous cup 6 × 2.2 cm) were used during a 5-year period to measure soil water tension,ψ, during the growing season in the studied plots at depths of 15, 30, 45 and 60 cm (Table 2). Because of the shallow root zone, most of the tensiometers were installed at 15 and 30 cm depths. They were read manually once a week.

Table 2. Number of installed tensiometers in different depthes during 1988 - 1992.

Year	Number of measurements taken at			
	15	30	45	60 (cm)
1988	17	9	7	1
1989	40	20	7	7
1990	39	25	7	8
1991	44	25	8	7
1992	37	27	7	6

Climatic conditions during the growing seasons

Annual mean air temperatures were 7.4, 8.2, 8.3, 7.1 and 7.7 °C during 1988-1992, respectively. The annual total precipitation varied between 974 mm (1989) and 1220 mm (1992). In spite of the high total amounts, a deficiency occurred in early summer each year, except for June 1991 when more than 200 mm of precipitation was recorded.

Potential transpiration was calculated with the Penman-Montieth combination formula (Montieth, 1965), assuming a surface resistance of 60 s m^{-1} (Alavi & Jansson 1995). Since the potential transpiration was high during early summer when precipitation was low, a considerable soil water deficit developed (Fig. 2).

During 1988, the major dry period occurred in early summer and lasted until June 24, whereas the corresponding period in 1989 was longer and lasted until July 12. There were no extremely severe drought periods during the 1990 growing season, although there were two minor dry periods, one in late April and early May and another in late July and early August. An extremely long period with low temperatures occurred in May and June 1991, which led to the potential transpiration in early summer 1991 being lower than in any of the other of the five years investigated. The summer 1992 was the driest for many years, with almost no precipitation between May 12 and July 10.

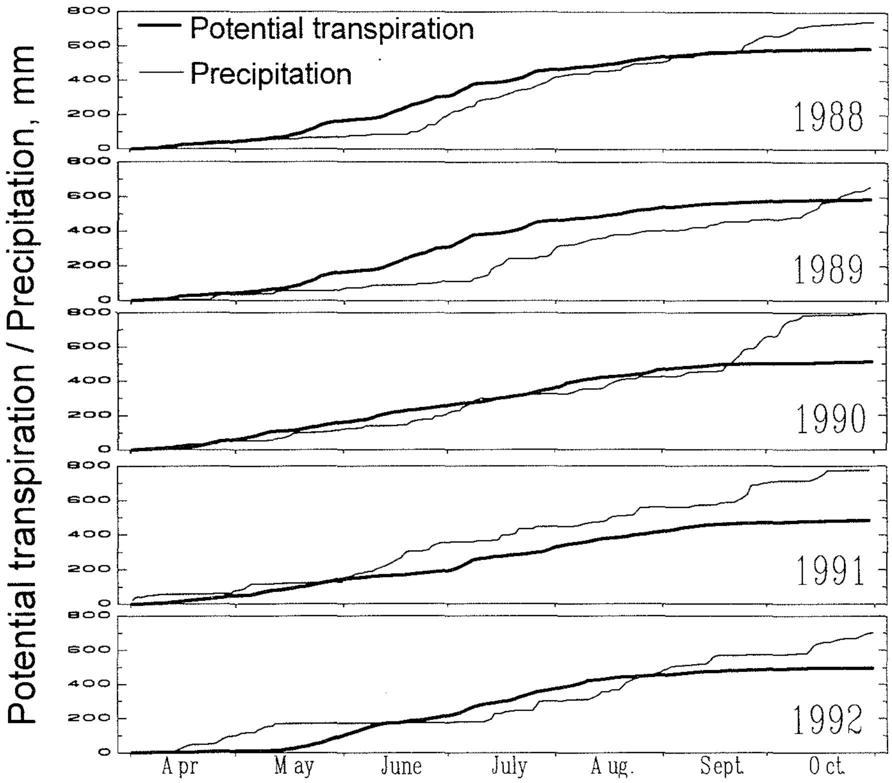

Fig. 2 Accumulated potential transpiration and precipitation for the period from April 1 to October 31.the potential transpiration in early summer 1991

Measured plots and periods

Table 3 shows measured plots. The measurement of ψ started in mid-June and lasted until October in the first growing season, 1988, while it started 20 days earlier during 1989, on May 25, and lasted until October. All measurements of ψ in 1988 occurred in blocks I and II, but two plots belonging to block IV, 3C and 8D2, were added in 1989. Soil water tension was measured in blocks I, II and IV during the growing seasons of 1990 and 1991. The measurement of ψ started in mid-May and finished in October during 1990, while it started on June 1 and finished in October during 1991. As in the first growing season, ψ was measured only in blocks I and II during 1992. It started in the last week of May and lasted until October.

Table 3. Measured plots during 1988 - 1992.

Year	plots
1988	15C, 16D2, 17V, 19N, 20N, 21V, 23D2, 24C
1989	3C, 8D2, 15C, 16D2, 17V, 19N, 20N, 21V, 23D2, 24C
1990	1V, 2ND, 3C, 5VD, 7N, 8D1, 16D1, 19N, 21V, 23D1, 24C
1991	1V, 2ND, 3C, 5VD, 7N, 8D1, 16D1, 19N, 21V, 23D1, 24C
1992	15C, 16D1, 17V, 19N, 20N, 21V, 23D1, 24C

Teory and method of calculation

It has long been recognized that the ability of plants to remove water from soils is related more to soil water tension than to water content (cf. Foth, 1984 and Hillel, 1982). Thus, soil moisture availability in each plot was represented by the average value of the soil water tension, ψ, at different depths. In order to identify differences in drying rate, measurements of ψ during dry periods were selected. Because the upper limit for measurement of ψ by tensiometers is about 800 cm water, all days on which ψ in all plots was about or higher than 800 cm water were excluded. Soil water tension consists of two parts at each point of time during a dry period, as shown below:

$$\psi(t) = \psi_{\text{field capacity}} + \frac{\Delta\psi}{\Delta t} \times \Delta t$$

Where $\psi(t)$ is measured soil water tension at any time during a dry period, $\psi_{\text{field capacity}}$ is soil water tension at field capacity, prevailing after a rainy period and soon after drainage water is lost, $\Delta\psi$ is increasing soil water tension during the dry period (until the time of measurement) and Δt is the drying up time period. $\frac{\Delta\psi}{\Delta t}$ shows the rate of soil desiccation. The most important factors affecting field capacity are: soil texture, type of clay present and organic matter content (Hillel, 1982), while factors affecting desiccation rate are not only these soil properties but also rate of inflow from ground water and subsoil and the rate of evapotranspiration. Consequently, $\psi(t)$ is the result of soil and vegitation properties.

Trees in each plot were represented by BA and annual Basal Area Growth, BAG. In fact, BA is the accumulated value of BAG ever since 1966, the year of planting. It was assumed that:

$$BAG = f(E_{pot}, \psi(t))$$
$$BA = \int BAG = f\int (E_{pot}, \psi(t))$$

Where E_{pot} is the potential transpiration which represents the water vapour demand from the atmosphere and the capacity of the vegetation to transfer water to the atmosphere when the soil moisture is not limiting transpiration.

If positive correlations are found between BA or BAG and ψ for different plots then the interpretation is that ψ had not limited stem growth. Instead a higher E_{pot} may has caused higher drying up rates at sites with higher BA. If negative correlations are found between BA or BAG and ψ then the interpretation is that lower ψ values leads to higher tree growth because high ψ values reduce water uptake and transpiration and consequently also the stem growth at sites with higher drying up rate. The alternative explanation that higher BA or BAG would have reduced the water uptake rate can be excluded. If positive correlations between BA and ψ but negative correlations between BAG and ψ are found then the interpretation is that soil moisture may has become to be a limiting factor in sites with denser stands.

Results

Basal area in relation to soil moisture

During 1988, the dry period in early summer was followed by a long wet period. Therefore, there were only 3 days that were rather suitable (Table 4), none of which showed significant ($p<0.05$) correlation between BA and ψ, even though simple linear regression of BA against ψ showed a declining BA with increasing ψ on June 16, 1988 at all measured depths (Fig. 3A).

Table 4. Suitable days for studying the relation between ψ and BA or BAG.
+a: Significant positive correlation ($p<0.05$) between BA and ψ at 15 or 30 cm depth.
-a: Significant negative correlation ($p<0.05$) between BA and ψ at 15 or 30 cm depth.
+b: Significant posotive correlation ($p<0.05$) between BAG and ψ at 15 or 30 cm depth.
-b: Significant negative correlation ($p<0.05$) between BAG and ψ at 15 or 30 cm depth.

Year	1988	1989	1990	1991	1992
Suitable days	880616	890525 -a -b	900523	910603 -a	920529 -a -b
	880818	890707 +b	900529 -a	910624 -a	920603 -a -b
	880923	890727 -a	900606 -a	910715 -a	920610 -a -b
		890901	900612	910729	920617 -a -b
		890921 -b	900705	910805	920722
		891005 -a	900801	910902 -a	920805 -b
			900815	910910 -a	920820 +a
			900829	910916 -a	920909
			900905	911007 -a	920923
			900911		920929
			900918		

During the 1989 growing season, there was a total of 6 days suitable for observations of the correlation between ψ and stem growth (Table 4). On 3 days, significant negative correlations could be found for plots belonging to blocks I and II (Table 5).

There was a total of 12 suitable days during 1990, but no significant correlation was observed between BA and ψ at 15 and 30 cm depths even though the regression lines had negative slopes. However, without 7N, which was an outlier, two cases of significant negative correlation were obtained at the 15 cm depth in the early summer (Table 5, Fig. 3C).

There were 8 cases of significant negative correlation at depths of 15 and 30 cm on 7 of 9 suitable days during 1991. There were no significant correlations on July 29, 1991 or August 5, 1991, possibly because of too few measured plots on these days.

Finally, four cases of negative correlations and one case of a positive significant correlation were obtained at 15 and 30 cm depths on 5 of 10 suitable days during the 1992 growing season. (Tables 4-5, Fig. 3E).

Annual basal area growth in relation to soil moisture

A similar tendency was observed in plotting BAG against ψ during the growing seasons in 1989 and 1992, the two driest summers, but almost no correlation could be observed at depths of 15 and 30 cm during 1988, 90 and 91 (Table 6, Fig. 4).

Discussion and conclusions

The majority of correlations between BA, BAG and ψ were negative. The results indicated that water availability had a positive effect on stem growth. Till and similar soils have the capacity to store a major part of autumn and winter precipitation on the uppermost

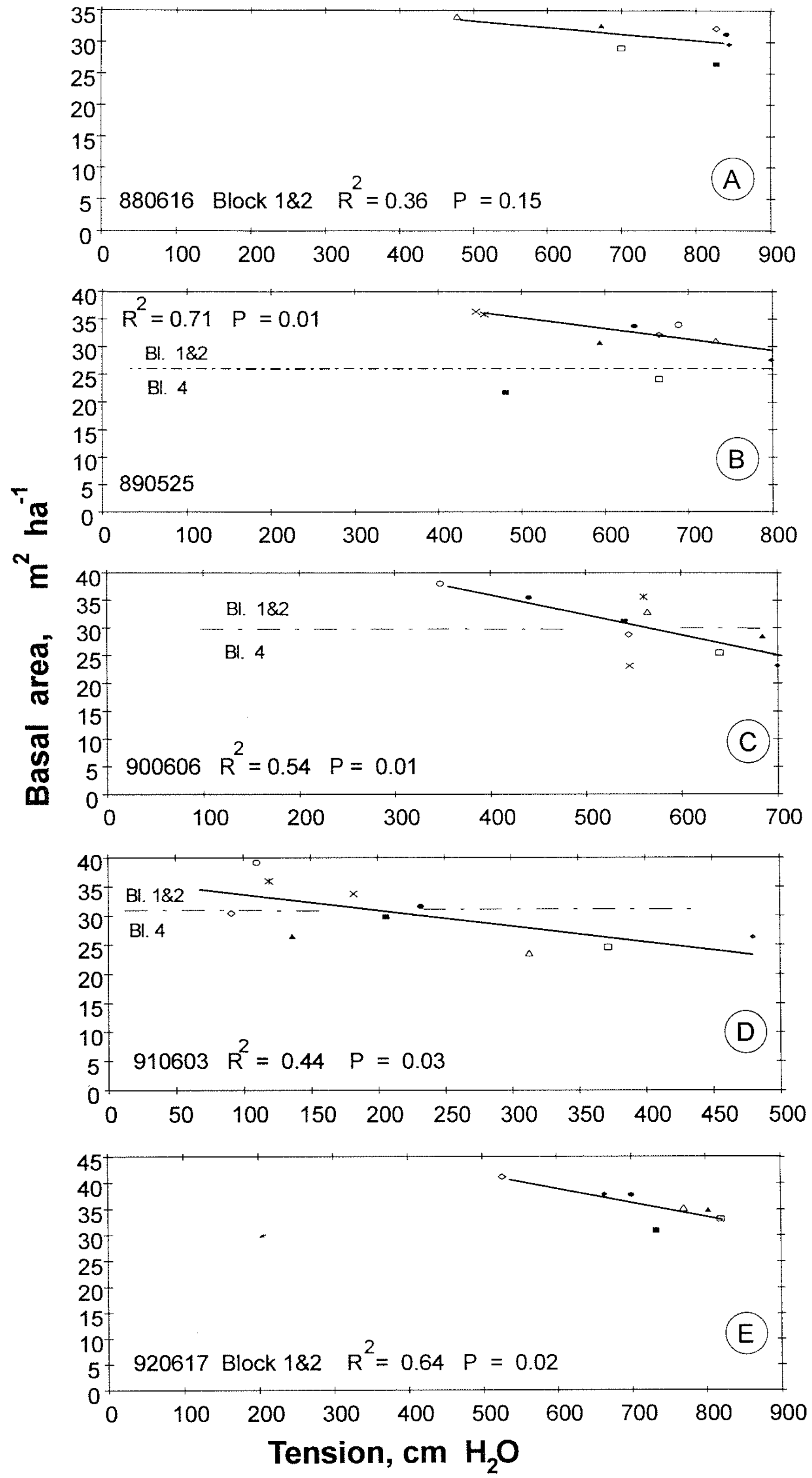

Fig. 3 Relationship between basal area and soil water tension at 15 cm depth in early summer, 1988-92.

Table 5. Significant correlations ($p<0.05$) between BA and ψ during growing seasons 88-92.

Date	Dep., cm	n	Description of plots	R^2	Intercept, $m^2\ ha^{-1}$	Slope, $m^2\ ha^{-1}\ (cm\ H_2O)^{-1}$
890525	15	8	15C,16D2,17V,19N,20N, 21V,23D2,24C	0.71	44.84	-0.02
890727	30	8	15C,16D2,17V,19N,20N, 21V,23D2,24C	0.51	42.28	-0.026
891005	15	8	15C,16D2,17V,19N,20N, 21V,23D2,24C	0.62	42.63	-0.02
900523	45	4	2ND,3C,5VD,8D1	1	32	-0.018
900529	15	10	1V,2ND,3C,5VD,8D1,16D1,19N,21V, 23D1,24C	0.51	50.4	-0.0356
900606	15	10	1V,2ND,3C,5VD,8D1,16D1,19N,21V, 23D1,24C	0.54	50.66	-0.0368
900905	45	7	2ND,3C,5VD,8D1,16D1, 19N,23D1	0.94	48.3	-0.03
900918	45	7	2ND,3C,5VD,8D1,16D1, 19N,23D1	0.89	51.74	-0.039
910603	15	10	1V,2ND,3C,5VD,7N,8D1, 16D1,19N,21V,23D1	0.44	36.1	-0.0265
	45	7	2ND,3C,5VD,8D1,16D1,19N,23D1	0.58	35.98	-0.02
910624	15	5	16D1,19N,21V,23D1,24C	0.8	43.76	-0.071
910715	15	10	1V,2ND,3C,5VD,8D1,16D1,19N,21V, 23D1,24C	0.48	43.9	-0.0276
	30	9	1V,3C,5VD,8D1,16D1,19N,21V,23D1, 24C	0.59	51.65	-0.0606
	45	8	2ND,3C,5VD,8D1,16D1, 19N,23D1,24C	0.66	43.5	-0.04
910902	15	11	1V,2ND,3C,5VD,7N,8D1, 16D1,19N,21V,23D1,24C	0.42	44.88	-0.04
	45	8	2ND,3C,5VD,8D1,16D1, 19N,23D1,24C	0.62	39.61	-0.02
910910	15	11	1V,2ND,3C,5VD,7N,8D1, 16D1,19N,21V,23D1,24C	0.42	46.88	-0.0245
	45	8	2ND,3C,5VD,8D1,16D1, 19N,23D1,24C	0.8	45.73	-0.03
910916	15	11	1V,2ND,3C,5VD,7N,8D1, 16D1,19N,21V,23D1,24C	0.52	48.43	-0.026
	45	8	2ND,3C,5VD,8D1,16D1, 19N,23D1,24C	0.64	45.3	-0.02
911007	15	6	1V,2ND,3C,5VD,7N,8D1	0.81	42.84	-0.12
920529	30	7	15C,16D1,17V,19N,20N, 21V,24C	0.9	45.06	-0.024
	60	4	15C,17V,19N,24C	0.97	43.03	-0.04
920603	30	7	15C,16D1,17V,19N,20N, 21V,24C	0.86	45.07	-0.02
	60	4	15C,17V,19N,24C	0.96	41.91	-0.02
920610	15	7	15C,16D1,17V,19N,20N, 21V,24C	0.59	47.4	-0.0171
920617	15	7	15C,16D1,17V,19N,20N, 21V,24C	0.64	55.19	-0.0271
	60	5	15C,16D1,17V,19N,24C	0.87	43.33	-0.0181
920820	30	8	15C,16D1,17V,19N,20N, 21V,23D1,24C	0.76	24.95	0.021

layers (Jonsson 1969). Despite that annual precipitation exceeded potential transpiration, dry periods occurred during the growing seasons, in particular during the early summers, when transpiration exceeded precipitation and created soil water deficits (Fig. 2). Many significant negative correlations were found in the early summers, probably because differences in the soil water storage at field capacity from the spring were governing the drying up rates. During 1991, when early summer was cold and rainy, the depletion of the soil moisture storage was delayed and negative correlations occured almost during the whole summer. It was difficult to determine significant correlation between ψ and stem growth during the middle of the summers (Fig. 5). This may be interpreted as that the common precipitation in summer was not high enough to create the same type of differences in soil water storages as in springs. Also, plots with higher water storage in spring may have had higher rates of transpiration and interception losses.

Table 6. Significant correlation ($p<0.05$) between BAG and ψ during growing seasons 88-92.

Date	Dep., cm	n	Description of plots	R^2	Intercept, $m^2\ ha^{-1}\ year^{-1}$	Slope, $m^2\ ha^{-1}\ year^{-1}\ (cm\ H_2O)^{-1}$
890525	15	7	3C,15C,17V,19N,20N,21V,24C	0.76	2.75	-0.002
	30	7	3C,15C,17V,19N,20N,21V,24C	0.75	2.25	-0.001
890707	15	9	3C,8D2,16D2,17V,19N,20N,21V,23D2,24C	0.63	0.06	0.002
890921	15	8	15C,16D2,17V,19N,20N,21V, 23D2,24C	0.51	2.205	-0.0027
900529	45	7	2ND,3C,5VD,8D1,16D1,19N, 23D1	0.61	2.16	-0.001
900606	45	7	2ND,3C,5VD,8D1,16D1,19N, 23D1	0.6	2.2	-0.001
900612	45	7	2ND,3C,5VD,8D1,16D1,19N, 23D1	0.71	2.31	-0.001
910729	45	4	2ND,3C,5VD,8D1	0.99	4.16	-0.01
920529	15	7	15C,16D1,17V,19N,20N,21V, 24C	0.67	2.23	-0.002
	30	7	15C,16D1,17V,19N,20N,21V, 24C	0.64	2.13	-0.002
920603	15	7	15C,16D1,17V,19N,20N,21V, 24C	0.68	2.31	-0.0015
	30	7	15C,16D1,17V,19N,20N,21V, 24C	0.87	2.24	-0.001
920610	30	7	15C,16D1,17V,19N,20N,21V, 24C	0.77	2.62	-0.0016
	60	5	15C,16D1,17V,19N,24C	0.8	1.94	-0.0013
920617	15	7	15C,16D1,17V,19N,20N,21V, 24C	0.6	2.99	-0.0021
	60	5	15C,16D1,17V,19N,24C	0.96	2.14	-0.0015
920805	30	8	15C,16D1,17V,19N,20N,21V, 23D1,24C	0.67	3.92	-0.004

Two linear equations were obtained using the medians for all the intercepts and slopes shown in Tables 5 and 6:

$$BA = 44.84 - 0.026\,\psi \qquad (a)$$

$$BAG = 2.24 - 0.0015\,\psi \qquad (b)$$

Where:

$BA = m^2\ ha^{-1}$

$BAG = m^2\ ha^{-1}\ year^{-1}$

$\psi = cm\ H_2O$

Assuming ψ = 100 cm H_2O at field capacity, equation (b) gives a yearly basal area growth equal to 2.09 $m^2\ ha^{-1}$. This is fairly close to the average for BAG in the irrigated plots during 1988-92 (Nilsson & Wiklund, 1994). Linear regression of BAG against ψ showed negative correlation for the two driest years, whereas linear regression of BA against ψ showed almost exclusively negative correlation for all years investigated. It is because BA is accumulated BAG and therefore less sensitive to the climate of each individual year. A good example of this sensitivity may be found during 1991, a year with a rainy early summer, when BA showed the most significant negative correlation with ψ during the five years investigated whereas BAG showed hardly any correlation. However, the overwhelming majority of negative correlation in regressing BA versus ψ indicates that soil moisture has determined stem growth for many years at Skogaby. It also indicates that stem growth is generally hampered on shallow soils in this part of Sweden.

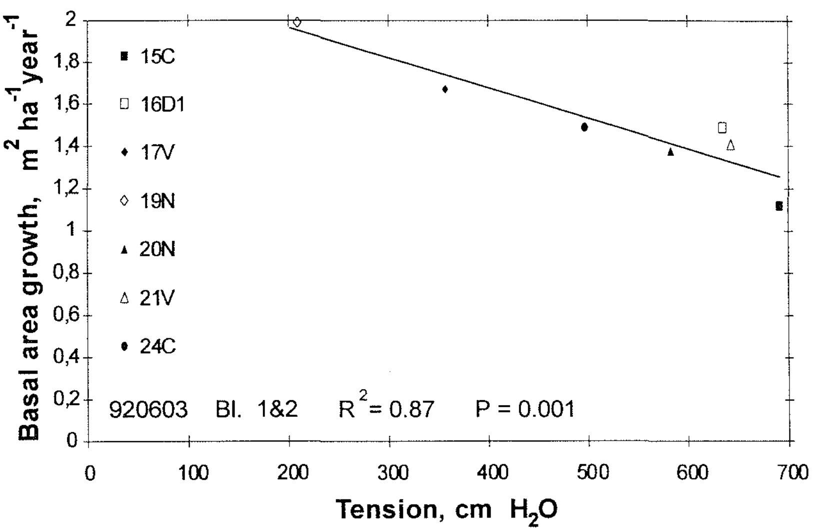

Fig. 4 Relationship between basal area growth in 1992 and soil water tension at 30 cm depth on a dry day in early summer, 1992.

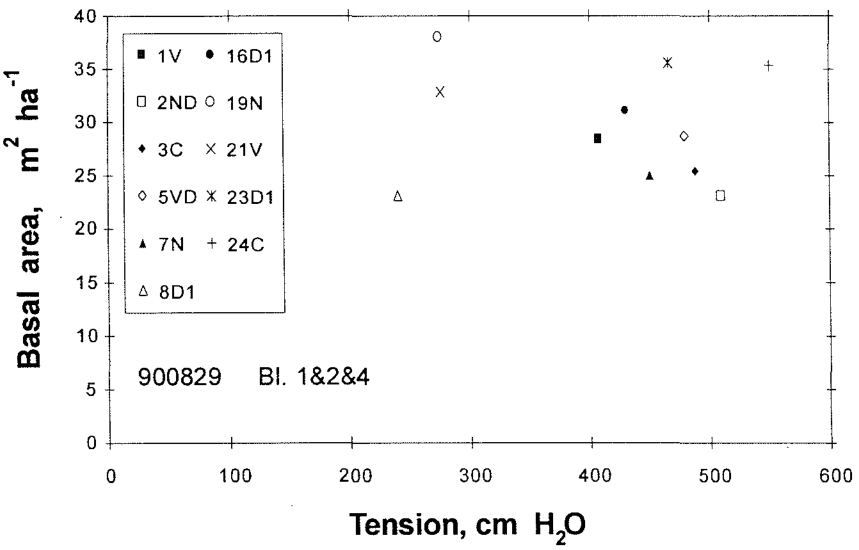

Fig. 5 Basal area plotted against soil water tension at 15 cm depth on a dry day in August,1990.

Lindroth & Halldin (1986) showed that the surface resistance of pine forest more or less become constant at a minimum level for a leaf area index between six to seven. The fact that the studied plots in this paper had leaf area indexes higher than six (Nilsson & Wiklund, pers.comm. 1995), suggests that the effect of stand density on evaporation rate has already become constant at the maximum level. To illustrate this problem, two control plots and two NS-treated plots with different soil moisture conditions were analysed (Fig. 6, top).

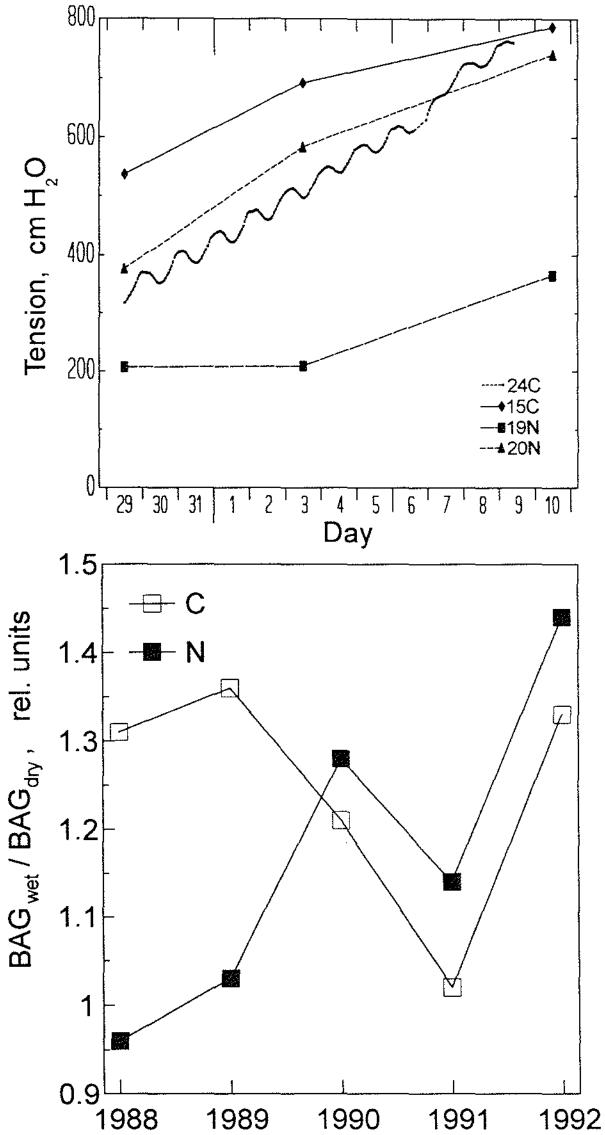

Fig. 6 Top: Soil water tension at 30 cm depth in four plots during a dry period, May 29, 1992 - 10 June 1992. Soil water tensions were measured weekly in 15C, 19N and 20N, whereas it was measured hourly in 24C. Bottom: Ratios between basal area growth in plots with low soil water tension, BAG_{wet} 24C & 19N, and plots with high soil water tension, BAG_{dry} 15C & 20N, for control and ammonium sulphate treatments respectively (Basal area growth from Nilsson and Wiklund, 1993).

The ratio of BAG in plots with wet soils to BAG in plots with drier soils within the same treatments showed substantial variations between years. It seems as though trees were unable to utilise available nutrients, and growth was suppressed in the absence of adequate water. However, the ratio did not show any trend for the control, whereas an increase by 50% for N fertilisation was found after five years of treatment (Fig. 6, bottom). In general, between-year variation was similar for the two treatments but an obvious change in the ratio occured after the second year for the N treatment. Perhaps another element than N become limiting for growth in 20N, possibly because of a lower mineralisation rate. In a recent study of soil chemistry by Bergholm & Alavi (1995) the nitrification rate was found to be much higher in 19N than in 20N. However, more investigations are required to explain this synergism.

One could speculate that because the most humid region in Sweden happens to also be the most air-polluted part of country, attempts to explain the observed forest decline have neglected to consider the role of water deficit. Landberg (1987) stated that "trees growing in well watered regions subjected to sudden drought are likely to suffer more severely than trees acclimated to drought". Many recent studies emphasize the need to consider the possible effect of global warmning on forest dieback (cf. Auclair et al., 1992). In fact, the use of annual precipitation as a measure of water availability is clearly misleading. To get a fairly accurate picture of water availability, both the spatial and temporal distribution of precipitation and evaporation and the topography and the capacity of the soil to store water on the uppermost layers must be taken into consideration.

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