EFFECTS OF SITE PREPARATION IN INTERIOR PLATEAU CLEARCUTS ON THE SOIL WATER REGIME AND THE WATER RELATIONS OF CONIFER SEEDLINGS

By

ROBERT LESUEUR FLEMING

B.A., Queen's University

M.Sc.F., University of Toronto

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ABSTRACT

Site preparation effects on growing season soil water regimes were investigated on three clearcut, grass-dominated sites in the Interior Douglas-fir (IDFdk), Montane Spruce (MSxk) and Engelmann spruce-Subalpine fir (ESSFxc) Biogeoclimatic Subzones, near Kamloops, British Columbia. The response of newly planted Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) and lodgepole pine (Pinus contorta Dougl.) to these treatments was determined at the IDFdk site.

Soil water regimes were measured in scalped, ripped and herbicide site preparation treatments and in an untreated control using a neutron moisture meter, a two-probe gamma-density gauge, tensiometers and thermocouple psychrometers. At the IDFdk, seedlings were spring planted in each of the treatments and control to determine whether microclimate modification by site preparation would improve seedling water relations, growth and survival during the first growing season.

Root zone soil water content was most limited at the low-elevation site (IDFdk) and least limited at the high-elevation site (ESSFxc). The different site preparation treatments provided similar increases in root zone soil water content, profile water storage and drainage at each site. This resulted in substantial increases in soil water supply at the lowest two sites.

Site preparation resulted in increased Douglas-fir and lodgepole pine stomatal conductance (g_s), transpiration (E), leaf area, root egress, root

collar basal area and dry matter production. Survival of both species was high in the control and in all site preparation treatments.

Both species had similar seasonal patterns of g_s and E in the control. In the site preparation treatments, lodgepole pine had greater g_s, and by late summer, greater E than Douglas-fir. Although lodgepole pine had substantially higher twig xylem pressure potentials and lower soil-plant liquid flow resistances than Douglas-fir, both species appeared well adapted to survive drought.

First growing season stomatal responses of both species to environmental conditions, including normalized vapor pressure deficit at seedling height (D_S/P), solar irradiance (R_s) and root zone extractable water (θ_e), were similar when normalized against annual maximum conductance (g_{smax}).

A multiplicative model with non-linear least squares optimization (NLLS) of response functions to R_s, D_s/P and θ_e provided a simple, reasonably accurate description of g_s/g_{smax} for both species, and accounted for differences in g_s between the control and ripped treatment. In most cases, the NLLS models developed for a given species and year resulted in relatively precise (R^2>0.60) and unbiased estimates of g_s/g_{smax}, and yielded estimates of mean daily stomatal conductance (G_s) and total daily transpiration (T) within 20% of measured values, for the same species in other years.

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LIST OF SYMBOLS

Symbol	Description	Units
Roman Symbols		
A	projected leaf area	cm^2
AWC_v	total available water capacity	$m^3\ m^{-3}$
AWC_{vf}	fine soil available water capacity	$m^3\ m^{-3}$
D	saturation deficit	$g\ cm^{-3}$
D_r	soil drainage	mm
D_s	seedling height vapor pressure deficit	Pa
D_0	leaf surface vapor pressure deficit	Pa
$D_{1.3}$	screen height (1.3 m) saturation deficit	$g\ cm^{-3}$
D_s/P	normalized seedling height vapor pressure deficit	$Pa\ kPa^{-1}$
D_0/P	normalized leaf surface vapor pressure deficit	$Pa\ kPa^{-1}$
$D_{0.5}/P$	value of D_s/P at which $g_s = 0.5\ g_{smax}$	$Pa\ kPa^{-1}$
E	seedling transpiration rate	$\mu mol\ s^{-1}$
E_A	seedling transpiration flux density	$\mu mol\ cm^{-2} s^{-1}$
E_{Ad}	daily seedling transpiration flux density	$mol\ cm^{-2} d^{-1}$
E_{Am}	midmorning seedling transpiration flux density	$\mu mol\ cm^{-2} s^{-1}$

E_m	midmorning seedling transpiration rate	$\mu mol\ s^{-1}$
E_{mr}	lodgepole pine E_m/ Douglas-fir E_m	dimensionless
ET	surface evapotranspiration	mm
g_b	boundary layer conductance (projected leaf area basis)	$mol\ m^{-2}s^{-1}$
g_s	stomatal conductance (projected leaf area basis)	$mol\ m^{-2}s^{-1}$
G_s	mean daily stomatal conductance (projected leaf area basis)	$mol\ m^{-2}s^{-1}$
g_{sm}	midmorning stomatal conductance (projected leaf area basis)	$mol\ m^{-2}s^{-1}$
g_{smax}	mean maximum seasonal stomatal conductance (projected leaf area basis)	$mol\ m^{-2}s^{-1}$
g_{smr}	lodgepole pine g_{sm}/ Douglas-fir g_{sm}	dimensionless
L_v	rooting density	$cm\ cm^{-3}$
Q_p	photosynthetic photon flux density	$mol\ m^{-2}s^{-1}$
P	atmospheric pressure	Pa
P	precipitation	mm
R	gas constant	$J\ mol^{-1}K^{-1}$
R_s	solar irradiance	$W\ m^{-2}$
R_{sp}	soil-plant liquid flow resistance	$MPa\ cm^2\ s\ \mu mol^{-1}$
RH	relative humidity	dimensionless
r_l	root egress (total length of new roots extending into the soil from the plug)	cm
S_p	profile soil water storage	mm

t	time since sunrise	h
T	absolute temperature	K
T_a	seedling height air temperature	°C
T_H	high temperature limit for stomatal response	°C
T_L	low temperature limit for stomatal response	°C
T_l	leaf temperature	°C
T_s	soil temperature	°C
T_{s15}	soil temperature at 15 cm	°C
Z	Ψ_m/Ψ_{min}	dimensionless
z	soil depth	cm

Greek Symbols

ε	error term in regression equation	
θ	soil volumetric water content	$m^3\ m^{-3}$
θ_e	extractable soil water $(\theta_{19}-\theta_{min})/(\theta_{max}-\theta_{min})$	$m^3\ m^{-3}$
θ_{max}	soil volumetric water content at field capacity (Ψ_{sr}=-0.03 MPa)	$m^3\ m^{-3}$
θ_{min}	soil volumetric water content below which soil water is no longer available for seedling uptake (Ψ_{m15}=-2.0 MPa)	$m^3\ m^{-3}$
θ_r	residual soil volumetric water content	$m^3\ m^{-3}$
θ_s	saturated soil volumetric water content	$m^3\ m^{-3}$

θ_{19}	soil volumetric water content measured with the neutron probe centered at the 19 cm depth	$m^3\ m^{-3}$
θ_{34}	soil volumetric water content measured with the neutron probe centered at the 34 cm depth	$m^3\ m^{-3}$
Ψ_h	soil hydraulic potential	MPa
Ψ_m	soil matric potential	MPa
Ψ_{m15}	soil matric potential at the 15 cm depth	MPa
Ψ_{m30}	soil matric potential at the 30 cm depth	MPa
Ψ_{min}	soil matric potential below which soil water is no longer available for seedling uptake (Ψ_{m15}=-2.0 MPa)	MPa
Ψ_{sr}	bulk root zone soil water potential	MPa
Ψ_{tx}	shoot xylem pressure potential	MPa
Ψ_{txb}	predawn (base) shoot xylem pressure potential	MPa
Ψ_{txm}	midmorning shoot xylem pressure potential	MPa

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INTRODUCTION

In British Columbia over 300 million tree seedlings are currently outplanted each year to regenerate forest lands (Mitchell et al. 1990). While most of the resulting plantations are successfully established, about 15% must be replanted and a larger number suffer from growth reductions, often resulting from seedling water stress (Burdett 1990; Mitchell et al. 1990). In the Southern Interior (Interior Plateau) of the province, which contains about one quarter of British Columbia's productive forest land base (Bickerstaff et al. 1981), limited root zone soil water supply and near-surface temperature extremes create microclimatic conditions which often exacerbate seedling water stress (McLean and Clark 1980; Meidinger and Pojar 1991).

This study formed part of a larger project that investigated site preparation procedures to minimize seedling water and temperature stress on grass-dominated backlog sites in the Southern Interior of British Columbia (Black et al. 1987; 1988; 1989; 1991). The project was funded by the Canada-B.C. Forest Resources Development Agreement (FRDA) (1985-1990), and consisted of four major components: 1) microclimate of backlog clearcut sites dominated by pinegrass (Calamagrostis rubescens Buckl.) in the Interior Douglas-fir (IDFdk), Montane Spruce (MSxk) and Engelmann Spruce-Subalpine Fir (ESSFxc) Biogeoclimatic Subzones (Mitchell et al. 1981); 2) effects of site preparation on the soil and aerial microclimate in these three Subzones; 3) effects of site preparation on the first growing

season water relations and growth of Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) and lodgepole pine (Pinus contorta Dougl.) at the IDFdk; and 4) effects of site preparation treatments on the long term survival and growth of planted Douglas-fir, lodgepole pine and Engelmann spruce (Picea Engelmannii Parry) in the three Subzones.

This thesis addresses aspects of the first three components. Other research carried out on aspects of one or more of the four components includes that reported by Bilesky (1987), Koch (1988), Adams (1990), Adams et al. (1991), Simpson (1990), Scott (1991) and Vaisanen (1992). Information on longer-term treatment effects on seedling growth and survival can be found in Black et al. (1991) and also will be the subject of future reports.

Three sites were chosen within 70 km of Kamloops, British Columbia (50°40′ N, 120°20′ W), one within each of the IDFdk, MSxk and ESSFxc Biogeoclimatic Subzones. This provided a gradient of decreasing growing season length and seasonal climatological water deficit with increasing elevation under similar macroclimatic conditions. At each site an automated weather station was installed in the spring of 1986 and maintained throughout the study to measure solar irradiance, precipitation, screen height air temperature, relative humidity, and windspeed and direction. Seedling height and root zone temperatures were also measured continuously in an untreated control and in the different site preparation treatments.

Site preparation treatments were carried out in the spring of 1986 and in the fall of 1986 and 1987 at each site, and included scalping (removal of the upper 5-10 cm of the soil), scalping followed by ripping (soil loosening to a depth of 50 cm), and broadcast herbicide application. At each site

these treatments were set out in plots adjacent to one another and an untreated control, and consisted of: 1) 8 x 8 m microclimate plots, 2) 20 x 5 m physiology plots, and 3) 10 x 5 m growth and survival plots.

Seedling root zone and profile soil water supply were monitored in the microclimate plots with a dual-probe gamma-density gauge, a neutron moisture meter, soil tensiometers and thermocouple psychrometers. Additional measurements of soil water supply, soil bulk density and coarse fragment content, and pinegrass rooting density were made in the physiology and the growth and survival plots.

At the IDFdk about 1,000 Douglas-fir and lodgepole pine containerized seedlings were planted in the control and site preparation treatments in May of 1987, 1988 and 1989. Seedlings in the physiology plots were destructively sampled over the growing season to examine water relations characteristics while seedlings in the growth and survival plots, which were laid out using a randomized complete block design, were assessed for survival, height increment and root collar diameter at the end of the first growing season.

The results of this study form the basis of the three chapters and three appendices comprising this thesis, which has been written in paper format. For the sake of brevity, a recently published paper which forms an integral part of this thesis is included as Appendix I, rather than as a separate chapter.

Chapter 1 describes root zone and profile growing season soil water supply on untreated clearcuts and in site preparation treatments at the IDfdk, Msxk and ESSFxc sites. Results are discussed in terms of growing

season climate, treatment effects on surface and soil properties, and the soil water balance.

Chapter 2 compares patterns of stomatal conductance, transpiration, xylem pressure potential and growth of Douglas-fir and lodgepole pine in the control and site preparation treatments at the IDFdk. Responses are related to time since planting, autecological characteristics and environmental conditions. Relationships among water relations measurements and between these measurements and the seasonal development of leaf area and root egress from the plug are explored.

Chapter 3 describes first growing season stomatal response of Douglas-fir and lodgepole pine to environmental variables at the IDFdk. Changes in response over time, between different years and in different treatments are discussed. Three phenomenological models to describe stomatal response are compared and evaluated using independent data sets for each species.

Appendix I reports on the use of a two-probe gamma-density gauge in stony forest soils to determine root zone water content, bulk density and coarse fragment content, and to calibrate a neutron meter. Field and laboratory calibration procedures for the gamma-density gauge are outlined and a correction factor for actual tube spacing is derived. Neutron meter field calibration procedures using the gamma-density gauge, which incorporate bulk density effects, are presented and problems relating to sampling volume are discussed.

Appendix II presents a method for determining soil water potential in the seedling root zone using thermocouple psychrometers.

Appendix III describes the construction and use of a small rainout shelter to study drought and site preparation effects on soil microclimate and seedling response.

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CHAPTER 1

EFFECTS OF SITE PREPARATION ON ROOT ZONE SOIL WATER REGIMES IN HIGH ELEVATION FOREST CLEARCUTS

EFFECTS OF SITE PREPARATION ON ROOT ZONE SOIL WATER REGIMES IN HIGH ELEVATION FOREST CLEARCUTS

I. INTRODUCTION

Soil water supply is one of the principal factors limiting the establishment, growth and development of forests (Waring and Franklin 1979; Kozlowski et al 1990). On drier sites in the Southern Interior (Interior Plateau) of British Columbia, reduced growth and survival of planted seedlings is commonly observed and is often attributed to soil water deficits (Vyse 1981; Mitchell et al. 1990).

Site preparation is now receiving increased attention as a means of improving root zone soil water supply. This may be accomplished through removal of competing species, by increasing soil water storage or by encouraging more extensive seedling root development (Flint and Childs 1987; Spittlehouse and Childs 1990). The effectiveness of these measures will depend on microclimatic conditions and soil characteristics as well as the size, density and physiological characteristics of the competing vegetation (Lambert et al. 1971; Örlander et al. 1990).

The objectives of this chapter are: (1) to compare growing season root zone soil water regimes at three clearcut sites situated along an elevational gradient in the Southern Interior of British Columbia; (2) to determine the capability of various site preparation treatments to ameliorate soil water regimes at each site; and (3) to assess the effects of

these treatments on total evaporative and drainage losses from the soil profile.

II. EXPERIMENTAL METHODS

A. Site Descriptions

The three experimental sites were located on grassy backlog clearcuts in different Biogeoclimatic Subzones on the Thompson Plateau near Kamloops, British Columbia (50°40′ N, 120°20′ W)(Mitchell et al. 1981). The research areas chosen were typical of mesic sites within each Subzone, and together represented a gradient of decreasing growing season length with increasing elevation under relatively dry conditions and similar growing season precipitation. Pinegrass (Calamagrostis rubescens Buckl.), in conjunction with various other herbs, represented the dominant vegetation at each site (Angove and Bancroft 1983). Gravel and cobbles of volcanic origin occupied 20-30% of the soil volume at each location.

The lowest site was a level, well-drained clearcut near Fehr Mountain at an elevation of 1220 m in the Interior Douglas-fir (IDFdk) Biogeoclimatic Subzone (Thompson Plateau-Very Dry Montane Interior Douglas-fir variant) (Mitchell et al. 1981). The soil, an Orthic Gray Luvisol with a 4-6 cm thick Xeromor humus layer, consisted of 20-30 cm of gravelly silt loam overlying a clay loam basal till. A very dense layer of compact basal till, with a fine soil (coarse fragment-free) bulk density of ≅ 1900 kg m^{-3}, began 75-80 cm below the surface. The previous lodgepole pine (Pinus contorta Dougl.) - Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) stand was clearcut in

1982, and pinegrass accounted for 80% of the vegetative cover in late June, 1986.

The mid-elevation site was a gently sloping, moderately well drained clearcut near Paska Lake, at an elevation of 1450 m in the Very Dry Southern Montane Spruce (MSxk) Biogeoclimatic Subzone (Mitchell et al. 1981). The soil was an Orthic Eutric Brunisol with an 8-14 cm thick Hemimoder humus layer and consisted of 60 cm of gravelly sandy clay loam overlying a compact clay loam basal till with a fine soil bulk density of ≅ 1700 kg m^{-3}. The previous lodgepole pine - Engelmann spruce (Picea engelmannii Parry) stand was clearcut in 1981. Pinegrass and blue wild rye grass (Elymus glaucus Buckl.) were the major herbaceous species and together comprised 60% of the vegetative cover in late June, 1986.

The highest site was a level, moderately well drained clearcut located near Tsintsunko Lake, at an elevation of 1670 m in the Very Dry Southern Engelmann Spruce-Subalpine Fir (ESSFxc) Biogeoclimatic Subzone (Mitchell et al. 1981). The soil was an Orthic Humo-Ferric Podzol with a 5-10 cm thick Hemimor humus layer, and consisted of 70 cm of gravelly sandy clay loam overlying a clay loam basal till. The previous subalpine fir (Abies lasiocarpa (Hook.) Nutt.) - lodgepole pine - Engelmann spruce stand was clearcut in 1981. Pinegrass and bluejoint small reed grass (Calamagrostis canadensis (Michx.) Nutt.) accounted for 30% of the vegetative cover in late June, 1986. Unlike the other two sites, bryophytes such as hair cap moss (Polytrichum juniperinum Hedw.) accounted for a substantial portion (28%) of the vegetative cover.

B. Experimental Layout

In the spring of 1986, scalping, scalping followed by ripping, and herbicide treatments were uniformly applied and assigned randomly to unreplicated 8 x 8 m microclimate plots at each site. Large, uniform treatments were chosen so that water flow would be predominantly one dimensional and edge effects would be minimized in the interior of each plot. All plots, including untreated controls of similar size, were located adjacent to one another.

Scalping involved removal of the top 5-10 cm of soil, including the organic horizons, with the straight blade of a Caterpillar D6 crawler tractor. Ripping was conducted by making several passes over scalped areas with flanged ripper teeth (Coates and Haeussler 1987). These teeth were mounted on a drawbar immediately behind the tracks of a crawler tractor and penetrated the soil to a depth of about 50 cm. Ripper tooth paths were spaced 0.3-0.5 m apart and the soil was subsequently mixed and leveled with shovels and rakes. Glyphosate (*N*-[phosphonomethyl]glycine) was applied at 30 ml active ingredient/100 m^2 in the herbicide plots, producing a thin organic mulch of dead vegetation and surface organic horizons (LFH) over the mineral soil. Spot applications of glyphosate were applied as required over the growing season in the scalped, ripped and herbicide plots to eliminate all herbaceous vegetation. This ensured the effects of different surface treatments on the seedling microclimate and seedling response could be studied without confounding by the ingress of vegetation.

C. Measurements.

1. Microclimate

An automated climate station consisting of a data logger (Campbell Scientific Inc., Logan, UT, Model 21X) and associated sensors was installed at each site. Mean hourly values of precipitation (Sierra-Misco, Inc., Berkeley, CA, Model RG2501 tipping bucket rain gauge), solar irradiance (LI-COR Inc., Lincoln, NB, Model LI200S silicon cell pyranometer), and wind speed (Met One Inc., Grants Pass, OR, Model 014A cup anemometer), air temperature and relative humidity (Campbell Scientific Inc., Logan, UT, Model 207 probe with a Fenwall Electronics, Framingham, MA, UUT-51J1 thermistor and Phys-Chem Scientific Corp., New York, PCRC-11 sulphonated polystyrene relative humidity sensor) at a height of 1.3 m were collected throughout the 1986-1989 growing seasons.

2. Root Zone Soil Water Content

This study focused primarily on soil water regimes in the seedling root zone, the upper 40 cm of the soil profile. However, site and treatment effects on profile soil water storage to a depth of 87 cm (S_p) were also considered. Douglas-fir, lodgepole pine and Engelmann spruce have been found to root to this depth within 6-8 years of outplanting (Eis 1978; Burdett et al. 1984).

Volumetric soil water content (θ) was determined with a Campbell Pacific Nuclear Corp., Martinez, CA, Model 503 Hydroprobe (Am 241-Be source and He 3 detector) neutron meter. Aluminum neutron meter access tubes (5.1 cm outside

diameter) were installed vertically from the surface to depths of 40 and 90 cm. The deeper tubes were set out by digging triangular soil pits, placing the tube in the resulting V-shaped notch, and then backfilling the soil to approximate the original bulk density (Price and Black 1991). The shallower tubes were inserted in holes excavated with a power auger and undersized bit, and enlarged with a hand auger. At least three deep tubes and three shallow tubes were used to measure water content in each treatment.

Thirty-second neutron meter readings were taken weekly or once every two weeks throughout the growing season in 15-cm vertical increments within each tube, beginning 19 cm below the surface. This provided integrated measurements of θ over a 10-15 cm radius at each depth while ensuring that the shallowest readings were not markedly influenced by proximity to the soil surface (Greacen et al. 1981; Hauser 1984).

Separate neutron meter field calibrations were developed for readings at 19 cm (θ_{19}) in each of the IDFdk control and ripped plots and for readings at 34+ cm in all plots, using a dual-probe gamma-density gauge (Troxler Electronic Laboratories Inc., Triangle Park, NC, Model 2376 Two Probe Density Gauge with 5 mCi Cs 137 source and NaI scintillation detector). Both the IDFdk control calibration, which was applied in the control, herbicide and scalped plots, and the IDFdk ripped calibration were used at all three sites because the soils were of similar geologic origin and composition. Further details on the calibration and use of the neutron meter and the gamma-density gauge to measure soil water contents in these stony forest soils is given in Appendix I.

3. Soil Matric Potential

Soil matric potentials (Ψ_m) were determined in the field with tensiometers and thermocouple psychrometers (assuming negligible soil osmotic potentials) at depths of 15, 30 and occasionally 45 and 75 cm. These instruments were installed in clusters around individual neutron tubes and read concurrently with the neutron meter to facilitate construction of field soil water retention curves (Greminger et al. 1985) and to provide information on vertical hydraulic gradients. At the IDFdk, a rainout shelter (Appendix III) was used to provide a wider (drier) range of θ and Ψ_m values for fitting retention curves.

Tensiometers were constructed following the design of Marthaler et al. (1983) and read with a pressure transducer (Soil Measurement Systems, Tucson, AZ, Model SW-010 Tensimeter). Screen cage thermocouple psychrometers (J.R.D. Merrill Speciality Equipment, Logan, UT, 74 series) were individually calibrated with NaCl solutions using calibration chambers (J.R.D. Merrill Speciality Equipment, Model 81-500) and a temperature-controlled water bath (Brown and Collins 1980). They were installed following procedures outlined by Brown and Chambers (1987) and read with a microvoltmeter (Wescor Inc., Logan, UT, Model HR-33T) or a data logger (Campbell Scientific Inc., Logan, UT, Model CR7X) equipped with Campbell Scientific Inc. Model A3497 cooling current interfaces and software. Readings were taken between 7:00 and 11:00 PST, when vertical soil temperature gradients were smallest (Brown and Chambers 1987) (Appendix II). The calibration model of Brown and Bartos (1982) was used to determine Ψ_m from thermocouple psychrometer soil temperature, zero-offset and microvolt output readings.

Laboratory soil water retention data (desorption) between Ψ_m values of -0.005 and -1.5 MPa were obtained for various soil depths and treatments at the three sites using intact soil cores and a pressure chamber apparatus (Soilmoisture Equipment Corp,, Santa Barbara, CA) (Klute 1986). In a given treatment, four to ten replicate soil cores were collected at 10-cm depth intervals to a depth of 60 cm using brass rings, 5.1 cm in diameter and 3 cm deep. The cores were placed directly on pressure plates and allowed to equilibrate with the applied air pressure until no further drainage from the plate was obtained over a period of 4-7 days. Soil water contents for these cores were calculated on a fine soil (coarse fragment-free) volumetric basis and then converted to a total soil volumetric basis using mean volumetric coarse fragment contents determined by field excavation.

4. Pinegrass Rooting Density

Replicate soil cores 6.6 cm deep and 10.2 cm in diameter were taken at 7.5-cm intervals from the soil surface to a depth of 60 cm in the IDFdk control plot to determine pinegrass rooting density (root length per unit volume of soil). Root lengths for each core were measured to the nearest 2 mm after being separated from other material by gentle wet sieving. Root density as a function of soil depth was adequately described by the empirical formula of Gerwitz and Page (1974).

$$L_v(z) = L_v(0)\exp(-kz) \qquad (1)$$

where L_v is the rooting density (cm of root per cm^3 of soil), z is depth (cm) from the mineral soil surface, and k is the rate of decline in rooting

density with depth. Optimum values and standard errors for $L_v(0)$ and k, derived by nonlinear regression using a quasi-Newton minimization method (Wilkinson 1989), were 15.724 (± 1.200) cm of root per cm^3 of soil and 0.0373 (±0.0053) cm^{-1}, respectively. These values indicate that over 80% of the pinegrass rooting density occurred in the top 50 cm of the soil profile.

D. Calculations and Data Analysis

1. Error Analysis of Neutron Meter Measurements

The accuracy of neutron meter soil water content estimates was investigated using the 1987 IDFdk 19-cm data. Variance components were calculated following Sinclair and Williams (1979) and Vauclin et al. (1984) for 16 different sampling periods, for each of the control, scalped, herbicide and ripped plots. For each sampling period, measurements were obtained from six different tubes within a given plot. These were used to calculate three components of the error term: the location error, which is a function of site heterogeneity and probe positioning; the calibration error, which arises from the calibration equation; and the instrument error, which reflects the influence of random counts over a specified time period (Sinclair and Williams 1979).

The magnitude of the total error in θ estimates for a particular plot, and each of the three error components, remained fairly stable from one measurement period to the next; as a result, only mean growing season values per plot are discussed here. The mean total standard error and mean coefficient of variation for the growing season were greatest for the ripped plot and quite similar for the herbicide, scalped and control plots

(Table 1.1). The calibration error accounted for the major portion of the total standard error in the control (58%), herbicide (69%), scalped (60%) and ripped (86%) plots. The larger total standard error for the ripped plot, and the high calibration component of this error reflects the poorer precision of the calibration equation developed for this treatment (Appendix I). Virtually all the remaining error for each plot was attributed to the location component.

2. Soil Water Retention Curves and Available Water Capacity

Soil water retention curves were described by (Van Genuchten 1980):

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{(1 + (\alpha\Psi_m)^n)^m} \qquad (2)$$

where θ is the actual water content, θ_r is the residual water content, θ_s is the saturated water content, Ψ_m is the soil matric potential expressed as pressure head (cm), α and n are empirically derived parameters, and $m = 1-1/n$ (Van Genuchten and Nielsen 1985). In this study, θ_r was set to zero (Greminger et al. 1985) while θ_s was considered an empirical variable following Van Genuchten and Nielsen (1985). Best-fit values of θ_s, α and n were estimated for various site - treatment - depth combinations by non-linear regression using a quasi-Newton minimization algorithm (Wilkinson 1989).

Field soil water retention curves derived with Eq. [2] were used to calculate seedling root zone total available water capacities (AWC_v) based on the difference in calculated total volumetric water content at matric potentials of -0.033 and -1.5 MPa (Ratliff et al. 1983; Cassel and Nielsen

Table 1.1. Error analysis of IDFdk 1987 soil water content values estimated from neutron meter measurements taken at 19 cm. Presented are arithmetic mean values, standard errors and coefficients of variation for the growing season, based on calculation of the location, calibration and instrument error components for 16 different measurement periods between April 24 and September 14.

	Growing Season Values		
Treatment	Mean Volumetric Water Content (m^3m^{-3})	Mean Total Standard Error (m^3m^{-3})	Mean Coefficient of Variation (%)
Ripped	0.168	0.0155	22.63
Herbicide	0.208	0.0090	10.66
Control	0.173	0.0093	14.10
Scalped	0.179	0.0093	12.93

1986). Fine soil (coarse fragment-free) available water capacities (AWC_{vf}) were calculated from laboratory retention samples using the same matric potential limits as above. Values for replicate samples were used in conjunction with independent two-tailed t-tests (Zar 1984) to establish differences among treatments.

3. Growing Season Site Water Balances

Site water balances were calculated at one to two week intervals throughout the growing season for each site and treatment to determine evapotranspiration (ET) together with drainage (D_r), $ET + D_r$, from measurements of precipitation (P) and the change in profile soil water storage (ΔS_p):

$$ET + D_r = P - \Delta S_p \tag{3}$$

ΔS_p was determined by integrating changes in soil water content over the 87 cm profile depth, P was measured directly, and surface runoff and lateral flow were assumed to be negligible. Gravimetric determinations of θ for the 0-10 cm depth were not included in calculations of S_p because of the uncertainty of the former (large differences between replicate values and overlap with θ_{19} measurements) and the very limited effect they had on S_p. Losses due to D_r or ET alone were not measured, but an indication of D_r during rain-free periods was obtained by examining the position of the zero flux plane. The zero flux plane is the profile depth that marks the boundary between upward (ET) and downward (D_r) water movement (i.e., $d\Psi_h/dz = 0$ where Ψ_h represents the soil hydraulic potential (Arya et al. 1975a)).

Examination of soil water content and soil hydraulic potential profiles constructed from tensiometer, dual-probe gamma-density gauge and neutron meter measurements, and soil water retention curves indicated that the zero flux plane rarely occurred below a depth of 25 - 30 cm in the treated plots at any site. Consequently, changes in soil water storage below 27 cm in the treated plots were attributed to drainage (cf. Van Bavel et al. 1968; Davidson et al. 1969).

The above calculations likely underestimate actual drainage because: 1) rapid initial profile drainage losses following heavy rainfalls were often not accounted for because of the measurement interval; 2) the 0-27 cm depth undoubtedly contributed to drainage losses during wetter periods; and 3) calculated drainage ($\theta_{i-1} - \theta_i$, where i is the measurement period) was negative under conditions of soil water recharge (e.g., when sizable rainfall events followed periods of drought), whereas actual drainage was likely enhanced. When calculated drainage rates were negative, they were set to zero.

In the control plots, particularly those at the IDFdk and MSxk, the vegetation extracted water throughout much of the profile (cf. Eq. [1]). Consequently, drainage losses were not calculated for these plots.

III. RESULTS AND DISCUSSION

A. Growing Season Climate at the Three Sites

Growing season precipitation (May 1 to September 30) varied from 165 to 310 mm at the IDFdk and from 125 to 255 mm at the MSxk between 1986 and 1989. While restricted access limited the measurement period at the ESSFxc,

total precipitation from June 1 to August 31 was often similar at the three sites (Table 1.2). Rainfall was usually well distributed throughout the growing season, but rain-free periods of 2-3 weeks occurred at each site in each study year.

Total solar irradiance from June 1 to August 31 differed by less than 100 MJ m^{-2} among the three sites in any given year, and was inversely related to growing season precipitation. Daily mean screen height air temperatures over this period were often 1 - 2 °C higher at the IDFdk than at the MSxk and ESSFxc (Table 1.2). Despite similar mean air temperatures at the MSxk and ESSFxc over this period, the growing season (snow-free period) was considerably longer at the MSxk.

B. Seedling Root Zone Soil Water Regimes

Data from 1987, the driest study year, provided the greatest contrasts in θ between treatments and sites, and therefore was used to illustrate growing season trends.

1. Comparison of the Control Plots at the Three Sites

At the start of each growing season, soil profile θ values at each site were at least as high in the controls as in the site prepared plots. There was no evidence that soil water deficits which developed during a particular growing season carried over into subsequent growing seasons.

In 1987 θ_{19} in the control at the IDFdk fell below 0.10 m^3m^{-3} during periods of drought in mid-to-late June and in mid-to-late July (Fig. 1.1). Throughout August and early September θ_{19} remained higher than earlier in

Table 1.2. Cumulative precipitation and mean air temperature from June 1 to August 31 for the four study years at each site.

Precipitation (mm), June 1 - August 31

Site	Year 1986	1987	1988	1989
IDFdk	154	142	153	190
MSxk	171	110	121	160
ESSFxc	178†	127	198	150

Daily Mean Air Temperature at 1.3 m (°C), June 1 - August 31

	1986	1987	1988	1989
IDFdk	12.8	13.1	12.4	12.4
MSxk	11.4	11.7	11.0	11.2
ESSFxc	10.8	13.0	12.2	10.3

†Values for June 1-9 and August 27-31 estimated from MSxk data.

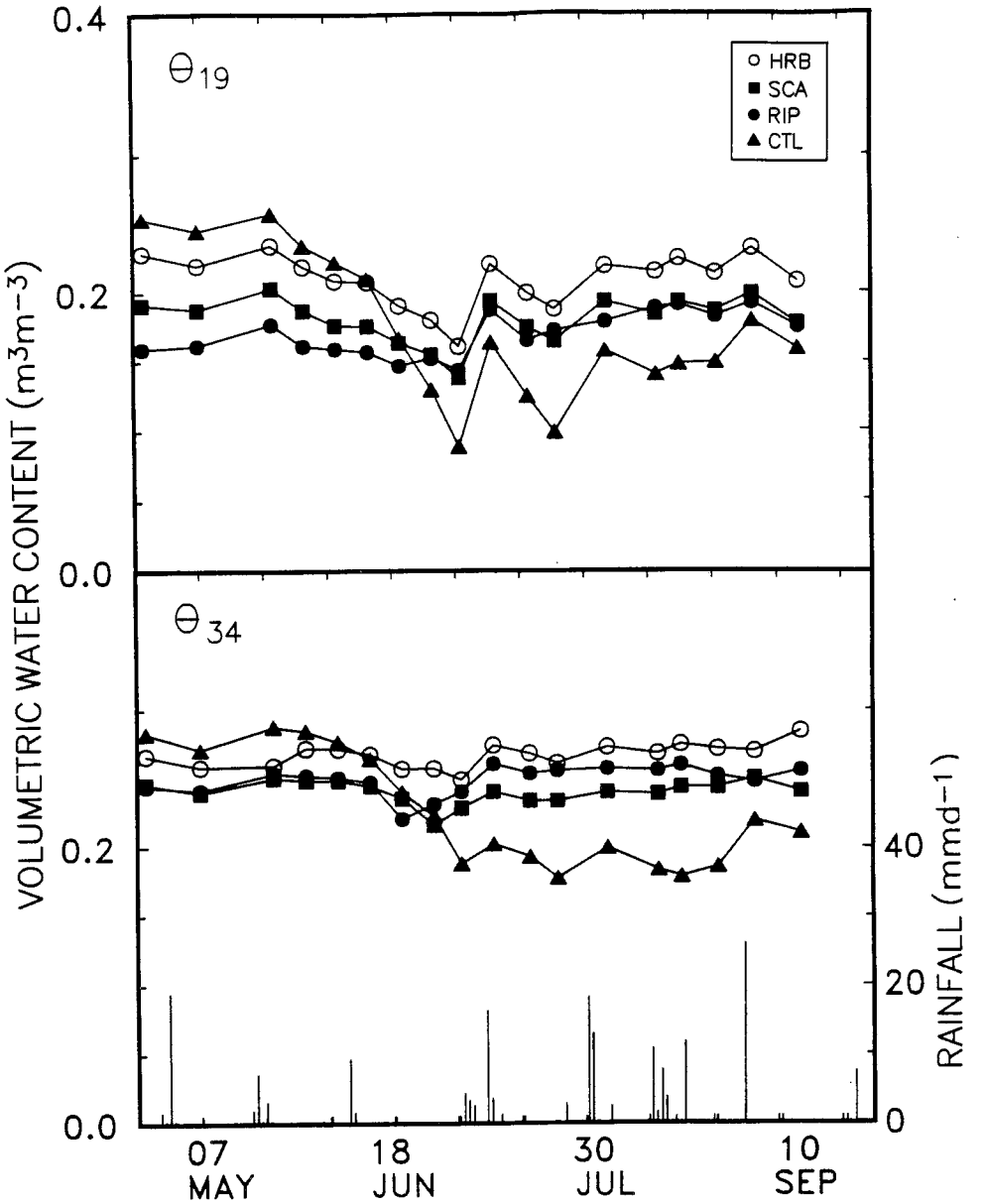

Fig. 1.1. IDFdk growing season courses of volumetric water content at 19 and 34 cm and daily rainfall during 1987. Values shown are for the control (Ctl), herbicide (Hrb), scalped (Sca) and ripped (Rip) treatments.

the summer. In contrast, θ_{34} rapidly decreased during June but then remained relatively stable at 0.18 - 0.20 m^3m^{-3} throughout the summer.

At the MSxk during 1987 θ_{19} in the control steadily declined from mid May to the beginning of August, reaching a minimum value of about 0.12 m^3m^{-3} (Fig. 1.2). Unlike the IDFdk, there were few large rainfall events at the MSxk during June or July of 1987 to recharge soil water reserves. The rate of decline of θ_{34} was not as great and values remained 0.04 - 0.06 m^3m^{-3} higher than those at 19 cm.

At the ESSFxc there was less of a decrease in θ_{19} and θ_{34} in the control during each growing season than at the other two sites. In 1987, θ_{19} and θ_{34} did not fall below 0.22 and 0.27 m^3m^{-3}, respectively (Fig. 1.3).

Although θ_{19} and θ_{34} values in the control were usually lowest at the IDFdk, the greatest declines in these values in late summer were usually found at the MSxk. This likely reflects differences in vegetation as well as in rainfall distribution and evaporative demand at the two sites. Pinegrass, the predominant vegetation at the IDFdk, begins to senesce by midsummer (Adams et al. 1991), and therefore has limited potential for water extraction later in the growing season.

2. Treatment Effects at the Three Sites

The ripping, scalping and herbicide treatments each conserved substantial amounts of soil water at the IDFdk and MSxk in comparison with the controls (Figs. 1.1-1.2). During the four growing seasons studied, θ_{19} never fell below 0.14 m^3m^{-3} in any of these treatments (Table 1.3). At the ESSFxc, θ_{19} values in all plots were higher and showed less seasonal change than at the other sites (Fig. 1.3). Values of θ_{34} in the treated plots varied less than

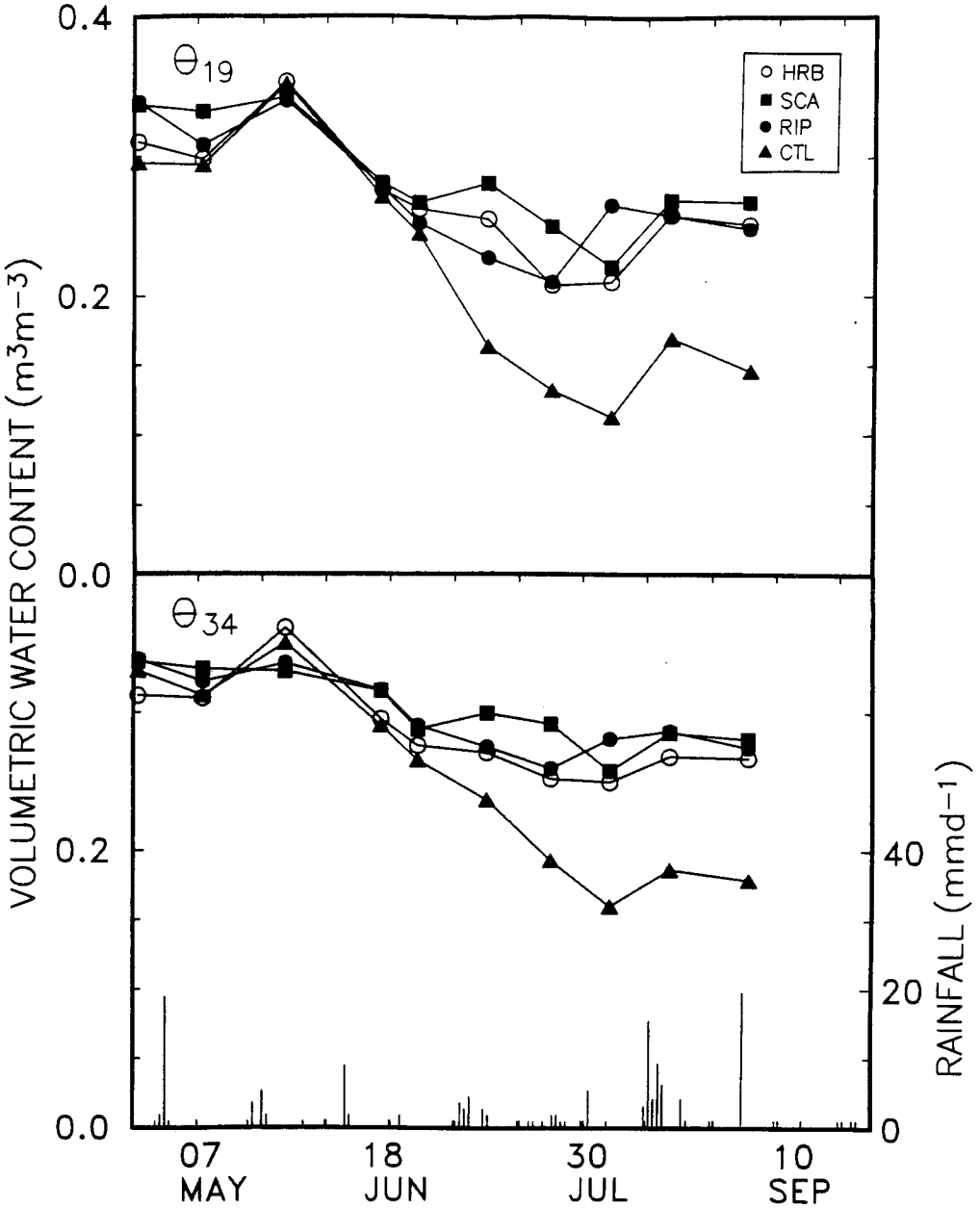

Fig. 1.2. MSxk growing season courses of volumetric water content at 19 and 34 cm and daily rainfall during 1987. Values shown are for the control (Ctl), herbicide (Hrb), scalped (Sca) and ripped (Rip) treatments.

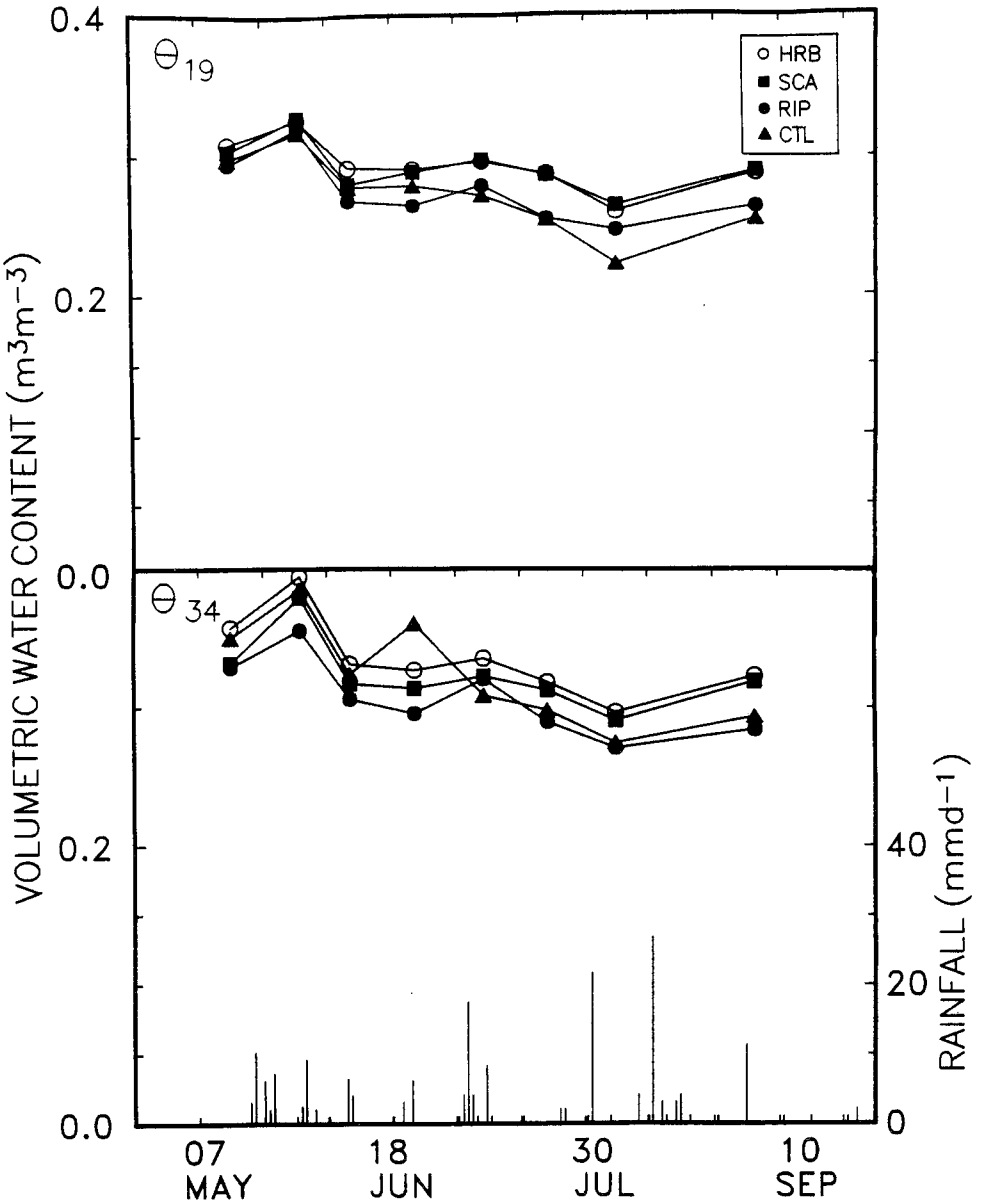

Fig. 1.3. ESSFxc growing season courses of volumetric water content at 19 and 34 cm and daily rainfall during 1987. Values shown are for the control (Ctl), herbicide (Hrb), scalped (Sca) and ripped (Rip) treatments.

Table 1.3. Minimum seasonal values of volumetric soil water content at 19 and 34 cm in the ripped and control plots established in 1986, by site and year.

Depth (cm)	Site	Treatment	Minimum Volumetric Soil Water Content (m^3m^{-3}) Year 1986	1987	1988	1989
19	IDFdk	Control	0.152	0.088	0.102	0.151
		Ripped	0.136	0.143	0.140	0.154
		Herbicide	0.202	0.160	*	*
		Scalped	0.167	0.140	0.181	*
	MSxk	Control	0.151	0.112	0.126	0.199
		Ripped	0.246	0.211	0.259	0.263
		Herbicide	0.238	0.208	*	*
		Scalped	0.238	0.222	0.222	*
	ESSFxc	Control	0.245	0.223	0.251	0.261
		Ripped	0.248	0.247	0.252	0.276
		Herbicide	0.270	0.260	*	*
		Scalped	0.261	0.264	0.271	*
34	IDFdk	Control	0.222	0.178	0.160	0.196
		Ripped	0.235	0.220	0.213	0.224
		Herbicide	0.268	0.249	*	*
		Scalped	0.241	0.216	0.232	*
	MSxk	Control	0.213	0.160	0.179	0.233
		Ripped	0.264	0.260	0.242	0.280
		Herbicide	0.259	0.250	*	*
		Scalped	0.275	0.258	0.246	*
	ESSFxc	Control	0.286	0.275	0.290	0.307
		Ripped	0.271	0.271	0.288	0.302
		Herbicide	0.298	0.296	*	*
		Scalped	0.283	0.291	0.309	*

* Treatment not investigated.

and exceeded those of θ_{19} throughout the summer at each site. Even at the IDFdk, the driest site, θ_{34} in the treated plots rarely fell below 0.25 m^3m^{-3} and varied seasonally by less than 0.04 m^3m^{-3}.

At the IDFdk, the herbicide treatment resulted in somewhat greater summer values of θ_{19} than did scalping or ripping, but θ_{19} values among the three treatments were usually similar at the MSxk and ESSFxc. However, at the ESSFxc θ_{19} and θ_{34} in the ripped plots were up to 0.05 m^3m^{-3} lower than in the herbicide or scalped plots after periods of heavy rain.

The low spring θ_{19} values in the IDFdk ripped plots in the spring of 1987 are attributed to manual cultivation. Cultivation just prior to planting likely increased evaporative losses by increasing surface roughness and exposing moist soil from deeper in the profile (Unger 1984; Saxton et al. 1988). As the soil settled and soil water reserves were recharged, differences in θ_{19} between the ripped, scalped and herbicide plots diminished. These trends were not as apparent at the MSxk and ESSFxc where manual cultivation was less intensive.

3. Available Water Capacity

The effects of ripping on available water capacity were studied at the IDFdk. At this site control and ripped AWC_v values for θ_{19} were very similar (0.1332 and 0.1314 m^3m^{-3}, respectively). Mean AWC_{vf} values for the 0- 10 and 11 - 20 cm were significantly greater ($p \leq 0.10$) in the control (0.2383 and 0.2029 m^3m^{-3}, respectively) than in the scalped (0.2061 and 0.1783 m^3m^{-3}, respectively) or ripped plots (0.1989 and 0.1667 m^3m^{-3}, respectively). This reflects the removal of the upper 5 cm of mineral soil, with its high

colloidal content, from the scalped and ripped plots during site preparation. At greater depths (≥20 cm) AWC_{vf} values were not significantly different ($p>0.10$) among the control, ripped and scalped plots. These results, together with those pertaining to S_p (discussed later), suggest that ripping has relatively little effect on soil water supply. Similar results were reported by Unger (1970) following mixing of the top 90 cm of a compact silty clay loam agricultural soil. While treatments like ripping may increase soil porosity, they often have little effect on available water capacity.

C. Seedling Root Zone Matric Potentials

1. Soil Water Retention Relationships

There was usually good agreement between field and laboratory soil water retention curves, particularly when a broad range of $\theta - \Psi_m$ field values as well as laboratory values were obtained (Figs. 1.4 and 1.5) (Table 1.4). In contrast to Jones et al. (1990), there was little disparity in field versus laboratory θ-Ψ_m values at low Ψ_m. However, at Ψ_m values above -0.050 MPa, soil water contents were often lower for the field than the laboratory data. This may reflect disparities in the amount of entrapped air, hysteresis effects or differences in macropore characteristics between laboratory and field samples. Hysteresis tends to be greatest at high matric potentials (Klute 1973) and drying curves (i.e., laboratory retention data) would have greater soil water contents at given matric potentials than scanning curves (i.e., most field retention data).

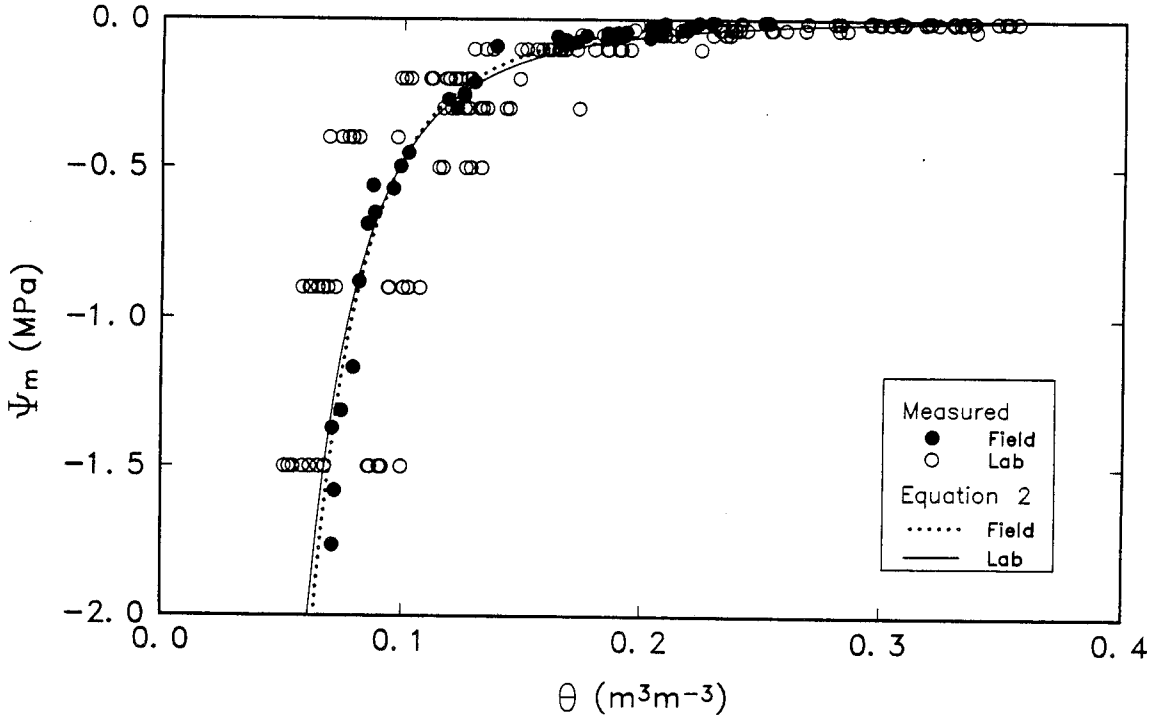

Fig. 1.4. Field and laboratory (pressure plate) soil water retention measurements (matric potential, Ψ_m, versus volumetric water content, θ) for the 15 cm depth in the IDFdk control plots. Also shown are curves fitted using Eq. [2] to the field and laboratory data. Parameter values for the fitted curves are given in Table 4.

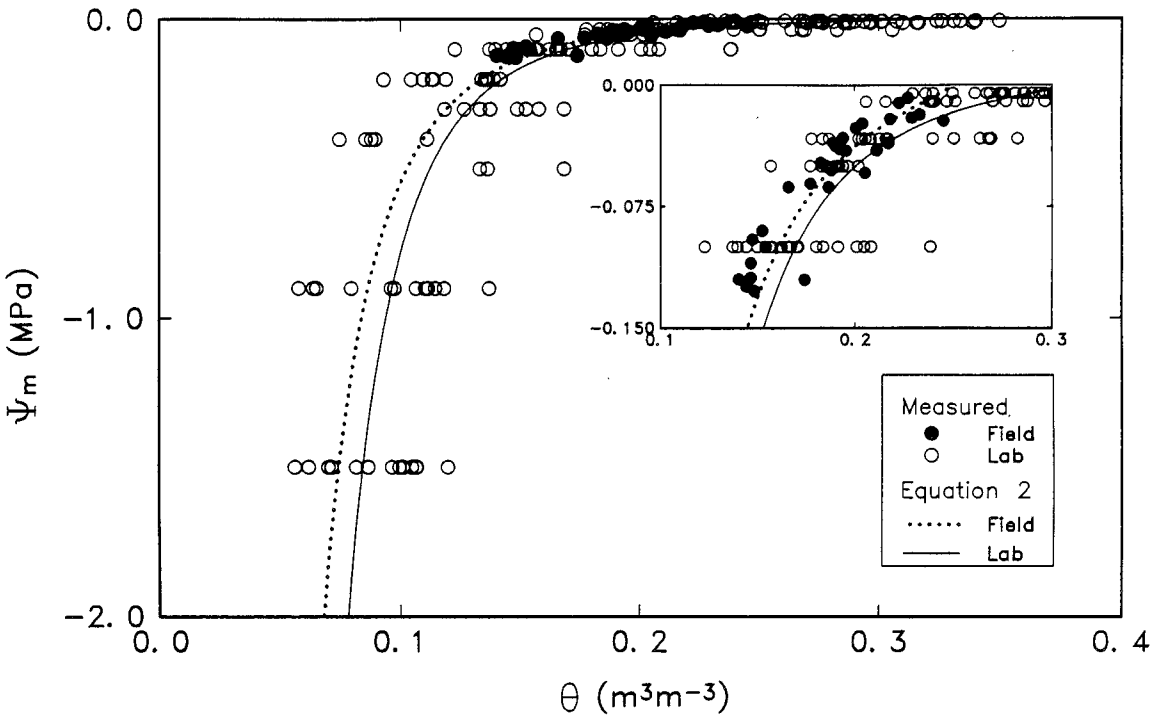

Fig. 1.5. Field and laboratory (pressure plate) soil water retention measurements (matric potential, Ψ_m, versus volumetric water content, θ) for the 15 cm depth in the IDFdk ripped plots. Also shown are curves fitted using Eq. [2] to the field and laboratory data. Parameter values for the fitted curves are given in Table 4. Inset is an expanded view of data in the 0 to -0.15 MPa range.

Table 1.4. Parameter values and associated statistics for field (F) and laboratory retention data (L) fitted to Eq. [2]. Parameter values (Value), asymptotic standard errors (ASE) and residual sum of squares from non-linear regression are presented for two depths in both the control and ripped plots at the IDFdk. For this data θ_r was set to zero and m was set to 1-1/n.

Treatment	Depth	θ_s		α		n		Residual Sum of Squares
	(cm)	Value	ASE	Value	ASE	Value	ASE	
Control (L)	19	.363	.0090	.0090	.0015	1.343	.0165	0.106
Control (F)	19	.244	.0037	.0034	.0003	1.320	.0117	.0035
Control (F)	34	.309	.0075	.0073	.0016	1.169	.0088	0.016
Ripped (L)	19	.310	.0090	.0095	.0024	1.263	.0173	0.131
Ripped (F)	19	.250	.0071	.0038	.0005	1.301	.0268	.0039
Ripped (F)	34	.303	.0340	.0347	.0576	1.103	.0238	0.012

Agreement between field and laboratory curves for neutron probe measurements centered at 34 cm was poorer than those for neutron probe measurements centered at 19 cm. This was attributed to a distinct change in soil structure and density (the occurrence of basal till) at a depth of 25-35 cm. Such discontinuities complicate comparison of retention functions when field and laboratory measurements pertain to different soil volumes.

2. Site Preparation Effects on Root Zone Soil Matric Potential

Site preparation effects on Ψ_m, and the goodness-of-fit of the retention functions are illustrated with the 1988 IDFdk Ψ_{m30}-θ_{34} data (Fig. 1.6). Measured and calculated values of Ψ_{m30} were usually quite close, although the control retention function underestimated Ψ_{m30} at lower values of θ_{34}. In the control Ψ_{m30} was notably lower than in the site prepared plots throughout the summer, reaching a minimum value of -0.60 MPa, compared to -0.07 MPa in the site prepared plots.

Based on the retention functions, Ψ_{m15} in the control plot dropped as low as -0.92 MPa at the IDFdk, -0.68 MPa at the MSxk and -0.12 MPa at the ESSF during the four study years. In all of the site prepared plots Ψ_{m15} remained >-0.15 MPa at the IDFdk, >-0.10 MPa at the MSxk and >-0.06 MPa at the ESSFxc over this same period..

These results suggest that soil water supply is likely a major factor limiting seedling growth on similar untreated areas in the IDFdk and MSxk, but not in the ESSFxc. While Ψ_{m15} never fell to values considered lethal for conifer seedlings (-1.5 to -3.0 MPa (Pharis 1966; Buxton et al. 1985; Livingston and Black 1987)) at any site, soil water supply may be an

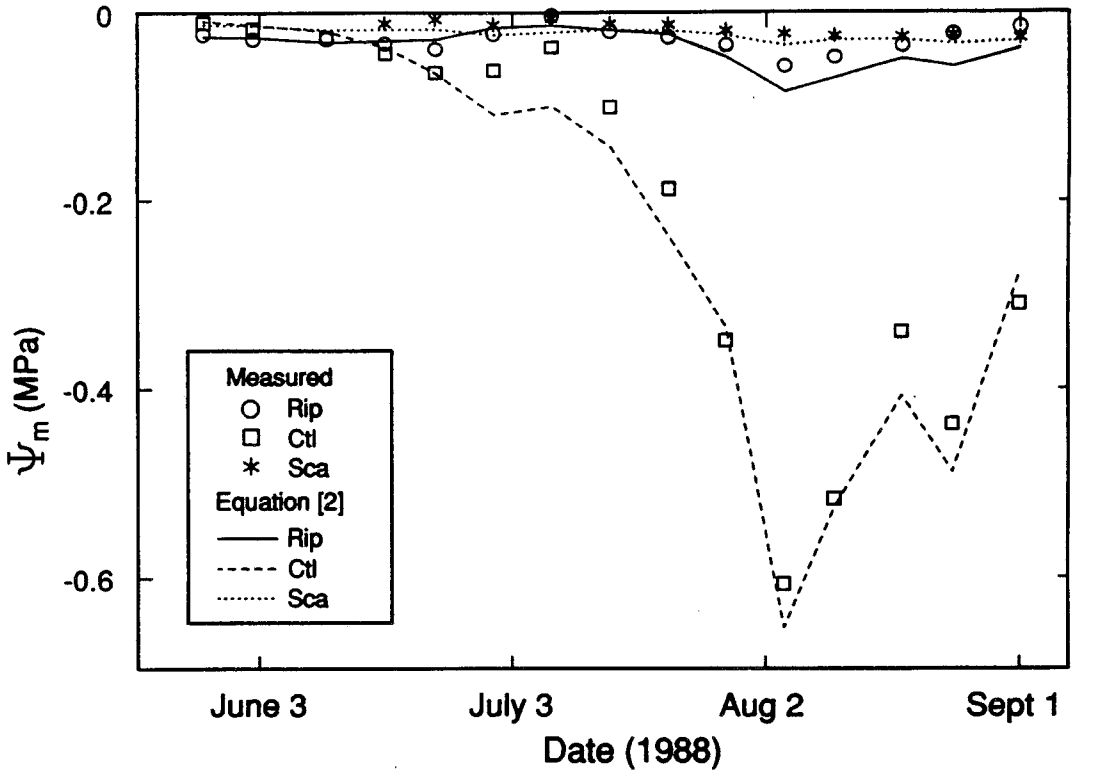

Fig. 1.6. IDFdk growing season courses of soil matric potential at 30 cm during 1988. Shown are measured and calculated (Eq. [2]) values for the control (Ctl), scalped (Sca) and ripped (Rip) treatments.

important factor limiting survival at the lower two sites when other stresses are also imposed.

D. Soil Water Balance

1. Water Content and Water Storage in the Soil Profile

The greatest seasonal changes in θ at each site occurred in the upper soil horizons of the control plots (cf. Fig. 1.7). Water extraction patterns in these plots reflected the root density distribution of the vegetation (Eq. [1]); seasonal water extraction decreased with depth and maximum losses at greater depths occurred later in the growing season. There were substantial seasonal reductions in θ in the upper 87 cm of the control plots at both the IDFdk and MSxk. At the ESSFxc, seasonal reductions in θ in the soil profile were much less pronounced and there was relatively little seasonal change in θ below 57 cm.

Profile soil water storage in the control plots declined more rapidly at the IDFdk (Fig. 1.8) than at the MSxk (Fig. 1.9) in spring and early summer but, as previously discussed, declines continued longer into the growing season at the MSxk. As a result, total profile water content drawdowns in the control, compared to those in the site prepared plots, were usually greater at the MSxk than at the IDFdk over the growing season. At the ESSFxc, profile water contents in the control also showed greater growing season declines than those in the treated plots, but not to the same extent as at the lower two sites.

Relatively small seasonal changes in profile soil water contents occurred in the treated plots at all three sites (cf. Fig. 1.7). Scalping, ripping

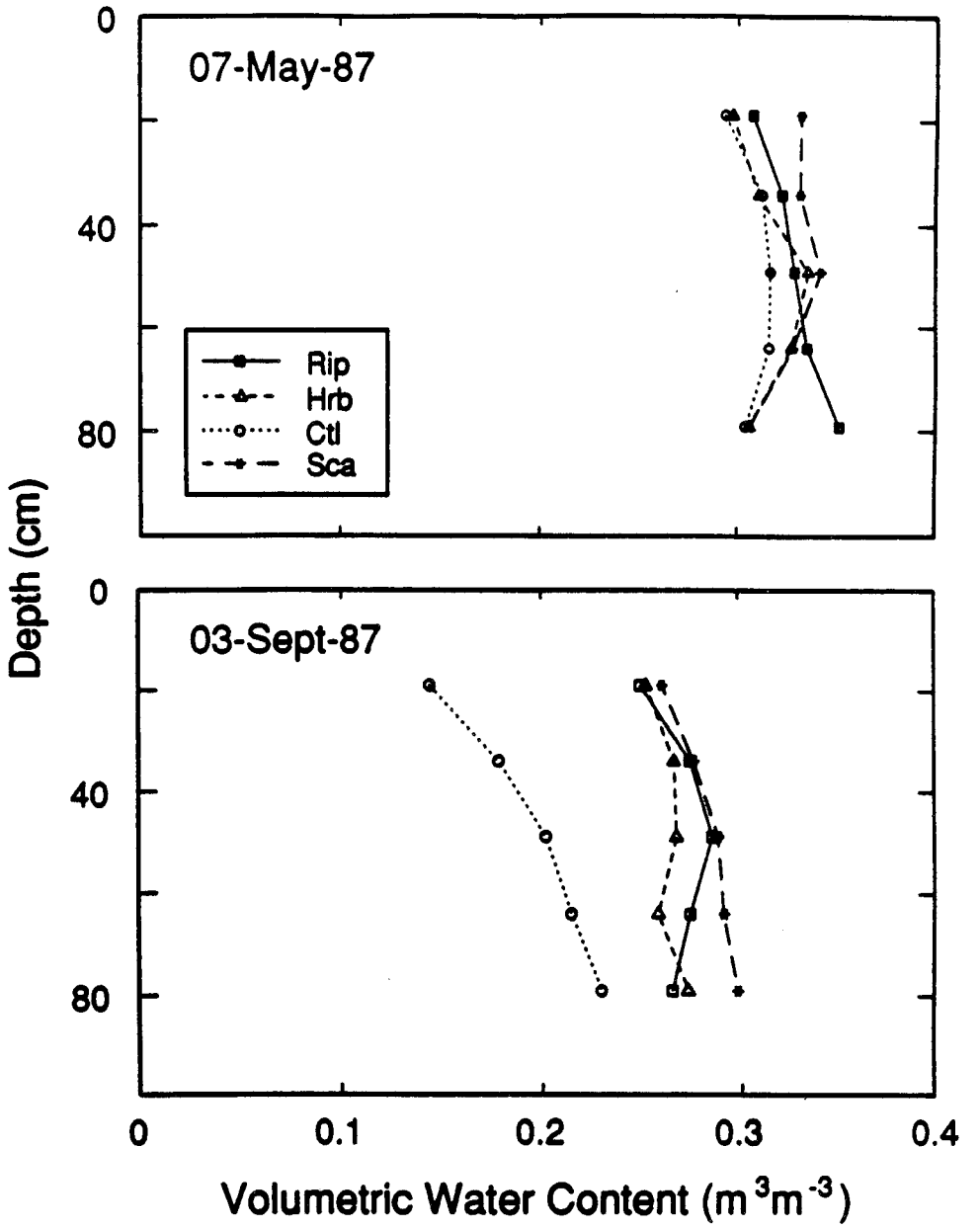

Fig. 1.7. Msxk soil water content profiles near the beginning (May 7) and end (September 3) of the 1987 growing season. Values shown are for the control (Ctl), herbicide (Hrb), scalped (Sca) and ripped (Rip) treatments.

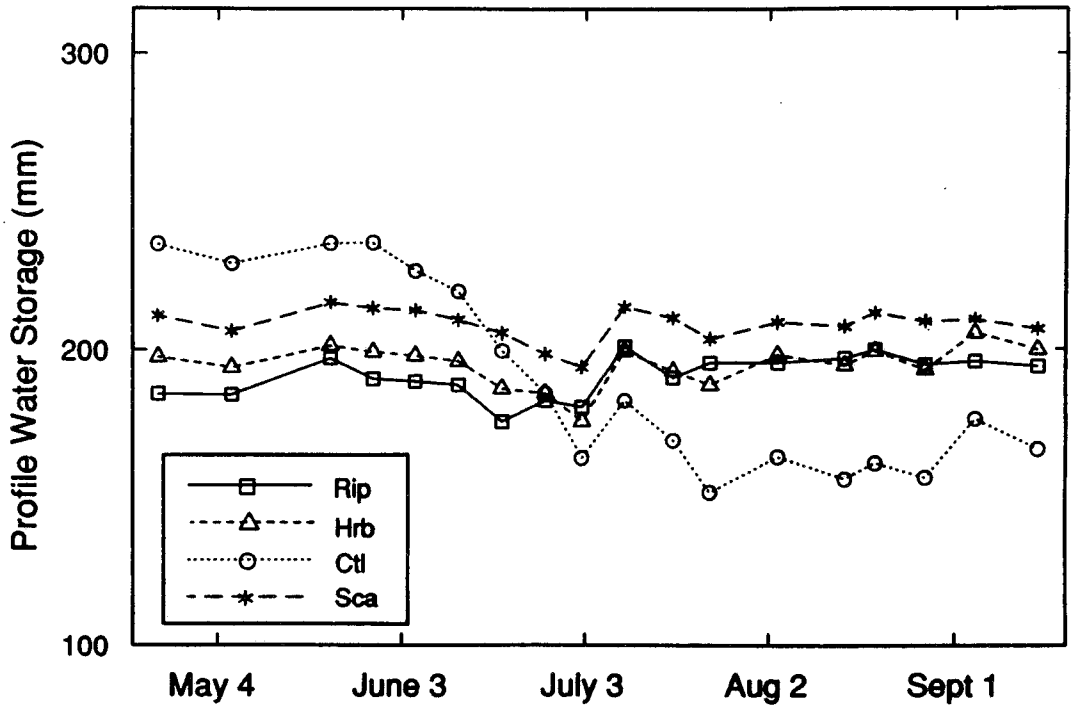

Fig. 1.8. IDFdk growing season courses of profile water storage to a depth of 87 cm during the 1987 growing season. Values shown are for the control (Ctl), herbicide (Hrb), scalped (Sca) and ripped (Rip) treatments.

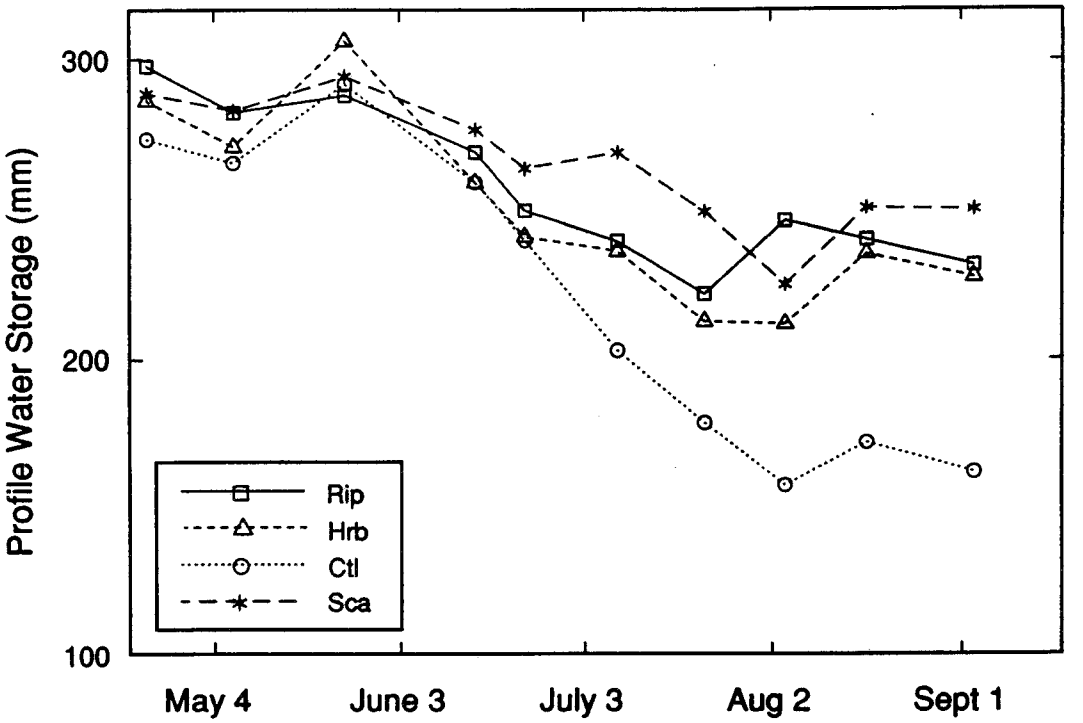

Fig. 1.9. MSxk growing season courses of profile water storage to a depth of 87 cm during the 1987 growing season. Values shown are for the control (Ctl), herbicide (Hrb), scalped (Sca) and ripped (Rip) treatments.

and herbicide application produced similar increases in S_p at each site (Figs. 1.8 and 1.9). The one notable exception was the low S_p values in the IDFdk ripped plot early in the growing season, discussed earlier in terms of θ_{19}.

In the two driest years (1987 and 1988) site preparation increased S_p over that in the control by 30-35 mm at the IDFdk and by 45-55 mm at the MSxk. In contrast, Lambert et al. (1971) reported an increase in S_p of only 10 mm following herbicide treatment of a reforested outwash sand. In the latter case, herbicide treatment reduced evaporative losses, but drainage losses increased proportionately. Soil hydraulic properties as well as climatic conditions strongly influence the ability of site preparation to increase soil water supply (Hillel and Van Bavel 1976).

The organic mulch created by the herbicide treatment did not consistently increase θ_{19}, θ_{34} or S_p over that in the scalped treatment at the three sites. While residue mulches can decrease evaporation and increase θ and S_p in comparison with bare soils (Chung and Horton 1987; Bristow and Albrecht 1989), their effectiveness varies with climatic conditions, mulch characteristics and soil properties (Gardner and Gardner 1969; Hammel et al. 1981; Jalota et al. 1988). At the MSxk and ESSFxc, 5-10 cm thick mulches composed of surface organic horizons had similar effects on θ_{19} and S_p as the scalped surfaces. At the IDFdk, the organic mulch resulted in slight increases in θ_{19} but not in S_p over that of the scalped surface.

2. Evapotranspiration and Drainage Loss from the Soil Profile

Profile water losses to $ET + D_r$ were usually much greater in the control than in the treated plots at the IDFdk and MSxk (cf. Fig. 1.10). In 1987,

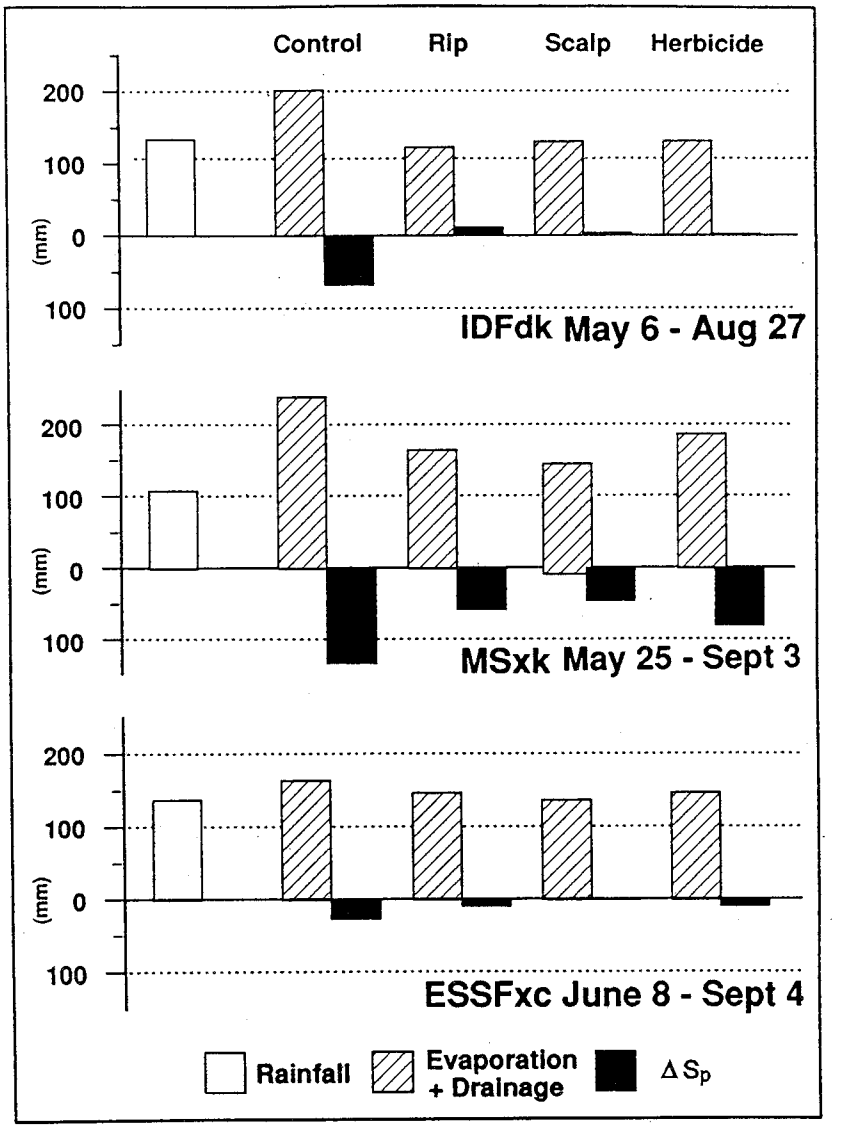

Fig. 1.10. Growing season soil water balance components, including seasonal change in profile water storage (ΔS_p), for different treatments at the IDFdk, MSxk and ESSFxc in 1987.

greater climatological deficits ($P - (ET + D_r)$) occurred at the MSxk than at the IDFdk (although calculated for slightly different time periods) as a result of both lower P and greater $ET + D_r$. At the ESSFxc, $ET + D_r$ in the control was also greater than in the treated plots, but was substantially less than in the control plots at the other two sites. As indicated earlier, there were no consistent differences in $ET + D_r$ among the scalped, ripped and herbicide plots at any given site.

Similar trends to those reported above were found in the other study years at each site, but in most years the climatological deficit was greatest at the IDFdk. In wetter years (i.e., 1986 and 1989) differences in $ET + D_r$ between the control and treated plots were not as great.

3. Partitioning Water Loss between Evaporation and Drainage

Upward hydraulic gradients (i.e., increasing soil hydraulic potential with depth) during much of the growing season in the IDFdk and MSxk control soil profiles indicated that profile water losses in these plots resulted largely from evaporation. Close agreement at the IDFdk between growing season water balance estimates of ET, assuming no net soil water flux below 87 cm, and eddy correlation/ energy balance estimates of ET (Adams et al. 1991) support this conclusion. At the ESSF there was relatively little soil water drawdown in the control at depths greater than 50 cm in some growing seasons, and sizable drainage losses may have occurred.

Calculations of growing season drainage losses in the site prepared plots, assuming a constant zero flux plane at 27 cm, showed no consistent differences among treatments at a given site. Mean three year (1986-1988) growing season estimates of D_r and $ET + D_r$ for the treated plots were: 1) 26

and 157 mm, respectively, over a 17 week period at the IDFdk; 46 and 171 mm, respectively, over a 13 week period at the MSxk; and 3) 55 and 185 mm, respectively, over a 12 week period at the ESSFxc. Based on these estimates, D_r accounted for 17-30% of the total profile water loss in the treated plots on these sites. In contrast, on coarser textured soils, D_r following vegetation removal may account for more than half of the total water loss from the profile (Lambert et al. 1971; Arya et al. 1975b). In this study, calculated drainage losses increased with elevation, probably because of greater profile water contents as a result of lower annual *ET*, and consequently higher hydraulic conductivities.

In some instances, increased D_r following site preparation may have important hydrologic and nutritional implications. Invasion of seral vegetation following forest harvesting can markedly reduce D_r and losses of soil nutrients to leaching. Depending on its extent (within a treatment block) and scale (within a landscape), site preparation which eliminates seral vegetation may significantly affect summer water yields and profile nutrient losses in small watersheds (Bormann and Likens 1979; Hicks et al. 1991).

IV. CONCLUSIONS

During the growing season, root zone and profile soil water content in untreated plots on these grass-dominated clearcuts increased with elevation. The largest declines and greatest variations in soil water content occurred near the surface at the lower two sites, the IDFdk and MSxk. At these two sites, soil water supply in the control plots probably limits seedling

growth throughout the summer months. These trends were related to a decrease in growing season length and evaporative demand with elevation, despite similar rainfall distribution and amount, and solar irradiance.

Soil water supply and storage patterns at the MSxk resembled those at the IDFdk more than those at the ESSFxc. However, temporal patterns of soil water depletion at the IDFdk and MSxk differed: water deficits developed later in the growing season but lasted longer into the fall at the MSxk. This likely reflects differences in vegetation as well as in microclimatic conditions.

At the ESSFxc, root zone soil water content in the control plots remained greater than 0.22 m^3m^{-3} throughout the growing season and there was little evidence of water use by vegetation in the lower portion of the soil profile. Nevertheless, poorer seedling growth in the control than in the herbicide plots at this site suggests that growing season soil water supply may be limited in near-surface horizons even at this site (Black et al. 1991).

At each site scalping, ripping and herbicide application increased root zone and profile soil water supply to a similar degree, primarily by decreasing evapotranspiration through the elimination of herbaceous vegetation. Soil matric potentials at 15 cm never fell below -0.15 MPa in any of the treatments during the four growing seasons at any site. Site preparation increased profile soil water storage and drainage losses by a similar degree at the lower two sites.

Future research should focus on determining the optimum dimensions of site preparation treatments from the perspective of both seedling microclimate and nutrition. Research is needed to determine how large an

area must be treated to ameliorate soil water supply, and to determine the effects such treatments will have on soil and aerial temperature regimes and nutrient availability.

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CHAPTER 2

EFFECTS OF SITE PREPARATION ON THE WATER RELATIONS AND GROWTH OF RECENTLY PLANTED DOUGLAS-FIR AND LODGEPOLE PINE SEEDLINGS

EFFECTS OF SITE PREPARATION ON THE WATER RELATIONS AND GROWTH OF RECENTLY PLANTED DOUGLAS-FIR AND LODGEPOLE PINE SEEDLINGS

I. INTRODUCTION

Harsh microclimatic conditions following clearcutting are among the most common factors limiting seedling survival and early growth (Burdett 1990; Kozlowski et al. 1991). In the drier biogeoclimatic subzones of the Southern Interior (Interior Plateau) of British Columbia, poor seedling establishment is often attributed to drought and associated seedling water stress (Vyse 1981; Mitchell et al. 1990). In this region, competition between tree seedlings and native grasses for soil water commonly occurs on clearcut sites (McLean and Clark 1980) while other factors such as frost damage and low soil temperatures further exacerbate seedling water stress (Fahey 1979; Running and Reid 1980; DeLucia and Smith 1987).

The use of site preparation to ameliorate the seedling microclimate and improve seedling physiological condition and growth is receiving increased attention (Lanini and Radosevich 1986; Örlander 1986; Flint and Childs 1987; Grossnickle and Heikurinen 1989). Site preparation is used prior to planting to remove competing vegetation and improve the seedling environment by altering plant canopy, surface and soil characteristics (Morris and Lowery 1988; Spittlehouse and Childs 1990). This, in turn, can greatly improve seedling establishment (Örlander et al. 1990).

The objectives of this paper are: 1) to compare the water relations, growth and survival of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco)

and lodgepole pine (Pinus contorta Dougl.) seedlings in the first growing season after outplanting on a grass-dominated clearcut in the Southern Interior; and 2) to examine how these characteristics change in response to site preparation.

II. EXPERIMENTAL METHODS

A. Site Description

The experimental site is a pinegrass (Calamagrostis rubescens Buckl.) dominated clearcut in the Interior Douglas-fir (IDFdk) Biogeoclimatic Subzone (Thompson Plateau-Very Dry Montane Interior Douglas-fir variant) within the Southern Interior of British Columbia (Mitchell et al. 1981). It is located near Fehr Mountain, 40 km west of Kamloops (50°40′ N, 120°20′ W), at an elevation of 1220 m and falls within the Pseudotsuga-Calamagrostis habitat type of McLean (1970). The mean annual precipitation is about 400 mm of which 220 mm falls from May through September (Mitchell et al. 1981). Growing season precipitation from May 1 to August 31 was 145 mm in 1987 and 200 mm in 1988.

Pinegrass comprised about 80% of the total vegetative cover, which consisted almost exclusively of herbaceous plants. Herbaceous leaf area index usually peaked at about 1.0 in mid-July and decreased thereafter (Adams et al. 1991).

The soil was an Orthic Gray Luvisol and consisted of 20-30 cm of gravelly silt loam overlying a clay loam basal till. A thin organic layer (4-6 cm) covered the mineral soil. The site was level and well drained with a few

small drainage depressions. The previous lodgepole pine-Douglas-fir stand was clearcut in 1982.

B. Experimental Layout

Site preparation was carried out in the fall of 1986 and 1987, and included scalping, scalping followed by ripping, herbicide (1987 only), trenching (1988 only) and a control. Scalping involved removal of the top 5-10 cm of soil, including the organic horizons, with the straight blade of a Caterpillar D8 crawler tractor. Ripping was conducted by making several passes over scalped areas with flanged ripper teeth mounted on a drawbar behind the tracks of the tractor. The ripper teeth penetrated the soil to a depth of about 50 cm and the treatment resulted in ripper tooth paths spaced 0.3-0.5 m apart. Subsequently, the upper 25 cm of the ripped plots was thoroughly mixed and then leveled with shovels and rakes. Trenches were created by a single pass over untreated ground with ripper teeth and a trailing heavy steel drag (Coates and Haeussler 1987). Debris was then cleared away and the furrows were excavated to create trenches 20-30 cm deep and 40-60 cm wide across the top. The herbicide treatment involved broadcast application of glyphosate (*N*-(phosphonomethyl)glycine) at 30 ml active ingredient per 100 m^2. Over the growing season vegetation ingress on all site preparation treatments was controlled with spot applications of glyphosate. Seedlings were covered with polyethylene bags during herbicide application to prevent contact with the spray.

Site preparation was applied uniformly in strips 20 x 5 m (physiology plots) or 10 x 5 m (growth and survival plots), and the different treatments were randomly assigned to individual plots set out adjacent to one another.

The growth and survival plots were installed in three blocks using a randomized complete block design. Large treatment sizes were used to ensure that the seedling environment was relatively unaffected by adjacent treatments.

During early May of 1987 and 1988, 1 - 0 Douglas-fir 3 - 13 plug stock and 1 - 0 lodgepole pine 2 - 12 plug stock were planted in the control and in each of the site preparation treatments created the previous fall. With the exception of the trenches, each plot consisted of two rows of Douglas-fir, alternating with two rows of lodgepole pine. There were 15 seedlings in each row of the growth and survival plots and 30 seedlings in each row of the physiology plots. Each trenched plot had two trenches, and seedlings alternated between the two species in each trench. There were 30 seedlings per trench in the growth and survival plots and 60 seedlings per trench in the physiology plots. All seedlings were marked with wire pins and individually identified with numbered aluminum tags.

C. Measurements and Analysis

1. Microclimate

An automated climate station, consisting of a data logger (Campbell Scientific Inc., Logan, UT, Model 21X) and associated sensors, was located at the site. Mean hourly values of precipitation (Sierra-Misco, Inc., Berkeley, CA, Model RG2501 Tipping Bucket Rain gage), solar irradiance (LI-COR Inc., Lincoln, NB, Model LI200S silicon cell pyranometer) wind speed (MEt One Inc., Grants Pass, OR, Model 014A cup anemometer), air temperature and relative humidity (Campbell Scientific Inc., Logan, UT, Model 207 probe

with a Fenwall Electronics, Framingham, MA, UUT-51J1 thermistor and Phys-Chem Scientific Corp., New York, PCRC-11 sulphonated polystyrene relative humidity sensor) 1.3 m above ground, and air temperature 15 cm above ground in different site preparation treatments (Fenwall Electronics, Framingham, MA, Model UUT-51J1 thermistors potted in Armstrong C7 epoxy, configured similarly to the Campbell Scientific Inc. Model 101 thermistor probe, and shielded with a two-plate radiation shield (Black et al. 1988)), were collected throughout the 1987 and 1988 growing seasons.

Measurements of ambient air temperature and relative humidity at seedling height were made concurrently with those of stomatal conductance and transpiration, using a ventilated porometer (described later). These values were used to calculate the vapor pressure deficit at seedling height, normalized with respect to atmospheric pressure (D_s/P, where D_s is the seedling height vapor pressure deficit and P is the atmospheric pressure ($\cong$ 89.1 kPa)). Normalized vapor pressure is identical to the mole fraction of water vapor (mol of water vapor per total mol of all gases).

2. Soil Water

Weekly measurements of volumetric soil water content (θ) were made with a neutron meter (Campbell Pacific Nuclear Corp., Martinez, CA, Model 503 Hydroprobe) with the probe centered at depths of 19 (θ_{19}) and 34 cm (θ_{34}). This gave integrated values of θ in 15 cm depth increments. Three to five neutron tubes were installed in each treatment for this purpose using holes initially dug with a power auger and undersized bit, and enlarged with a hand auger.

Soil matric potentials (Ψ_m) were determined in the field with

tensiometers and thermocouple psychrometers (assuming negligible solute potential) at depths of 15 and 30 cm. The tensiometers were read with a pressure transducer (Soil Measurement Systems, Tucson, AZ, Model SW-010 Tensimeter) and constructed following the design of Marthaler et al. (1983). Individually calibrated screen cage thermocouple psychrometers (TCPs) (J.R.D. Merrill Specialty Equipment, Logan, UT, 74 series) were installed following procedures outlined by Brown and Chambers (1987) and read with a microvoltmeter (Wescor Inc., Logan UT, Model HR-33T) or a data logger (Campbell Scientific Inc., Logan, UT, Model CR7X) equipped with Campbell Scientific Inc. Model A3497 Cooling Current Interfaces and software. Readings were taken between 7:00 and 10:00 PST, a time when vertical soil temperature gradients were smallest (Appendix II). The calibration model of Brown and Bartos (1982) was used to determine Ψ_m from thermocouple psychrometer soil temperature, zero-offset and microvolt output readings.

These data were used with the empirical equation of Van Genuchten (1980) to generate field retention curves. This allowed for 1) prediction of Ψ_m at 15 cm (Ψ_{m15}) using θ_{19} when Ψ_{m15} was not measured, and 2) determination of root zone extractable water ($\theta_e = (\theta_{19} - \theta_{min})/(\theta_{max} - \theta_{min})$ where θ_{max} is the volumetric water content at field capacity ($\Psi_{m15} = -0.03$ MPa), θ_{min} is the volumetric water content at $\Psi_{m15} = -2.0$ MPa, and $\theta_e \leq 1.0$). Further details on measurement of θ and Ψ_m and determination of retention curves are reported in Chapter 1 and Appendix I.

3. Plant Water Relations

a. Stomatal conductance, transpiration, leaf area and root egress

Seedling stomatal conductance (g_s) and transpiration rate (E) were

measured with a transient, ventilated porometer (Micromet Systems Inc., Vancouver, BC, Model CS-102) which enclosed the entire seedling (Livingston et al. 1984). Measurements of individual seedlings were taken over a 30 s period. The instrument calculates g_s (cm s^{-1}) from the rate of increase in vapor density in the porometer chamber, the projected leaf area of the seedling (A) and the instantaneous saturation deficit (D) in the chamber. Using these values of g_s and A, it calculates E (mg s^{-1}) as:

$$E = g_s AD \tag{1}$$

where D is measured at the start of the 30 s period. Seedling g_s and E values were corrected to reflect the actual projected leaf area once the latter was determined, and were converted to mole units using g_s(mol $m^{-2}s^{-1}$) = g_s(m s^{-1}) P/RT and E (mol s^{-1}) = g_s(mol $m^{-2}s^{-1}$)AD_s/P where $P = 89.1 \times 10^3$ Pa, R is the gas constant (8.3145 J mol^{-1} K^{-1}) and T is the absolute temperature (K).

These values of E are considered to be good estimates of actual seedling transpiration rate because: 1) conifer stomates show little response to changes in environmental conditions over the measurement period used (Livingston et al. 1984); 2) mean midmorning boundary layer conductances, calculated according to Dixon and Grace (1984) using seedling height windspeeds extrapolated from measurements at 1.3 m (Campbell 1977), were 8 -14 times greater than the maximum g_s of each species; and 3) the chamber volume (3700 cm^3) and short measurement period minimized differences in ambient versus chamber air temperature. Calculating E using screen height saturation deficit ($D_{1.3}$) rather than D at seedling height may substantially

underestimate E because $D_{1.3}$ is often lower than D at seedling height during the day (Choudhury and Monteith 1986; Monteith 1990).

The accuracy of the porometer measurements of seedling water flux was determined using filter paper discs 6-18 mm in diameter attached to a small water-filled pipette (LI-COR Inc., Lincoln, NB). These were inserted into the chamber to provide different evaporation rates. Water vapor fluxes measured with the porometer were within 10% of those determined with the pipette over fluxes ranging from 0.8 to 7.0 μmol s^{-1}, while the accuracy of g_s measurements was about 0.001 mol $m^{-2}s^{-1}$ over this same range.

The porometer was stored in the shade between readings and shaded whenever possible during readings. Measurements were not made before dew or rain had completely evaporated from the leaf surfaces or when relative humidities exceeded 85% (McDermitt 1990). The humidity sensor (Vaisala Inc., Woburn, MA, Humicap Model 6064) was calibrated with a dewpoint hygrometer (EG and G International Inc., Waltham, MA, Model 880) each spring using a range of dewpoint temperatures.

Daytime courses of g_s and E were determined for eleven days during each of the 1987 and 1988 growing seasons by measuring representative seedlings at two-hour intervals from sunrise until sunset. Midmorning values of stomatal conductance (g_{sm}) and transpiration rate (E_m) were determined between 9:30 and 11:00 PST. At this time g_s and E usually approached their diurnal maximum values. Comparisons of first growing season g_{sm} and E_m between species and among all site preparation treatments were made on 12 summer days during the 1987 and 1988 growing seasons. Similar comparisons were made in the control and ripped treatment on 25-30 days throughout each of the 1987 and 1988 growing seasons.

Following measurements of g_s and E for a 7-10 day period, seedlings were excavated and stored at 2 - 4 °C until leaf and rooting characteristics could be measured. Projected leaf areas were determined with a leaf area meter (LI-COR Inc., Lincoln, NB, Model 3000/3050-A). Root egress (r_l), the total length of roots egressing from the plug, was determined by severing the excavated root systems at the plug surface, placing them on 1 x 1 mm grid graph paper and determining their length.

b. Seedling xylem pressure potential

Twig and stem xylem pressure potentials (Ψ_{tx}) were measured in the field with a pressure chamber (Soilmoisture Equipment Corp., Santa Barbara, CA, Plant Water Status Console) following procedures outlined by Ritchie and Hinckley (1975) and Turner (1981). Stem Ψ_{tx} was measured by placing the entire stem with needles attached, in the pressure chamber. Midmorning measurements of xylem pressure potential (ψ_{txm}) were often made on days when g_{sm} and E_m were measured. On many of these days, base (predawn) xylem pressure potentials (ψ_{txb}) were also measured.

c. Soil-plant liquid path resistance

The soil-plant liquid flow resistance (R_{sp}), representing the sum of the soil, root and stem resistances along the flow path, was calculated using (Jones 1983):

$$R_{sp}=(\Psi_{sr} - \Psi_{tx})/E \qquad (2)$$

where Ψ_{sr} is the bulk root zone soil water potential and E is taken to represent the steady state water flux through the seedling. Measurement of E

with the CS-102 porometer, together with the simultaneous determination of stem Ψ_{txm} and Ψ_{m15} (i.e., Ψ_{sr}) allowed R_{sp} to be calculated on a flux basis (Eq. 2) or flux density basis (i.e., E replaced by $E_A=E/A$)) for the entire flow path (Richter 1973).

4. Seedling Growth

a. Survival, height and root collar diameter measurements

Survival, height and root collar diameter measurements were made on all seedlings in the growth and survival plots shortly after planting and at the end of the first growing season, in both 1987 and 1988. Results were analyzed using two way analysis of variance (ANOVA) with species and site preparation treatment as fixed effects. Survival data were arc sine transformed (Zar 1984) prior to statistical tests. Individual differences among treatments for a given variable were established using Newman-Keuls multiple comparison test, while differences between values for the control and the site preparation treatments were established using linear contrasts (Hintze 1991). An α level of 0.10 was used in all tests of significance of seedling growth because of substantial inherent variability among individual seedlings.

For illustrative purposes, seedling height and root collar measurements were also analyzed separately for each species using one way ANOVA. Individual differences among treatments for a given species were established with Newman-Keuls multiple comparison test.

b. Seedling dry matter

In September of 1987 and 1988, 8-10 randomly selected seedlings of each species were excavated from the control and each site preparation treatment for dry matter analysis. Roots, stems and needles of each seedling were dried separately at 70 °C for 48 h and then weighed to determine dry mass. Results were analyzed using both two way and one way ANOVA with Newman-Keuls multiple comparison test (α=0.10) in similar fashion to the seedling height and root collar data above.

III. RESULTS AND DISCUSSION

A. First Growing Season Stomatal Conductance and Transpiration

1. Diurnal Patterns

On clear days, Douglas-fir and lodgepole pine g_s usually peaked between 7:00 and 10:00 h (Fig. 2.1) while E usually peaked between 10:00 and 13:00 h (Fig. 2.2). The most pronounced diurnal trends and greatest treatment effects occurred on clear days with high D_s/P. On cloudy days with low D_s/P, g_s and E varied less throughout the day and among control and site preparation treatments. Under the latter conditions, g_s was relatively high while E was relatively low.

There were often substantial differences in g_s and E among individual seedlings of the same species and site preparation treatment at a given time, with coefficients of variation commonly ranging from 10% to 40%. However, diurnal trends among different seedlings for a given day and treatment were usually quite similar.

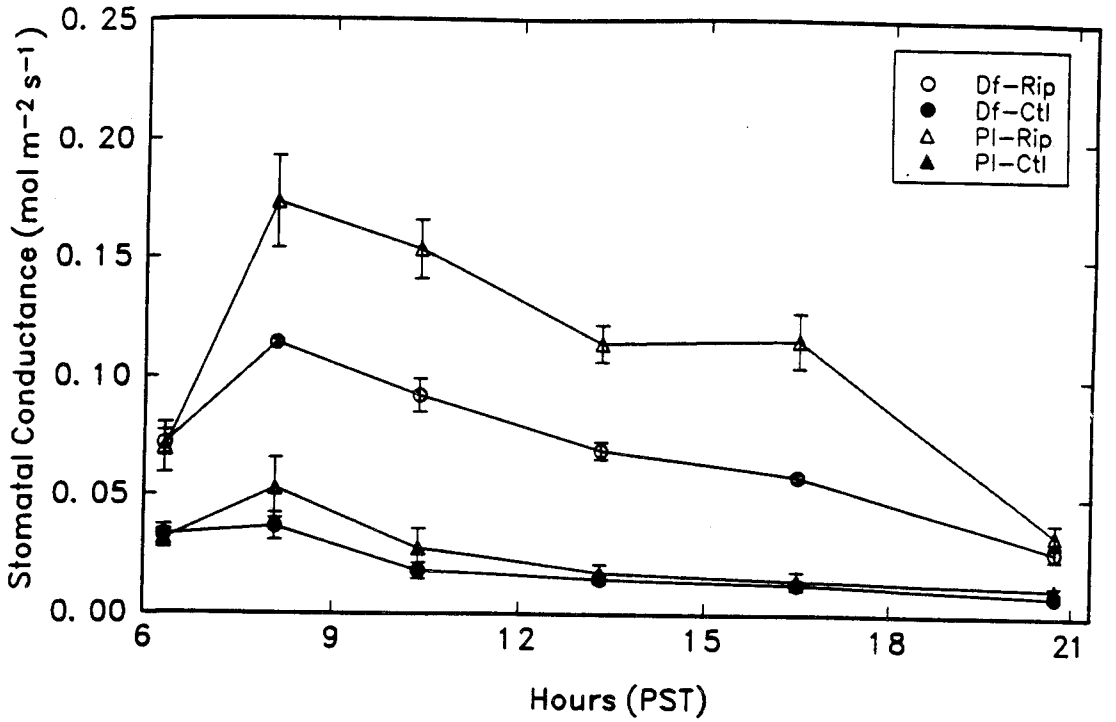

Fig. 2.1. Diurnal courses of stomatal conductance of 1988 spring-planted Douglas-fir (Df) and lodgepole pine (Pl) in the the control (Ctl) and the ripped treatment (Rip) on July 27, 1988. Shown are the mean and standard error for four seedlings per species and treatment, sampled within 30 min of each other.

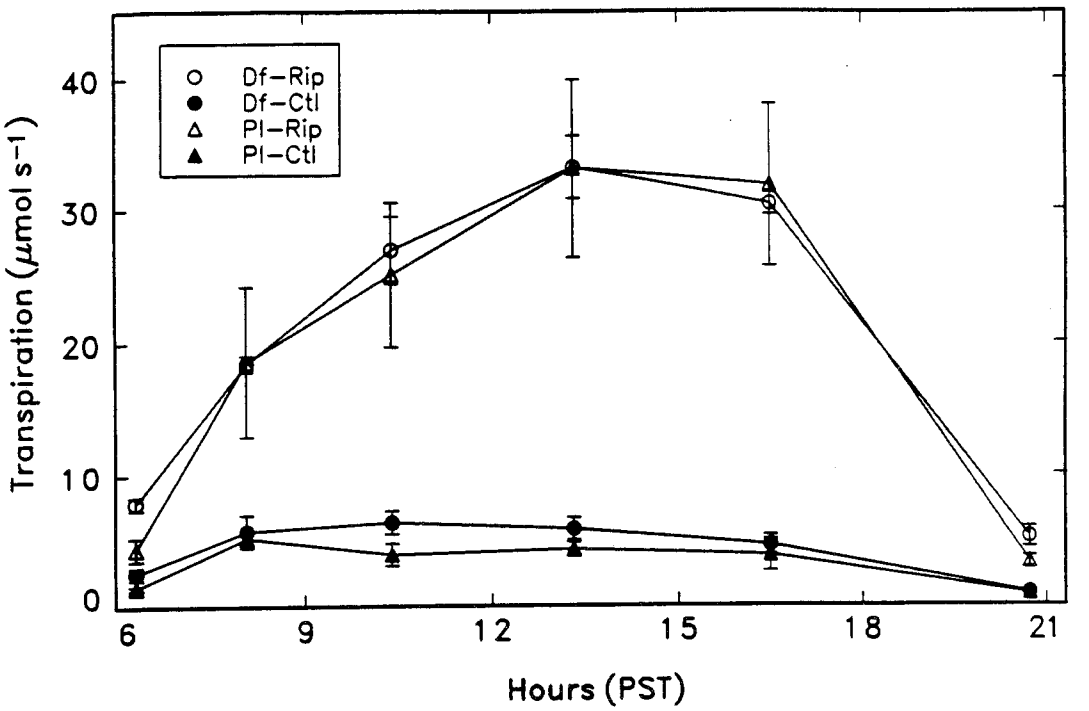

Fig. 2.2. Diurnal courses of transpiration of 1988 spring-planted Douglas-fir (Df) and lodgepole pine (Pl) in the control (Ctl) and the ripped treatment (Rip) on July 27, 1988. Shown are the mean and standard error for four seedlings per species and treatment, sampled within 30 min of each other.

2. Treatment Effects

Douglas-fir g_{sm} and E_m were larger ($p \leq 0.10$) in the site preparation treatments than in the control (cf. Figs. 2.1 and 2.2) on eight and nine days, respectively, of the 12 days when comparisons among the control and all treatments were made. Differences in Douglas-fir g_{sm} and E_m among site preparation treatments were evident ($p \leq 0.10$) on only three of these days. In these cases, g_{sm} and E_m were usually greater in the ripped treatment than in the other treatments.

Similar trends were evident with lodgepole pine; both g_{sm} and E_m were larger ($p \leq 0.10$) in the site preparation treatments than in the control (cf. Figs. 2.1 and 2.2) on 11 of the 12 days sampled, but differences ($p \leq 0.10$) in g_{sm} and E_m among site preparation treatments were found on only three of these days. In these cases, g_{sm} and E_m was greater in the ripped treatment than in the other site preparation treatments.

The consistent differences in g_{sm} and E_m found between the control and the site preparation treatments contrast sharply with the similarity in response among site preparation treatments. This likely reflects the ability of all site preparation treatments to provide large increases in root zone water supply in comparison with the control (Chapter 1). Differences in seedling g_{sm} and E_m among site preparation treatments may develop in subsequent years as the seedlings experience the full annual range of microclimate conditions provided by each treatment. There was some indication of greater g_{sm} and E_m developing in the ripped treatment than in the other site preparation treatments near the end of the first growing season.

3. Seasonal Patterns in the Control and Ripped Treatment

Seasonal patterns in first growing season g_{sm} and E_m for each species were similar in the two study years and are illustrated with the 1988 data.

a. Stomatal Conductance

Over the 1988 growing season, Douglas-fir g_{sm} varied from 0.02 to 0.15 mol m^{-2} s^{-1} while lodgepole pine g_{sm} varied from 0.02 to 0.31 mol m^{-2} s^{-1} (Figs. 2.3 and 2.4). There were no consistent differences in Douglas-fir or lodgepole pine g_{sm} between the ripped treatment and the control soon after planting, but by mid June, g_{sm} in the ripped treatment consistently exceeded that in the control for both species. Differences were most pronounced during periods with low θ_e and high D_s/P (e.g., late July and early August).

These results likely reflected both reductions in θ_e (Chapter 1) and higher midmorning D_s/P in the control during the summer (Chapter 3). Mean D_s/P values, determined from midmorning measurements on 52 clear to partially cloudy days during 1987 and 1988, were 1.8 Pa kPa^{-1} higher in the control than in the ripped treatment. Examination of continuous air temperature measurements 15 cm above ground revealed that the latter phenomenon was largely accounted for by differences in air temperature. Lower seedling height air temperatures in the bare-surface treatments than in the control, despite higher daytime surface temperatures, likely resulted from the greater distance between seedling height and the surface energy exchange plane in these treatments than in the control.

Douglas-fir g_{sm} was consistently higher than lodgepole pine g_{sm} in the ripped treatment until mid June and in the control until early July. Thereafter, lodgepole pine g_{sm} exceeded that of Douglas-fir in both the

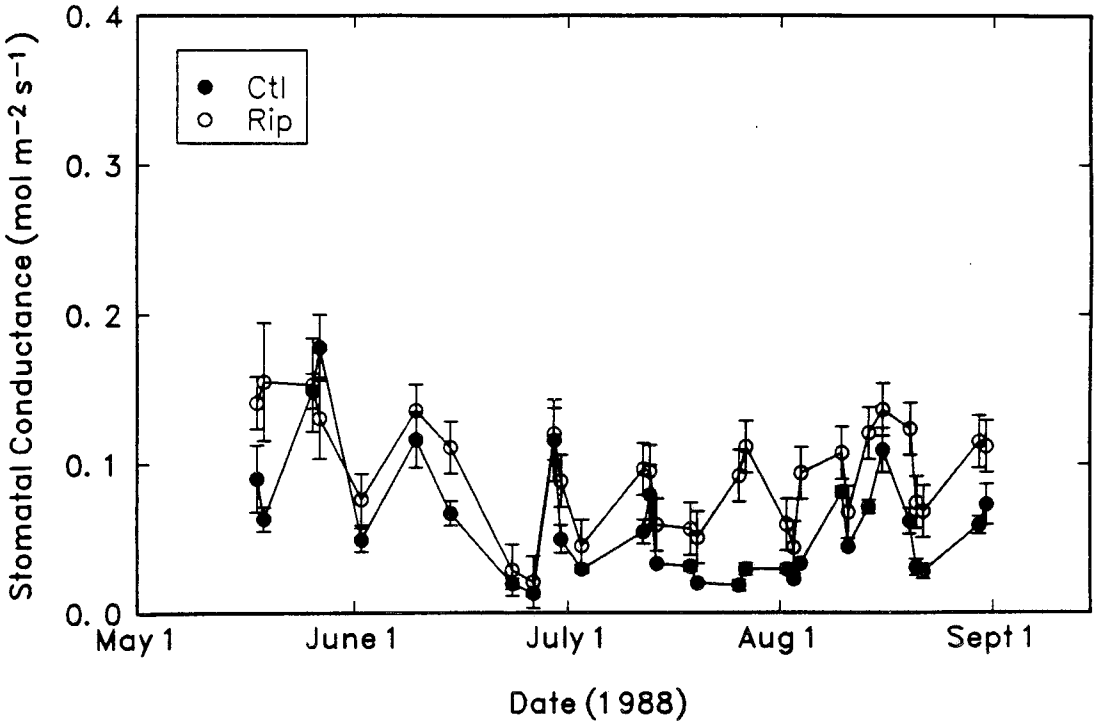

Fig. 2.3. Seasonal course of midmorning stomatal conductance of 1988 spring-planted Douglas-fir in the control (CTL) and the ripped treatment (Rip) during the 1988 growing season. Shown are the mean and standard error for four seedlings per species and treatment, sampled within 30 min of each other

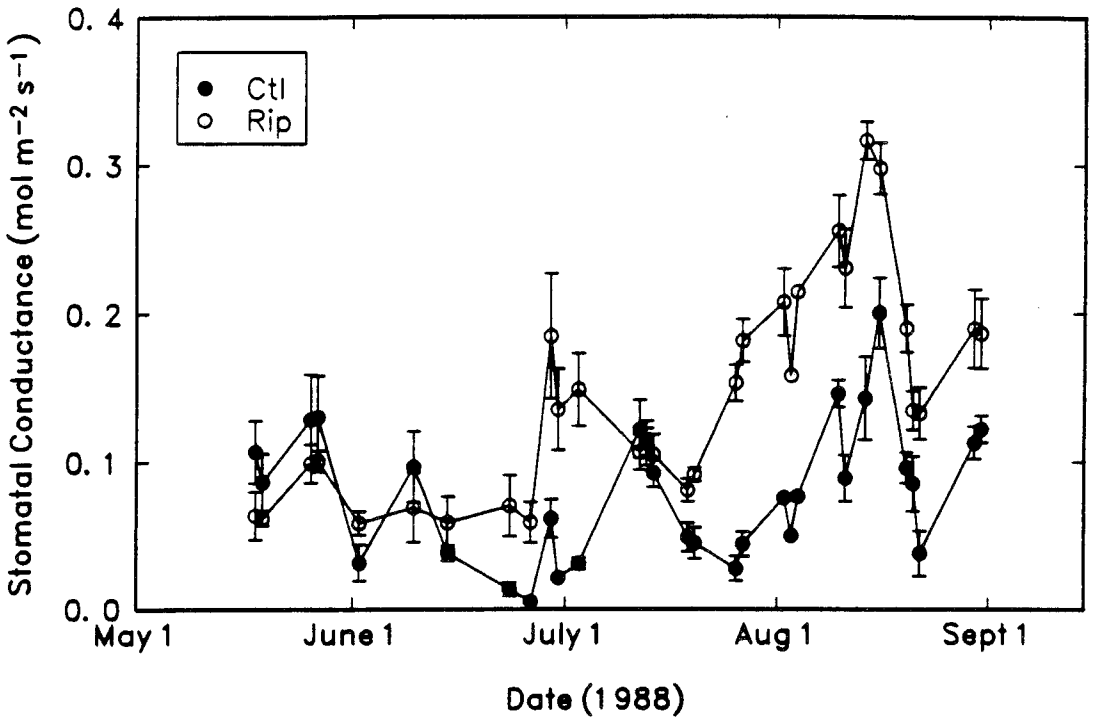

Fig 2.4. Seasonal course of midmorning stomatal conductance of 1988 spring-planted lodgepole pine in the control (CTL) and the ripped treatment (Rip) during the 1988 growing season. Shown are the mean and standard error for four seedlings per species and treatment, sampled within 30 min of each other.

control and the ripped treatment. Over July and August, 1988 the mean value of the ratio of lodgepole pine g_{sm} to Douglas-fir g_{sm} (g_{smr}) was 1.98 in the control and 2.07 in the ripped treatment.

b. Transpiration

Douglas-fir and lodgepole pine E_m remained at low, fairly stable levels in the control and ripped treatment throughout May and June (Figs. 2.5 and 2.6). In early July, there was a marked increase in E_m of both species in the ripped treatment and this was sustained through the rest of the first growing season. In the control, Douglas-fir and lodgepole pine E_m increased slightly over the summer months. For the 20 days sampled in July and August of 1988, mean Douglas-fir E_m in the control was 44% of that in the ripped treatment, while mean lodgepole pine E_m in the control was 39% of that in the ripped treatment.

A comparison of seasonal courses of the ratio of lodgepole pine E_m to Douglas-fir E_m (E_{mr}) revealed different patterns in the control and ripped treatment. In the control, E_{mr} declined to a minimum in late June, increased greatly in early July and showed no consistent pattern thereafter (Fig. 2.7*a*). In the ripped treatment, there was a progressive increase in E_{mr} throughout the summer (Fig. 2.7*b*).

Differences in the seasonal courses of E_m between species and between the control and ripped treatment reflect changes in A as well as in g_{sm} (Eq. [1]). Both species showed a substantial increase in A in late June, with the elongation of leaves from needle primordia in flushing buds (Fig. 2.8). The greatest increases in A in both the control and ripped treatment occurred with Douglas-fir and were essentially complete by early July. In contrast,

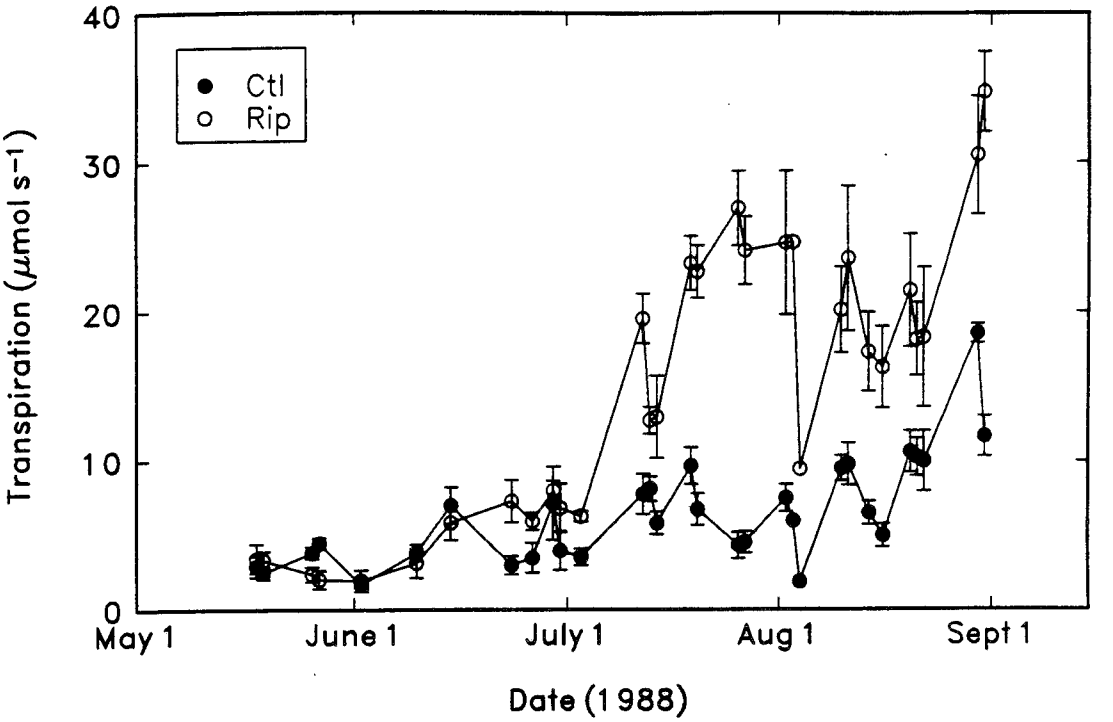

Fig. 2.5. Seasonal course of midmorning transpiration of 1988 spring-planted Douglas-fir in the control (CTL) and the ripped treatment (Rip) during the 1988 growing season. Shown are the mean and standard error for four seedlings per species and treatment, sampled within 30 min of each other.

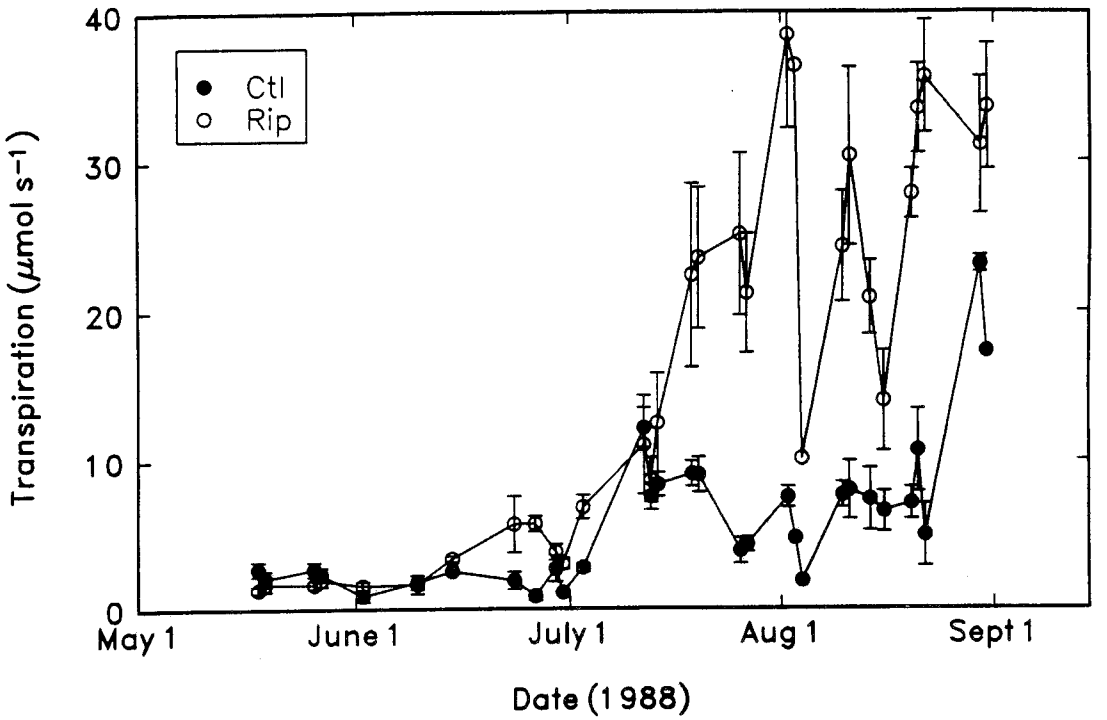

Fig 2.6. Seasonal courses of midmorning transpiration of 1988 spring-planted lodgepole pine in the control (CTL) and the ripped treatment (Rip) during the 1988 growing season. Shown are the mean and standard error for four seedlings per species and treatment, sampled within 30 min of each other.

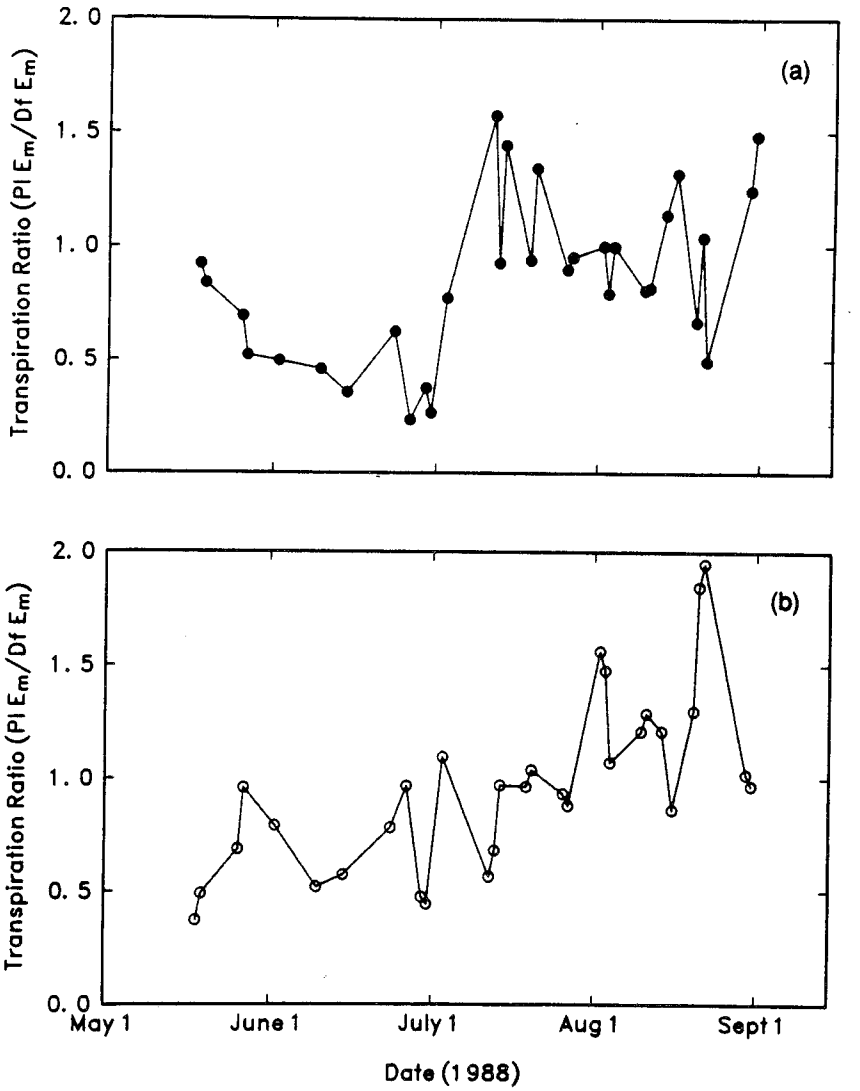

Fig. 2.7. Seasonal course of the ratio of midmorning transpiration of 1988 spring-planted lodgepole pine (Pl E_m) to that of Douglas-fir (Df E_m) (Pl E_m/ Df E_m) in (*a*) the control and (*b*) the ripped treatment during the 1988 growing season.

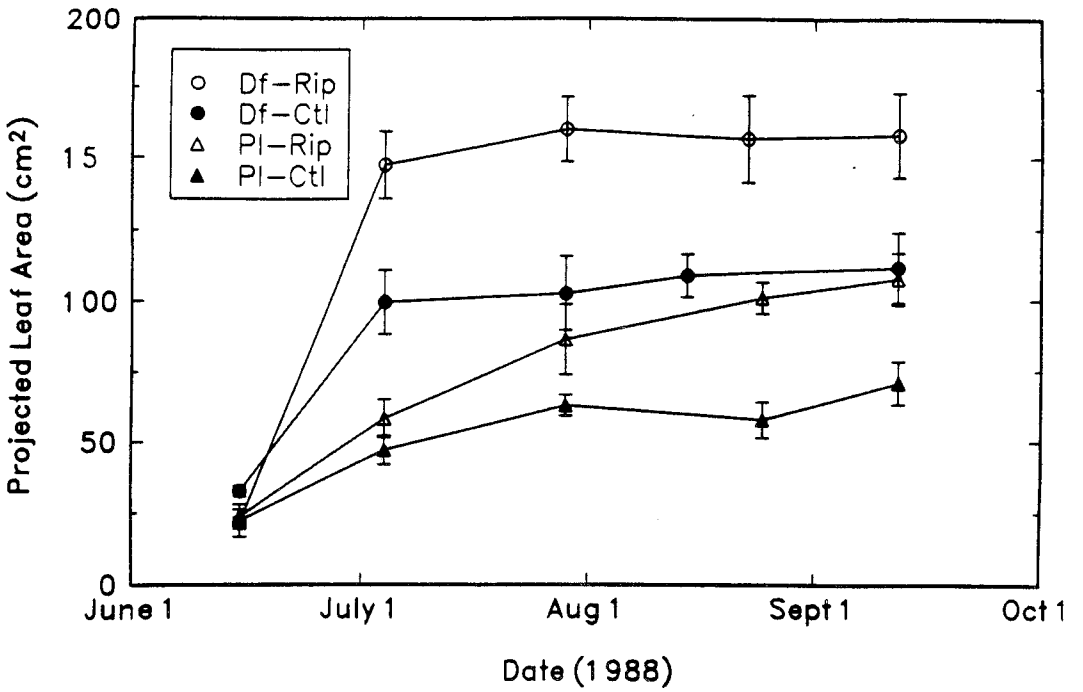

Fig. 2.8. Seasonal courses of projected leaf area of 1988 spring-planted Douglas-fir (Df) and lodgepole pine (Pl) in the control (Ctl) and the ripped (Rip) treatment during 1988. Shown are the mean and standard error for 6-12 seedlings per species per treatment sampled on a given date between June and September, 1988.

lodgepole pine A increased more slowly, but the increase was sustained for a longer period, particularly in the ripped treatment, through the development of long primary needles and the production of lammas and proleptic shoots (Kramer and Kozlowski 1979).

With both species there was a much larger increase in A in the ripped treatment than in the control, contributing to the divergence in Douglas-fir and lodgepole pine E_m between the ripped treatment and the control. The increase in E_{mr} in the ripped treatment as the summer progressed (Fig. 2.7*b*) was a function of continued increases in both lodgepole pine g_{sm} and A.

Rooting characteristics of the two species were also affected by site preparation. By late August Douglas-fir and lodgepole pine r_l and vertical root extension were substantially greater in the ripped treatment than in the control (Table 2.1). This may reflect the higher g_s and E in the ripped treatment which would likely be associated with greater net photosynthesis (Brix 1979) and, consequently, with an increased capacity for current season root growth (Van Den Driessche 1987; Philipson 1988). Unlike A, there was no significant difference ($p>0.10$) in r_l or vertical root extension between the two species within the control or the ripped treatment.

The two species showed similar relative responses in g_s and E to seasonally imposed water deficits, as evidenced by the lack of a distinct trend in summer g_{smr} and E_{mr} in the control. However, lodgepole pine took better advantage of favorable growing conditions, as evidenced by the rise in g_{smr} and E_{mr} in the ripped treatment as the summer progressed. The ability of lodgepole pine to increase water use and growth rates (Black et al. 1991) relative to Douglas-fir under favorable conditions may be an important factor allowing lodgepole pine to establish early dominance in

Table 2.1. Vertical root extension from the bottom of the plug and total length of new roots extending into the soil (r_1) in the first growing season after outplanting. Shown are mean values and corresponding standard errors (in brackets) for Douglas-fir and lodgepole pine seedlings harvested from the ripped treatment and the control between August 18 and August 25, 1988. There is no significant difference ($p > 0.10$) between mean values for each species with the same lower case letter in any given column using a two-tailed *t* test.

Species	Treatment	Vertical Root Extension (cm)	r_1 (cm)	Sample Size (seedlings)
Douglas-fir	Ripped	5.25b (0.95)	216.1b (43.9)	14
	Control	3.22a (0.79)	66.4a (22.2)	16
lodgepole pine	Ripped	5.00b (0.92)	214.8b (37.7)	16
	Control	2.61a (0.88)	47.0a (11.7)	20

mixed lodgepole pine-Douglas-fir stands in the Southern Interior. Greater consumption of soil water to promote growth, rather than high water use efficiency, represents optimum behavior in environments where soil water reserves are limited and there is strong competition between plants (Jones 1980; Passioura 1982).

B. First Growing Season Twig Xylem Pressure Potential

1. Predawn Values

Until late June, Ψ_{txb} of both species was considerably lower than Ψ_{m15}, reflecting the effects of planting stress (Grossnickle and Blake 1985; Örlander 1986; Rietveld 1989). Thereafter, Douglas-fir and lodgepole pine Ψ_{txb} was similar to but slightly lower than Ψ_{m15} and, as a result, Ψ_{txb} of both species was almost always lower in the control than in the site preparation treatments. Values of Ψ_{txb} rarely varied by more than 0.1 MPa among the different site preparation treatments on any given day.

2. Mid-morning Values

During both 1987 and 1988, Douglas-fir Ψ_{txm} was almost invariably lower ($p \leq 0.10$) than lodgepole pine Ψ_{txm} in the control or a particular treatment on a given day. Douglas-fir Ψ_{txm} values commonly varied from -1.6 to -2.2 MPa while those of lodgepole pine commonly varied from -1.0 to -1.8 MPa (Fig. 2.9).

Low Ψ_{txm} values for both species were found in the control during periods of drought (e.g., in early and late July of 1987). However, Douglas-fir Ψ_{txm} was often equally as low in both the control and site preparation treatments

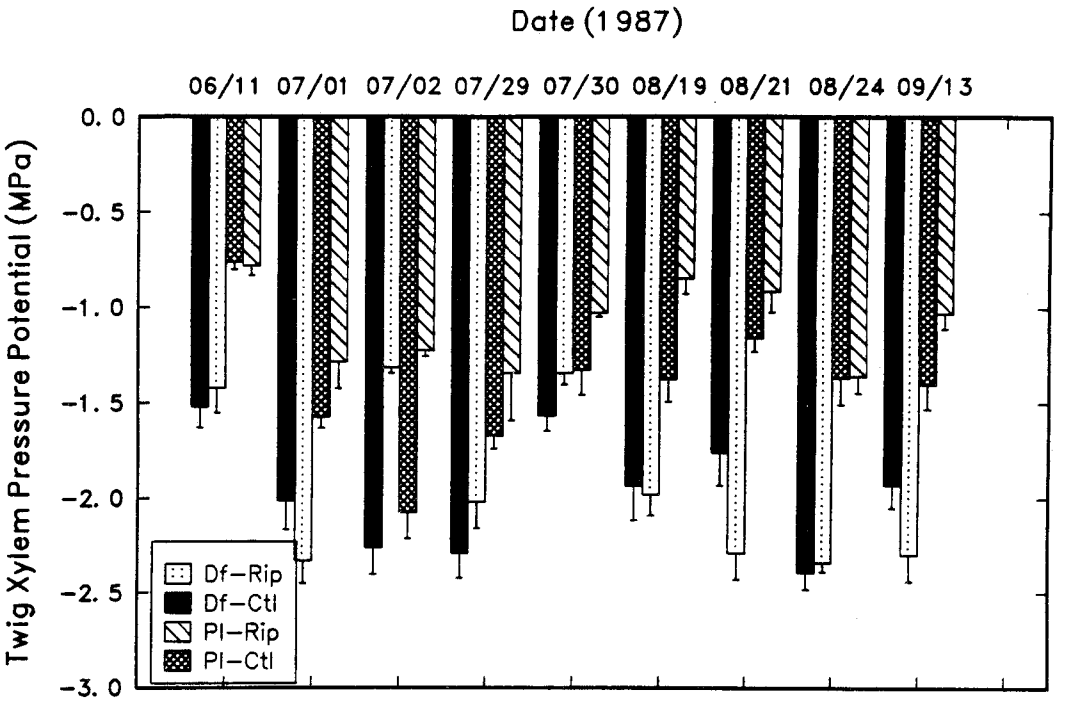

Fig. 2.9. Midmorning twig xylem pressure potentials of 1987 spring-planted Douglas-fir (Df) and lodgepole pine (Pl) in the control (Ctl) and the ripped treatment (Rip) on selected days during the 1987 growing season. Shown are the mean and standard error for four seedlings per species per treatment sampled on a given day.

on clear days with high D_s/P when soil water was plentiful. As a result, correlations between Douglas-fir Ψ_{txm} and Ψ_{m15} were relatively weak in both years (r=0.09, n=104 in 1987 and r=0.58, n=91 in 1988). In contrast, lodgepole pine Ψ_{txm} was almost always lower on a given day in the control than in the site preparation treatments, and correlations between Ψ_{txm} and Ψ_{m15} were stronger (r = 0.49, n = 94 in 1987 and r = 0.72, n = 87 in 1988).

Rearrangement of [Eq. 2] as $\Psi_{txm} = \Psi_{m15} - ER_{sp}$ demonstrates that both Ψ_{m15} and E_m affect Ψ_{txm}, and their relative effect is a function of their magnitude and the magnitude of R_{sp} (assuming it remains relatively constant). With Douglas-fir, high R_{sp} (see below), together with high E_m in the ripped treatment, combined to produce ψ_{txm} values in the ripped treatment as low as those in the control. With lodgepole pine, low R_{sp} resulted in higher Ψ_{txm} values in the ripped treatment than in the control, despite larger E_m in the ripped treatment.

Although Douglas-fir Ψ_{txm} values were often 0.7 - 1.2 MPa lower than those of lodgepole pine, the Douglas-fir seedlings remained vigorous and maintained adequate growth rates. Turgor maintenance mechanisms allow Douglas-fir to maintain positive turgor and achieve high growth rates at low Ψ_{tx}, particularly under recurrent drought conditions (Meinzer 1982; Livingston and Black 1987; Joly and Zaerr 1987).

C. First Growing Season Seedling Water Balance

1. Stomatal Conductance - Plant Water Potential

There was little relationship between g_{sm} and Ψ_{txm} for either species in 1987 (Fig. 2.10a). In 1988, apparent threshold g_{sm}-Ψ_{txm} relationships

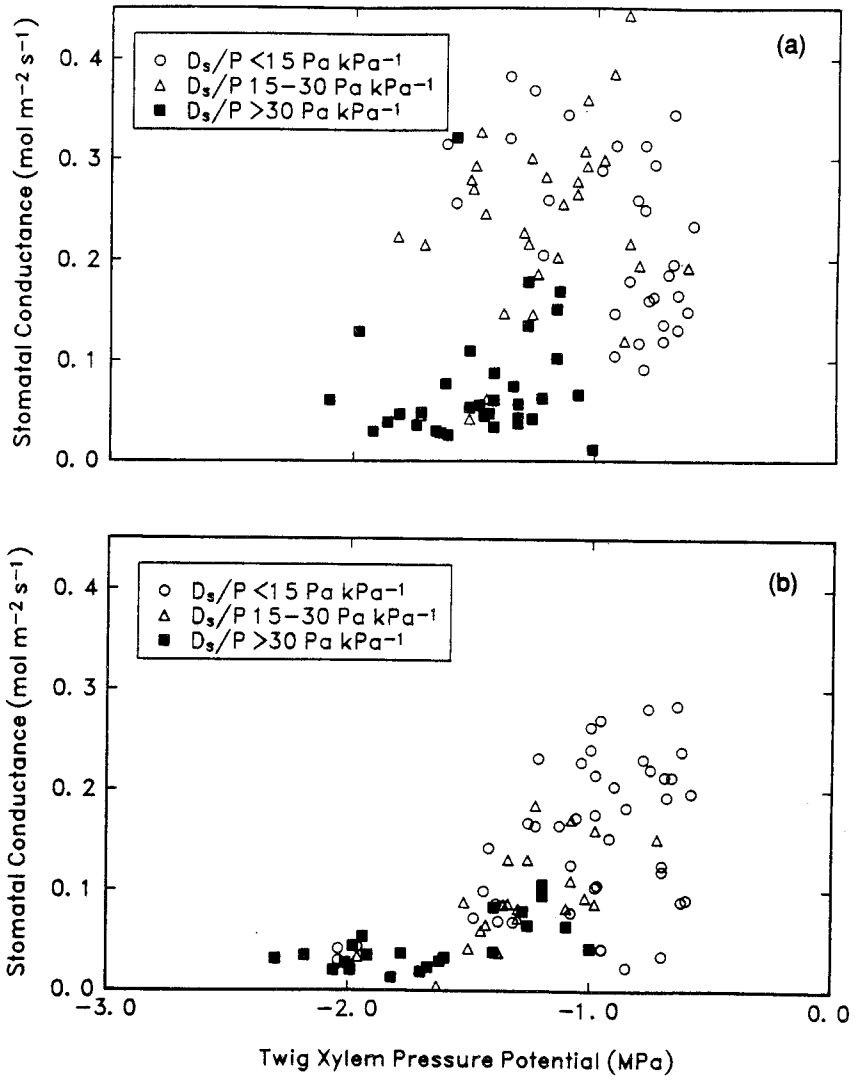

Fig. 2.10. Relationship between midmorning stomatal conductance and concurrent midmorning twig xylem pressure potential for spring-planted lodgepole pine for selected days in (*a*) 1987 and (*b*) 1988. Also shown are ranges of normalized vapor pressure deficit at seedling height (D_s/P) for each pair of measurements.

(Hinckley et al. 1978) were to a substantial degree accounted for by decreases in both g_{sm} and Ψ_{txm} in response to high D_s/P (Fig. 2.10*b*) (Turner et al. 1984). The latter interpretation supports the contention of Jones (1985) and Turner (1986) that g_s may play a greater role in determining Ψ_{tx} than vice-versa.

2. Stomatal Conductance - Rooting Egress

With Douglas-fir, large r_l and low A/r_l ratios were associated ($p \leq 0.10$) with high g_{sm}. As a result, Douglas-fir E_m tended to be higher for seedlings with large r_l, within a given range of D_s/P (Fig. 2.11). This was also true for E_{Am}, (i.e., E_m/A). With lodgepole pine, there were no significant relationships ($p>0.10$) between g_{sm} and r_l or A/r_l. Consequently the positive relationship found between E_m and r_l simply reflected increasing r_l with increasing A, and E_{Am} was not strongly correlated with r_l. More active stomatal function to balance water absorbing and transpiring surfaces may be more necessary for Douglas-fir than for lodgepole pine because of greater A, A/r_l and R_{sp} in Douglas-fir.

3. Liquid Flow Resistance

Douglas-fir R_{sp} was consistently greater ($p \leq 0.10$) than that of lodgepole pine in both the control and the ripped treatment throughout the summer (Fig. 2.12). Until midsummer Douglas-fir R_{sp} was higher ($p \leq 0.10$) in the control than in the ripped treatment, but by late summer R_{sp} in the control had fallen to levels resembling those in the ripped treatment. Lodgepole pine R_{sp} showed similar trends, although midsummer differences between the control and ripped treatment were less evident. These patterns likely

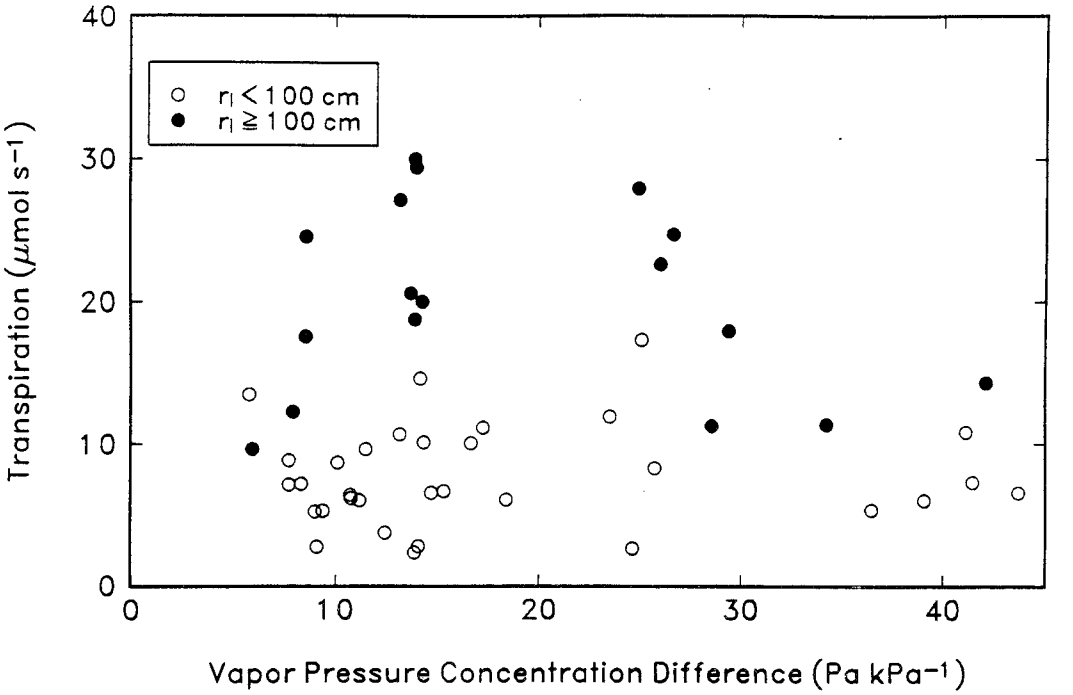

Fig. 2.11. Relationship between midmorning transpiration (E_m) and concurrent normalized vapor pressure deficit at seedling height (D_s/P) of 1988 spring-planted Douglas-fir for seedlings with: 1) $r_l \leq 100$ cm and 2) $r_l > 100$ cm for selected days in 1988 with $\theta_e > 0.30$.

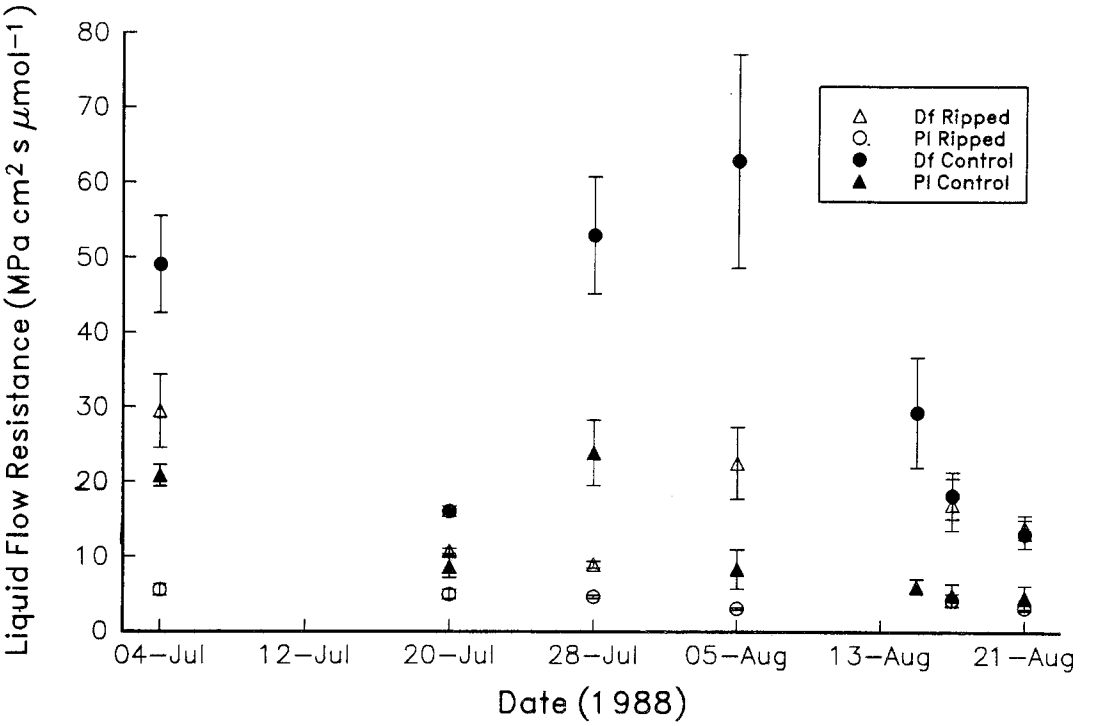

Fig. 2.12. Liquid flow resistances of 1988 spring-planted Douglas-fir and lodgepole pine seedlings in the control (Ctl) and the ripped treatment (Rip) for selected days in 1988. Shown are the mean and standard error for 4-12 seedlings per species per treatment sampled on a given day.

reflected markedly lower Ψ_{m15} in the control during periods of drought (i.e., early July and late July-early August, 1988), and considerable root extension together with higher Ψ_{m15} in the control later in August.

Douglas-fir and lodgepole pine R_{sp} showed weak positive correlations ($r \leq 0.55$) with Ψ_{m15} and Ψ_{txb} (cf. Eq. [2]). However, there were strong inverse relationships between R_{sp} and g_{sm} for both species, which were also influenced by D_s/P (Fig. 2.13). When R_{sp} was high, g_{sm} tended to be low, regardless of D_s/P. When R_{sp} was low, g_{sm} decreased substantially with increasing D_s/P. Much stronger relationships between g_s and R_{sp} than between g_s and Ψ_{tx} have also been reported by Küppers (1984), Meinzer et al. (1988) and Reich and Hinckley (1989).

These results support recent hypotheses that stomata respond directly or indirectly to changes in R_{sp} and vapor pressure deficit at the leaf surface (D_0) to maintain positive plant water balances (Meinzer et al. 1988; Meinzer and Grantz 1991). However R_{sp}, as calculated in this study (Eq. [2]), is a function of the experimentally determined values of g_s. Thus while the strong inverse relationship observed between g_s and R_{sp} may represent a functional link between root water status and stomatal behavior, it may be an artifact of the method of determining R_{sp}. Nevertheless, it is axiomatic that plant liquid and vapor phase resistances be strongly interrelated. A quasi-equilibrium state between these two resistances is necessary to maintain plant growth while avoiding excessive drops in plant water potential.

Analysis of stomatal response of Douglas-fir and lodgepole pine to environmental conditions (Chapter 3) has shown greater Douglas-fir stomatal sensitivity to changes in D_s/P and greater lodgepole pine stomatal

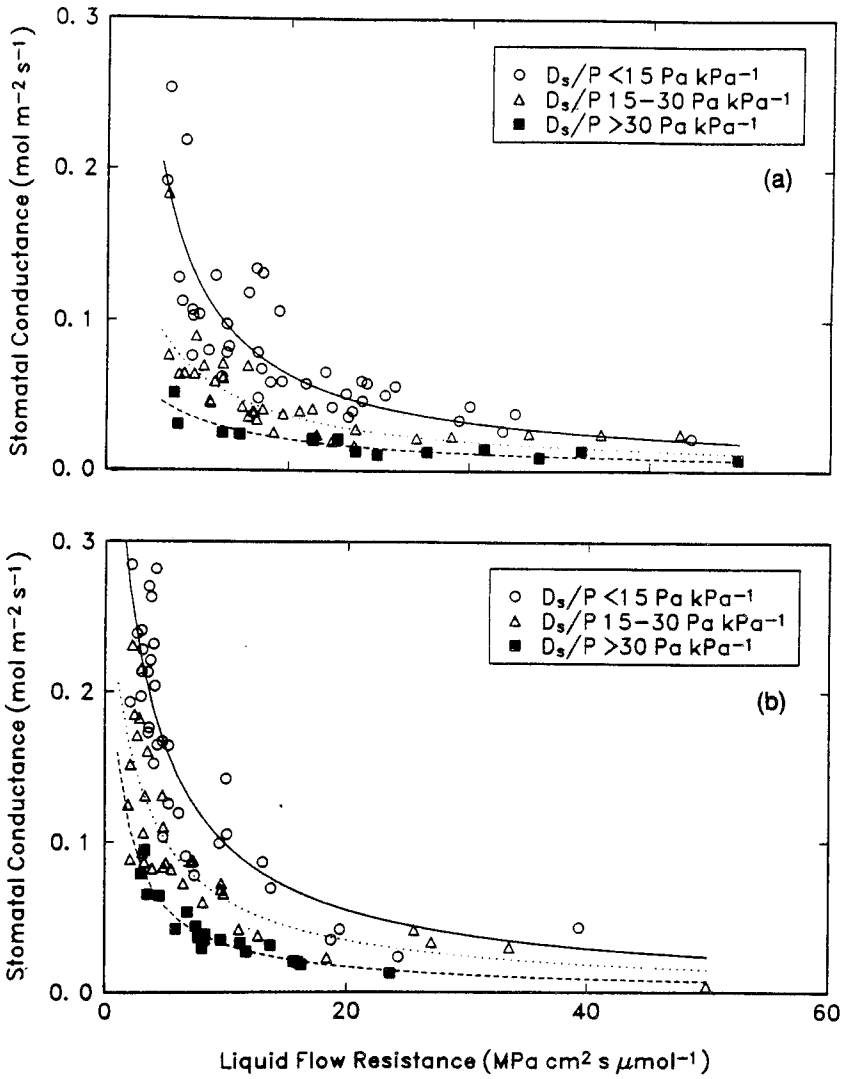

Fig. 2.13. Relationship between midmorning stomatal conductance and concurrent liquid flow resistance of (*a*) 1988 spring-planted Douglas-fir and (*b*) 1988 spring-planted lodgepole pine in both the control and site preparation treatments for selected days during the 1988 growing season. Also shown are best-fit curves ($g_s = 1/(K_1 + K_2R_{sp})$ for three categories of normalized vapor pressure deficit at seedling height (D_s/P) for each data set.

sensitivity to changes in Ψ_{m15}. The above results are consistent with Turner's (1986) suggestion that species with higher plant resistance to water flow (e.g., Douglas-fir) should demonstrate greater stomatal sensitivity to D_0 and less stomatal sensitivity to Ψ_m than species with lower plant resistance to water flow (e.g., lodgepole pine) because axial plant resistances will decrease leaf turgor more than root turgor.

D. First Growing Season Seedling Growth

1. Seedling Survival, Height Increment and Root Collar Cross-sectional Area

There were no significant differences ($p > 0.10$) in Douglas-fir or lodgepole pine first growing season survival among the control and all site preparation treatments in either 1987 or 1988. Douglas-fir survival exceeded 94% in the control and all treatments in both years, while lodgepole pine survival ranged from 86% to 96% among the control and treatments in 1987, and exceeded 95% in the control and all treatments in 1988.

Lodgepole pine first growing season height increment exceeded ($p \leq 0.10$) that of Douglas-fir but site preparation had no significant effect ($p > 0.10$) on height increment in 1987 (Table 2.2) and 1988. However in 1987 there was a significant species-treatment interaction ($p=0.01$), and one way ANOVA revealed that lodgepole pine height increment was smaller in the scalped treatment than in the herbicide treatment or control.

Douglas-fir root collar cross-sectional area exceeded ($p \leq 0.10$) that of lodgepole pine, and root collar cross-sectional area was greater for both species in the site preparation treatments than in the control in 1987 (Table 2.3) and 1988. However, differences in root collar cross-sectional

Table 2.2. Analysis of variance of first growing season Douglas-fir (Df) and lodgepole pine (Pl) height increment (cm) at the IDFdk, by species and site preparation treatment. Seedlings were planted May 12, 1987 and assessed September 11, 1987. There is no significant difference ($p > 0.10$) between mean values with the same lower case letter in any given row using one way ANOVA and Newman-Keuls multiple comparison test).

Source	df	Sum of Squares	*F*-Ratio	*P* > *F*
Species	1	76.13	152.98	0.000
Treatment	3	2.54	1.70	0.207
Species x Treatment	3	7.96	5.33	0.010
Error	16	7.96		

Height Increment (cm)

Species	Site Preparation Treatment			
	Control	Herbicide	Scalped	Ripped
Df	1.6a	2.5a	2.9a	2.5a
Pl	6.5b	6.8b	4.7a	5.7ab

Table 2.3. Analysis of variance of first growing season Douglas-fir (Df) and lodgepole pine (Pl) root collar cross-sectional area (cm^2) at the IDFdk, by species and site preparation treatment. Seedlings were planted May 12, 1987 and assessed September 11, 1987. There is no significant difference ($p > 0.10$) between mean values with the same lower case letter in any given row using one way ANOVA and Newman-Keuls multiple comparison test.

Source	df	Sum of Squares	*F*-Ratio	*P* > *F*
Species	1	0.00501	11.26	0.004
Treatment	3	0.01041	7.80	0.002
Species x Treatment	3	0.00029	0.22	0.881
Error	16	0.00712		

	Root Collar Cross-sectional Area (cm^2)			
Species	Site Preparation Treatment			
	Control	Herbicide	Scalped	Ripped
Df	0.13a	0.19b	0.18b	0.19b
Pl	0.11a	0.15b	0.15b	0.16b

areas among site preparation treatments were usually not significant ($p > 0.10$) for either species. Flint and Childs (1987) also reported greater initial seedling response in root collar diameter than in height increment to site preparation treatments which increased soil water supply.

2. Dry Matter Production and Allocation

Douglas-fir had greater seedling shoot, root and total dry matter ($p \leq 0.10$) but not needle dry matter than lodgepole pine at the end of the first growing season in 1987 (Tables 2.4 and 2.5) and 1988. Both species had greater needle, shoot and total dry matter and lower root/shoot dry matter ratios ($p \leq 0.10$) in the site preparation treatments than in the control. Total root dry matter was not significantly different ($p > 0.10$) among the control and the site preparation treatments despite differences in r_1 because of the large size and variability in initial plug root mass.

There were no significant differences ($p > 0.10$) in first growing season dry matter among site preparation treatments for Douglas-fir in 1987 (Table 2.6) and 1988. However, in 1987 lodgepole pine had greater ($p \leq 0.10$) needle and root dry matter in the ripped treatment than in the scalped and herbicide treatments, and greater shoot and total dry matter in the ripped treatment than in the herbicide treatment.

These growth responses are consistent with the seasonal trends in g_{sm} and E_m outlined earlier. Substantial improvements in seedling gas exchange and growth were achieved by controlling competing vegetation. The three major types of site preparation employed, scalping, ripping and herbicide, usually resulted in similar improvements in soil water supply, seedling water relations and first year seedling growth for both species. However, there is

Table 2.4 Analysis of variance of first growing season Douglas-fir (Df) and lodgepole pine (Pl) needle and shoot (needles + stem) dry matter (g) at the IDFdk, by species and site preparation treatment. Seedlings were planted May 12, 1987 and harvested September 11, 1987.

Source	df	Sum of Squares	*F*-Ratio	*P* > *F*
		Needle		
Species	1	0.4406	1.16	0.2855
Treatment	3	14.3996	12.67	0.0000
Species x Treatment	3	0.8289	0.73	0.5388
Error	56	21.2149		
		Shoot		
Species	1	4.8841	5.29	0.0252
Treatment	3	30.2852	10.93	0.0000
Species x Treatment	3	2.1257	0.77	0.5174
Error	56	51.735		

Table 2.5. Analysis of variance of first growing season Douglas-fir (Df) and lodgepole pine (Pl) root and total dry matter (g) and root/shoot dry matter ratio at the IDFdk, by species and site preparation treatment. Seedlings were planted May 12, 1987 and harvested September 11, 1987.

Source	df	Sum of Squares	*F*-Ratio	*P* > *F*
		Root		
Species	1	3.9353	5.58	0.0216
Treatment	3	1.3234	0.63	0.6013
Species x Treatment	3	2.7171	1.29	0.2885
Error	56	39.4695		
		Root/Shoot Ratio		
Species	1	0.1196	0.75	0.3902
Treatment	3	1.0899	2.28	0.0896
Species x Treatment	3	0.5717	1.19	0.3202
Error	56	8.9340		
		Total		
Species	1	17.5875	7.92	0.0067
Treatment	3	41.5479	6.24	0.0010
Species x Treatment	3	7.4091	1.11	0.3519
Error	56	124.3478		

Table 2.6. First growing season Douglas-fir and lodgepole pine needle, shoot (needles + stem), root and total dry matter (g), and root/shoot dry matter ratio in the control and site preparation treatments. Seedlings were planted May 12, 1987 at the IDFdk and harvested September 11, 1987. There is no significant difference ($p > 0.10$) between mean values with the same lower case letter in any given row using one-way ANOVA and Newman-Keuls multiple comparison test.

Treatment and Species

	Douglas-fir			
Dry Weight (g)	Control	Herbicide	Scalped	Ripped
Needles	0.82a	1.51b	1.93b	1.82b
Shoot	1.99a	3.28b	3.71b	3.53b
Root	2.06a	1.65a	1.61a	1.83a
Root/shoot Ratio	1.07a	0.51b	0.42b	0.53b
Total	4.05a	4.93b	5.32b	5.36b

	Lodgepole Pine			
Dry Weight (g)	Control	Herbicide	Scalped	Ripped
Needles	0.59a	1.32b	1.64b	2.13c
Shoot	1.48a	2.49b	2.88bc	3.64c
Root	0.87a	1.24a	1.29a	1.89b
Root/shoot Ratio	0.60a	0.54a	0.46a	0.56a
Total	2.36a	3.73b	4.16bc	5.53c

some indication that ripping may further enhance seedling growth, perhaps by increasing soil water or nutrient supply indirectly as a result of greater seedling root development (Wittwer et al. 1986).

IV. CONCLUSIONS

Lodgepole pine had substantially greater first growing season g_s and E than Douglas-fir in the site preparation treatments, where competing vegetation was eliminated and soil water was plentiful. In the control, where competing vegetation was abundant and soil water supply was restricted, both species showed large reductions in g_s, A and E. Douglas-fir consistently maintained lower Ψ_{txm} and higher R_{sp} than lodgepole pine, but despite this both species maintained healthy transpiration and growth rates in the site preparation treatments. Neither species showed a consistently strong g_{sm} response to Ψ_{txm}.

These findings support the contention of Minore (1979) and Lassoie et al. (1985) that the two species have similar drought resistance, but also suggests that this is achieved in different ways. Following Turner (1986), lodgepole pine achieves drought tolerance at relatively high plant water potentials (dehydration postponement), and low R_{sp} is a major factor contributing to this ability. In contrast, Douglas-fir achieves drought tolerance at relatively low plant water potentials (dehydration tolerance), and turgor maintenance mechanisms are an important adaptation of this species (Joly and Zaerr 1987; Livingston and Black 1987).

Effects of site preparation on the water relations and growth of Douglas-fir and lodgepole pine largely reflected increased soil water supply

resulting from the control of competing vegetation. Treatment effects on other factors such as air and soil temperature, and mineral nutrition appeared to have relatively little impact on first growing season seedling response.

The longer-term effects of these site preparation treatments on seedling response remain to be demonstrated. In some studies the greatest seedling response to weed control which alleviated water stress occurred soon after planting (Sands and Nambiar 1984). In other studies planted seedlings have shown continued and even increased response through to canopy closure (Cole and Newton 1987; Newton and Preest 1988). As the stands develop, microclimatic differences between treatments will be moderated while nutritional demands will increase (Morris and Lowery 1988). As a result, site preparation effects on nutrient availability may not be fully reflected in tree growth until a later stage of stand development.

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CHAPTER 3

STOMATAL CHARACTERISTICS OF RECENTLY PLANTED DOUGLAS-FIR AND LODGEPOLE PINE SEEDLINGS

STOMATAL CHARACTERISTICS OF RECENTLY PLANTED DOUGLAS-FIR AND LODGEPOLE PINE SEEDLINGS

I. INTRODUCTION

Stomata play an essential regulatory role in the growth and development of plants by controlling the rates of water loss and CO_2 uptake. They act to maintain healthy plant water status and carbon assimilation rates by responding to small changes in the aerial and soil environment (Mansfield and Davies 1985; Jarvis and McNaughton 1986). These responses are governed directly by phytohormone control and indirectly by hydroactive feedback mechanisms (Schulze 1986; Davies and Zhang 1991).

It is still not possible to construct rigorous, widely applicable mechanistic models of stomatal function (Jones and Higgs 1989). Increased emphasis is being placed on causal relationships between stomatal response and photosynthetic rates to gain understanding of fundamental physiological processes (Carlson 1991). However, the resulting conductance models are still largely empirical (Farquhar and Wong 1984; Ball et al. 1987; Collatz et al. 1991) and assumptions involving optimization of carbon gain versus water loss (Cowan 1977) have not been widely verified for conifers (Sanford and Jarvis 1986; Guehl and Aussenac 1987).

There is widespread demand for simple phenomenological models which accurately predict stomatal or canopy conductance as a function of readily measured or modeled environmental factors. Such models, while empirical by nature, incorporate simplified functions which account for known

physiological processes (Kaufmann 1989). Current applications in forestry-related fields include prediction of evapotranspiration and stand growth (Jarvis et al. 1985; Kaufmann 1989), modeling of site water balances and hydrology (Black and Spittlehouse 1981) and use in silvicultural decision support systems (Wagner et al 1989; Spittlehouse and Childs 1990).

One area of particular interest to silviculturists and tree physiologists is the role of stomata in maintaining healthy plant water relations during seedling establishment. Following timber harvest, forest sites often experience wide variations in surface microclimate and rapid vegetation ingress. Under these conditions, seedling water stress is often considered one of the principal factors limiting reforestation success (Kozlowski 1982; Burdett 1990). Conductance models would aid in the selection of silvicultural systems, site preparation techniques and planting stock best suited for reforesting particular sites.

The objectives of this paper are: 1) to investigate the stomatal response of recently planted Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) and lodgepole pine (Pinus contorta Dougl.) seedlings to environmental conditions on a grass-dominated clearcut in the dry Southern Interior (Interior Plateau) of British Columbia, 2) to evaluate several phenomenological models to describe these relationships, and 3) to examine the effects of site preparation, time since planting and year of measurement on these responses.

II. EXPERIMENTAL METHODS

A. Site Description

The experimental site was a pinegrass (Calamagrostis rubescens Buckl.) dominated clearcut in the Interior Douglas-fir (IDFdk) Biogeoclimatic Subzone (Thompson Plateau-Very Dry Montane Interior Douglas-fir variant) of southern British Columbia (Mitchell et al. 1981). It is located near Fehr Mountain, 40 km west of Kamloops (50°40′ N, 120°20′ W), at an elevation of 1220 m and falls within the Pseudotsuga-Calamagrostis habitat type of McLean (1970). The mean annual precipitation is about 400 mm (Mitchell et al. 1981), while the mean growing season precipitation (May 1 - August 31) from 1986 to 1989 was 192 mm (Chapter 1).

Pinegrass accounted for about 70% of the total vegetative cover, which was comprised almost entirely of herbaceous plants. The mean herbaceous leaf area index over the growing season was 0.56 and reached a maximum value of about 1.00 in mid July (Adams et al. 1991). On these and similar sites, herbaceous vegetation often competes vigorously with tree seedlings for soil water (McLean and Clark 1980; Petersen and Maxwell 1987).

The soil was an Orthic Gray Luvisol and consisted of 20-30 cm of gravelly silt loam overlying a compact clay loam basal till. A thin organic layer (4-6 cm) covered the mineral soil. The site was level and well drained with a few small drainage depressions. The previous lodgepole pine-Douglas-fir stand was clearcut in 1982.

B. Experimental Layout

Site preparation (ripping) was carried out in the fall of 1986 and 1987 and involved creation of 20 x 5 m ripped strips for physiological studies. First the top 5-10 cm of soil, including the organic horizons, were scalped off with the straight blade of a Caterpillar D8 crawler tractor. Then several passes were made over the scalped areas with flanged ripper teeth mounted on a drawbar immediately behind the tracks of the tractor (Coates and Haeussler 1987). These teeth penetrated the soil to a depth of about 50 cm and the treatment resulted in ripper tooth paths spaced 0.3-0.5 m apart. Subsequently, the upper 25 cm of the soil was thoroughly mixed and then leveled with shovels and rakes. Vegetation ingress in the ripped plots was controlled with spot applications of the herbicide glyphosate (*N*-(phosphonomethyl)glycine) at 30 ml active ingredient/100 m^2 during the growing season.

Both the control and ripped plots were planted in early May with 60 1 - 0 Douglas-fir 3 - 13 plug stock and 60 1 - 0 lodgepole pine 2 - 12 plug stock, set out in alternating rows of 30 seedlings of a given species. In 1989 additional measurements were made on drought stressed lodgepole pine planted in ripped and control treatments within a rainout shelter (Appendix III).

C. Measurements

1. Microclimate

An automated climate station, consisting of a data logger (Campbell Scientific Inc., Logan, UT, 21X micrologger) and associated sensors, was located at the site. Half-hour or hourly mean values of solar irradiance (R_s)(LI-COR Inc., Lincoln, NB, Model LI200S silicon cell pyranometer) and

soil temperature (Fenwall Electronics, Framingham, MA, Model UUT-51J1 thermistors potted in Armstrong C7 epoxy, configured as in the Campbell Scientific Inc., Model 101 thermistor probe), as well as other measurements, were collected throughout the 1987-1989 growing seasons. Measurements of ambient air temperature and relative humidity (*RH*) at seedling height were made with a porometer (described below), and used to calculate seedling height vapor pressure deficit (D_s), normalized with respect to atmospheric pressure (P) (i.e., D_s/P). Normalized vapor pressure is identical to the mole fraction of water vapor (mol of water vapor per mol of all gases).

2. Soil Water

Within plots, weekly measurements of volumetric soil water content (θ) were made at depths of 19 (θ_{19}) and 34 (θ_{34}) cm with a neutron meter (Campbell Pacific Nuclear Corp., Martinez, CA, Model 503 Hydroprobe). For this purpose, three to five neutron tubes were installed in each treatment using holes initially dug with a power auger and undersized bit, and enlarged with a hand auger. Additional neutron meter estimates of θ were available from a series of tubes installed in microclimate plots nearby (Chapter 1).

Soil matric potentials (Ψ_m) were determined in the field with tensiometers and thermocouple psychrometers (assuming negligible solute potential) at a depth of 15 cm (Ψ_{m15}). The tensiometers were read with a pressure transducer (Soil Measurement Systems, Tucson, AR, Model SW-010 Tensimeter) while individually calibrated screen cage thermocouple psychrometers (J.R.D. Merrill Speciality Equipment, Logan, UT, 74 series) were read with a microvoltmeter (Wescor Inc., Logan UT, Model HR-33T) or a

data logger (Campbell Scientific Inc., Logan, UT, Model CR7X) equipped with Campbell Scientific Inc. Model A3497 Cooling Current Interfaces and software. Thermocouple psychrometer readings were taken between 7:00 and 10:00 PST, when vertical soil temperature gradients were smallest (Appendix II). The calibration model of Brown and Bartos (1982) was used to determine Ψ_m from thermocouple psychrometer soil temperature, zero-offset and microvolt output readings.

These data were used to generate field retention curves with the equation of Van Genuchten (1980). This allowed for: 1) prediction of Ψ_{m15}, and 2) determination of root zone extractable water ($\theta_e=(\theta_{19}-\theta_{min})/(\theta_{max}-\theta_{min})$, where θ is the actual water content, θ_{max} is the volumetric water content at field capacity (Ψ_{m15}=-0.03 MPa), θ_{min} is the residual water content ($\Psi_{m15}\leq$-2.0 MPa) and $\theta_e\leq$1.0. Further details on soil water measurements, including instrument construction, calibration and use, are reported in Chapter 1 and Appendices I and II.

3. Stomatal Conductance

Seedling stomatal conductance (g_s) was measured over a 30 s period with a Micromet Systems Inc., Vancouver, B.C., Model CS-102 conifer seedling porometer (Chapter 2; Livingston et al. 1984). This transient-type ventilated porometer encloses the entire shoot and provided integrated values of g_s for the entire seedling over a 30 s measurement period. The instrument calculates g_s (cm s^{-1}) from the rate of increase in vapor density in the porometer chamber, the assumed projected leaf area of the seedling (A) and the instantaneous saturation deficit (D, g cm^{-3}) in the chamber. Values of g_s were corrected to reflect the actual projected leaf area of

each seedling once this was determined, and were converted to mole units using g_s (mol $m^{-2}s^{-1}$) = g_s(cm s^{-1})P/RT where $P \cong 89.1$ kPa, R is the gas constant (8.3145 J mol^{-1} K^{-1}) and T is the absolute temperature (K).

The accuracy of porometer measurements of seedling water flux was determined using filter paper discs 6-18 mm in diameter attached to a small water-filled pipette (LI-COR Inc., Lincoln, NB). These were inserted into the chamber to provide different evaporation rates. The accuracy of g_s measurements was about 0.001 mol m^{-2} s^{-1} for water vapor fluxes ranging from 0.8 to 7.0 μmol s^{-1}.

The porometer was stored in the shade between readings and shaded whenever possible during readings. Measurements were not made before dew or rain had completely evaporated from the leaf surfaces or when relative humidities exceeded 85% (McDermitt 1990). The humidity sensor (Vaisala Inc., Woburn, MA, Humicap Model 6064) was calibrated with a dewpoint hygrometer (EG and G International Inc., Waltham, MA, Model 880) each spring using a range of dewpoint temperatures, and was replaced twice during the three years.

In the field, individual seedlings were continually measured over a one-to-two week period and then harvested immediately. This was necessary to prevent confounding by changes in leaf area either during the measurement period or subsequently. Needles were stored at 2 - 4 °C until projected leaf areas could be measured with a leaf area meter (LI-COR Inc., Lincoln, NB, Model 3000/3050-A). Conductance measurements were made at various times during the day and over the growing season to cover as large a portion of the variable space for each environmental variable as possible (Reed et al. 1976). Yearly data files were constructed for each species, with each record

consisting of a mean conductance value (expressed on a projected leaf area basis) based on measurements of three to four seedlings in a given treatment taken within 30 min of each other, and associated environmental conditions.

D. Models of Stomatal Conductance

Stomatal response is often evaluated in terms of physiological responses to photosynthetic photon flux density (Q_p), vapor pressure deficit at the leaf surface, normalized with respect to atmospheric pressure (D_0/P, where D_0 is the vapor pressure deficit at the leaf surface), leaf and soil temperature (T_l and T_s, respectively), ambient CO_2 concentration, and soil water supply (θ_e or Ψ_m) (Jarvis 1976; Turner 1991). Global solar irradiance (R_s), can be used as a surrogate variable for Q_p since the former is linearly related to the latter (Meek et al. 1984). Likewise, T_l and D_0/P can be replaced by ambient seedling height air temperature (T_a) and D_s/P, respectively, because of large conifer needle boundary layer conductances (Grace et al. 1975; Dixon and Grace 1984).

In this study, three phenomenological models of stomatal response were compared: 1) a multiplicative model derived from boundary line functions fitted by eye (MBL)(Livingston and Black 1987), 2) a multiplicative model employing non-linear least squares optimization of response functions (NLLS) (Reed et al. 1976), and 3) a limiting function model derived from boundary line functions fitted by eye (LFBL) (Price and Black 1989). Boundary line functions for each environmental variable were determined by first constructing a scatter diagram of g_s versus the variable of interest. Mathematical functions with appropriate parameterization were then used to describe a line defining the upper boundary of the scatter of points across

the variable space. This upper boundary was taken to represent stomatal response to the particular environmental variable when other variables were not limiting (Webb 1972).

The MBL and NLLS approaches are derived from a multiplicative phenomenological model proposed by Jarvis (1976) which describes g_s as a function of several environmental variables. It is assumed that g_s responds to each environmental variable independently and in multiplicative fashion (with the exception of the error term ε which is additive (Reed et al. 1976)) such that:

$$g_s(R_s, D_s/P, T_a, \cdots) = g_{smax} f_1(R_s) f_2(D_s/P) f_3(T_a) \cdots + \varepsilon \qquad (1)$$

where g_{smax} represents the mean maximum seasonal value of conductance when environmental conditions are not limiting. Thus the combined effect of all environmental stresses is equal to the product of the limitations imposed by each stress, i.e., the limiting factors are of the Mitscherlich type and no synergistic, antagonistic or additive effects are present (Wallace 1989).

In contrast, the LFBL approach of Price and Black (1989) assumes the principle limiting environmental factors operate in a Liebig manner; response to other factors is arrested or greatly limited until the most limiting condition is relieved (Wallace 1989). This may be written as:

$$g_s(R_s, D_s/P, T_a, \cdots) = g_{smax} \text{ minimum } \{f_1(R_s),\ f_2(D_s/P),\ f_3(T_a), \cdots\} \qquad (2)$$

In all models, conductance values were normalized by dividing g_s by an appropriate g_{smax} for the data set in question (Jones and Higgs 1989).

E. Response Functions

The mathematical functions describing the relationship between g_s and individual environmental variables were chosen by comparing commonly reported response curves with scatter plots of the field data (Jarvis 1976). Parameter values for these functions were evaluated using boundary line curves fitted by eye (MBL and LFBL) and response functions determined by NLLS using the three term multiplicative model:

$$g_s/g_{smax} = f_1(R_s)f_2(D_s/P)f_3(\theta_e) \tag{3}$$

Stomatal response to solar irradiance was represented with an exponential function (Eq. [3]) (Jones 1983; Reid et al. 1983):

$$f_1(R_s) = 1-\exp(-K_1R_s) \tag{4}$$

where K_1 is an experimentally determined parameter. Equation [4] was preferred over a hyperbolic function representing a Michaelis-Menten type reaction (Collatz et al. 1991; Massman and Kaufmann 1991) because the former provided for a steeper initial increase and more rapid achievement of maximum g_s, in accordance with the field measurements.

The sigmoidal function of Livingston and Black (1987) was used to describe stomatal response to D_s/P:

$$f_2 = 1/(1 + ((D_s/P)/(D_{0.5}/P))^{K_2}) \tag{5}$$

where $D_{0.5}/P$, the value of D_s/P when g_s is half the maximum, and K_2 are experimentally determined parameters. This equation describes the characteristic g_s - D_s/P relationship found with conifers: an initial response plateau at low D_s/P, a region of maximum decrease in g_s with increasing D_s/P, and an asymptotic approach to full stomatal closure at high D_s/P (Waring and Franklin 1979; Sandford and Jarvis, 1986).

Sigmoidal functions were used to represent the effects of θ_e and Ψ_{m15} on g_s:

$$f(\theta_e) = 0.05 + 0.95\ (1/(1 + \exp(-100(\theta_e - K_3))))^{K_4} \tag{6}$$

$$f(\Psi_m) = (1-Z)^{K_5 Z^{K_6}} \tag{7}$$

where $Z = \Psi_m/\Psi_{min}$, Ψ_{min} is a minimum soil matric potential (-2.0 MPa) below which there is no further decline in g_s, and K_3 - K_6 are experimentally determined parameters.

The relationship between g_s and T_a was represented with the function of Reed et al. (1976):

$$f_3(T_a) = (T-T_L)(T_H-T)^{K_7}/[(T_O-T_L)(T_H-T_O)^{K_7}] \tag{8}$$

where $K_7 = (T_H-T_O)/(T_O-T_L)$ and defines the skew about the optimum temperature value (T_O), T_L is the low temperature limit and T_H is the high temperature limit for stomatal response. Values for T_L and T_H were treated either as variables, or set at 0 and 40°C, respectively.

The relationship between g_s and time since sunrise (t) (Leverenz et al. 1982; Livingston and Black 1987) was described with a third order polynomial which allowed for maximum g_s early in the day, and an increasing rate of stomatal closure as the day progressed:

$$f(t) = 1-K_8t^3 \tag{9}$$

where K_8 is an experimentally determined parameter.

F. Model Comparisons

With the MBL and LFBL approaches, model parameters were determined iteratively. After the first estimates of the parameters were chosen by eye to fit the appropriate functions to each environmental variable, either the resulting equations were multiplied together (MBL) or the lowest value calculated by any of the equations was chosen (LFBL) to provide estimates of g_s/g_{smax}. Parameter values were then readjusted iteratively to determine whether a better MBL or LFBL fit could be achieved while maintaining

reasonable boundary lines. Goodness-of-fit was evaluated using the standard error of the estimate (SEE), the slope and R^2 of the linear regression passing through the origin (b') of the observed on the predicted values of g_s/g_{smax}, and residual analysis using plots of residual values against both predicted values and environmental variables (Reed et al. 1976; Kaufmann 1982).

With the NLLS approach, derivative - free nonlinear regression based on a least squares pseudo-Gauss-Newton iterative algorithm (Ralston 1988), was used to determine parameter estimates for the different functions. Initial parameter estimates were chosen by inspection of scatter plots as described above. Goodness-of-fit for different combinations of functions (Eq. [4-9])) was then determined by examining the SEE, the standard errors of the parameter values, the pseudo R^2 (1-[weighted residual SS/{(N-1) weighted variance}]), and residual analysis as described above.

The best-fit MBL, LFBL and NLLS models were evaluated and compared for each year and species using the means and standard deviations of the predicted values; the intercept, slopes and R^2 of the best-fit linear regressions of the observed on the predicted values of g_s/g_{smax}; and the root mean square error (RMSE) together with the magnitude of its systematic ($RMSE_s$) and unsystematic ($RMSE_u$) components (Willmott 1982). Subsequently, the robustness and veracity of the NLLS models were tested by comparing measured g_s with modeled g_s for each species based on parameter values determined for different years. Each data set was scaled using an appropriate g_{smax} value (Thorpe et al. 1980; Jones and Higgs 1989). The NLLS models were also used to investigate stomatal response separately in the control and ripped treatment.

Transpiration flux densities (E_A), corresponding to the times at which g_s was measured, were calculated as:

$$E_A = g_s D_s / P \tag{10}$$

This makes the assumption, discussed previously, that g_b is large enough that D_s/P provides a good approximation of D_0/P (Livingston and Black 1987; McDermitt 1990). Daily transpiration flux densities (E_{Ad}) (μmol $m^{-2}d^{-1}$) and mean daily stomatal conductance (G_s) (mol $m^{-2}s^{-1}$) were calculated from measured and modeled g_s values for 11 days in both 1987 and 1988, and for nine days in 1989. Measurements made at two hour intervals from early morning until sunset were used to calculate E_{Ad} as $\sum_{i=1}^{n} E_i$ and G_s as $\sum_{i=1}^{n} g_{si}/n$, where n is the number of measurements. Modeled values of G_s and E_{Ad} were calculated as above, but using modeled (Eq. [3]) rather than measured values of g_s as inputs.

III. RESULTS AND DISCUSSION

A. Stomatal Response to Environmental Variables

1. Seasonal Mean Maximum Stomatal Conductance

Values of g_{smax} ranged from 0.17 to 0.19 mol $m^{-2}s^{-1}$ for Douglas-fir and from 0.30 to 0.32 mol $m^{-2}s^{-1}$ for lodgepole pine (Table 3.1). The Douglas-fir values are similar to those reported for this species by Tan et al. (1977), Murphy and Ferrell (1982) and Livingston and Black (1987), while the lodgepole pine values are somewhat higher than those reported for this species by Dykstra (1974) and Smith et al.(1984). As in this study, Smith et

Table 3.1. Goodness-of-fit of the NLLS, MBL and LFBL models for the different data sets. Shown are the sample size (n), the seasonal mean maximum stomatal conductance (g_{smax}), the mean observed ($\bar{O}$) and predicted ($\bar{P}$) relative conductance (g_s/g_{smax}) and their associated standard deviations ($SD\bar{O}$ and $SD\bar{P}$), the intercept (a) and slopes (b and b') of the best fit equations $\hat{O}_i = a + bP_i$ and $\hat{O}_i = b'P_i$, and the root mean square error (RMSE) with its systematic ($RMSE_s$) and unsystematic ($RMSE_u$) components.

Data Set (control and ripped treatment combined)

Model	$\bar{O}$	$SD\bar{O}$	$\bar{P}$	$SD\bar{P}$	a	b	b'	RMSE	$RMSE_s$	$RMSE_u$
Douglas-fir 1987, n=160, g_{smax}=0.19 mol $m^{-2}s^{-1}$										
NLLS	0.391	0.199	0.384	0.183	0.026	0.949	1.004	0.098	0.011	0.098
MBL			0.339	0.245	0.153	0.692	1.001	0.141	0.090	0.106
LFBL			0.514	0.233	0.041	0.664	0.730	0.188	0.153	0.121
Douglas-fir 1988, n=102, g_{smax}=0.17 mol $m^{-2}s^{-1}$										
NLLS	0.349	0.236	0.346	0.201	0.025	1.078	1.025	0.095	0.016	0.094
MBL			0.308	0.249	0.096	0.841	1.034	0.131	0.071	0.127
LFBL			0.501	0.227	-0.067	0.833	0.721	0.211	0.195	0.147
Lodgepole pine 1987, n=153, g_{smax}=0.32 mol $m^{-2}s^{-1}$										
NLLS	0.524	0.274	0.527	0.245	0.008	1.011	0.998	0.117	0.004	0.117
MBL			0.463	0.290	0.114	0.790	0.954	0.142	0.072	0.121
LFBL			0.625	0.271	-0.042	0.867	0.812	0.157	0.116	0.119
Lodgepole pine 1988, n=102, g_{smax}=0.30 mol $m^{-2}s^{-1}$										
NLLS	0.312	0.231	0.317	0.203	0.005	1.000	0.989	0.110	0.005	0.110
MBL			0.307	0.251	0.071	0.805	0.940	0.144	0.060	0.131
LFBL			0.500	0.246	-0.085	0.808	0.674	0.239	0.169	0.138
Lodgepole pine 1989, n=209, g_{smax}=0.30 mol $m^{-2}s^{-1}$										
NLLS	0.376	0.234	0.380	0.190	0.005	1.004	0.993	0.136	0.039	0.136
MBL			0.463	0.275	0.059	1.026	1.168	0.200	0.130	0.153
LFBL			0.573	0.265	-0.165	1.203	0.877	0.259	0.212	0.147

al. (1984) found maximum conductance values for lodgepole pine to be 1.5 - 2 times greater than those for Douglas-fir.

2. Seasonal Trends in g_s

Stomatal conductance of both species was usually lower during May and June than during July, August and September. Spring g_s showed less response to environmental variables and was considerably overestimated by both MBL and NLLS models. This likely reflected the combined effects of transplanting stress, dehardening and needle emergence, and a predominance of older (one-year-old) needles (Christersson 1972; Örlander 1986; Grossnickle 1988). The best MBL and NLLS models for each species explained 10-35% less of the variation in g_s when all data in the 1987 and 1988 data sets were used, compared to when only the July-September data were used. Consequently, all subsequent analysis was carried out using only measurements taken during July, August and September.

3. Solar Irradiance

The MBL and NLLS curves describing the relationship between g_s/g_{smax} and R_s were similar for the five principle data sets (Fig. 3.1*a*). However, at very low light levels, some g_s values were often located considerably above the fitted curves. These measurements were usually taken near sunset when R_s was rapidly declining and likely reflected both lack of equilibration with current R_s levels and incomplete night time stomatal closure (Running 1976; Leverenz 1981; Grossnickle and Blake 1985).

With the exception of lodgepole pine in 1987, both species showed remarkably similar NLLS light response curves in all years (Fig. 3.1*b*).

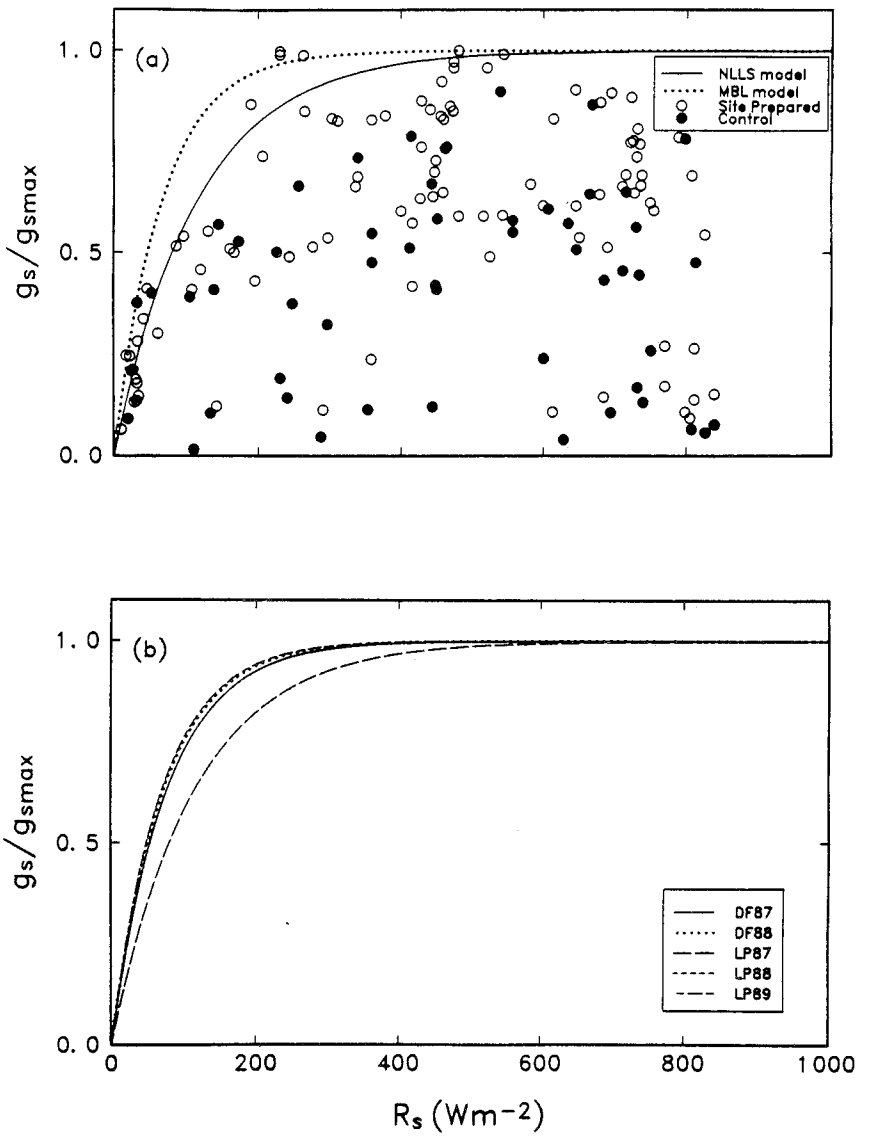

Fig. 3.1. Relationship between relative stomatal conductance (g_s/g_{smax}) and half hourly average global solar irradiance (R_s). (*a*) Best-fit MBL and NLLS response functions (Eq. [4]) for the 1987 lodgepole pine data for the control and site ripped treatment. (*b*) Best-fit NLLS R_s response functions (Eq. [4]) for the 1987, 1988 and 1989 Douglas-fir and lodgepole pine and 1987 and 1988 Douglas-fir data sets.

Light saturation (90% of g_{smax}) was approached at R_s values of 160 - 180 W m^{-2} in both Douglas-fir and lodgepole pine, despite the later successional status and greater shade tolerance of Douglas-fir (Minore 1979). Apparently, R_s rarely limits daytime conifer seedling g_s in open grown conditions.

4. Seedling Height Vapor Pressure Deficit

The MBL curves describing stomatal response to D_s/P for each data set had a much wider plateau at low D_s/P and a steeper descent at high D_s/P than the respective NLLS curves (Fig. 3.2*a*). A sizable number of data points were located above the NLLS curves, implying considerable variation in response among seedlings, sizable random error, or inclusion of response to other variables correlated with D_s/P (e.g., T_a) in the error term for $f(D_s/P)$ with the NLLS models. These models provided best-fit equations which attributed all variation in g_s to changes in the environmental variables considered or to measurement error. In comparison, the MBL curves did not account for variation among seedlings or measurement error.

The form of the NLLS D_s/P curves was similar for most data sets and was characterized by a very narrow plateau at low D_s/P, followed by an exponential decline at values of $D_s/P > 5$ Pa/kPa (Fig 3.2b). In most cases, both species showed similar trends in g_s at values of $D_s/P < 20$ Pa/kPa, but there was greater stomatal closure in Douglas-fir than in lodgepole pine at high D_s/P.

Recently interest has focused on the use of *RH* in place of D_s/P and T_a as a response variable for g_s (Ball et al 1987; Grantz 1990). Well-defined g_s-*RH* boundary line relationships were not readily apparent with most data sets, and replacement of D_s/P in Eq. [3] with linear or symmetrical logistic

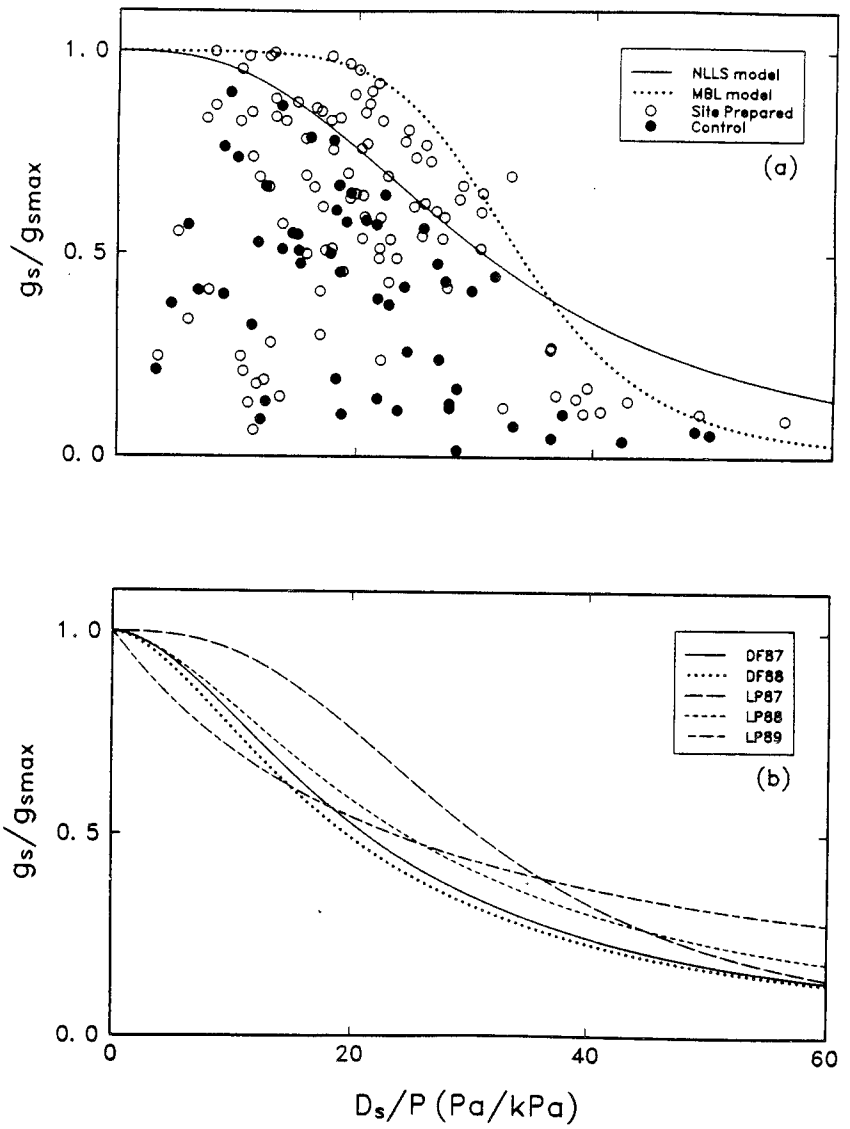

Fig. 3.2. Relationship between relative stomatal conductance (g_s/g_{smax}) and normalized vapor pressure deficit at seedling height(D_s/P). (*a*) Best-fit MBL and NLLS response functions (Eq. [5]) for the 1987 lodgepole pine data for the control and ripped treatment. (*b*) Best-fit NLLS D_s/P response functions (Eq. [5]) for the 1987, 1988 and 1989 lodgepole pine and 1987 and 1988 Douglas-fir data sets.

RH functions usually reduced the accuracy of the best fit NLLS models. These results support the contention of Aphalo and Jarvis (1991) that D_0/P provides a better and more meaningful g_s response variable than *RH*. They are also consistent with the results of Mott and Parkhurst (1991) showing that g_s is determined by E, and thus indirectly by D_0/P (see Eq. [10]), rather than directly by *RH* or D_0/P.

5. Soil Water Supply

Lodgepole pine exhibited similar g_s-θ_e relationships in all three years (Fig. 3.3); these were characterized by a lack of response above θ_e of 0.45-0.50, and an exponential decrease below this to a g_s/g_{smax} value of 0.20-0.30 at $\theta_e = 0$. In contrast, the Douglas-fir g_s-θ_e response functions were quite different in 1987 and 1988 (Fig. 3.3*b*), and values of g_s/g_{smax} at $\theta = \theta_{min}$ ranged from 0.25 to 0.42. Seedlings of both species were able to obtain sufficient soil water to permit stomatal opening when the calculated θ_e was completely depleted. This likely reflected supply of soil water from deeper depths through vertical seedling root extension and possibly upward movement of soil water. The form of the g_s-θ_e response functions found here, i.e., little response above but a sharp decline below some critical θ_e value, minimizes desiccation damage and is characteristic of most higher plants (Jones 1980).

Use of Ψ_{m15} in Eq. [3] instead of θ_e usually reduced the pseudo R^2 of the NLLS model by 10-15% while having little effect on the the best-fit parameter values for D_s/P and R_s. The poorer goodness-of-fits usually obtained with Ψ_{m15} as opposed to θ_e reflect both better data coverage of the g_s-θ_e than the g_s-Ψ_{m15} variable space, and the utility of θ_e as an

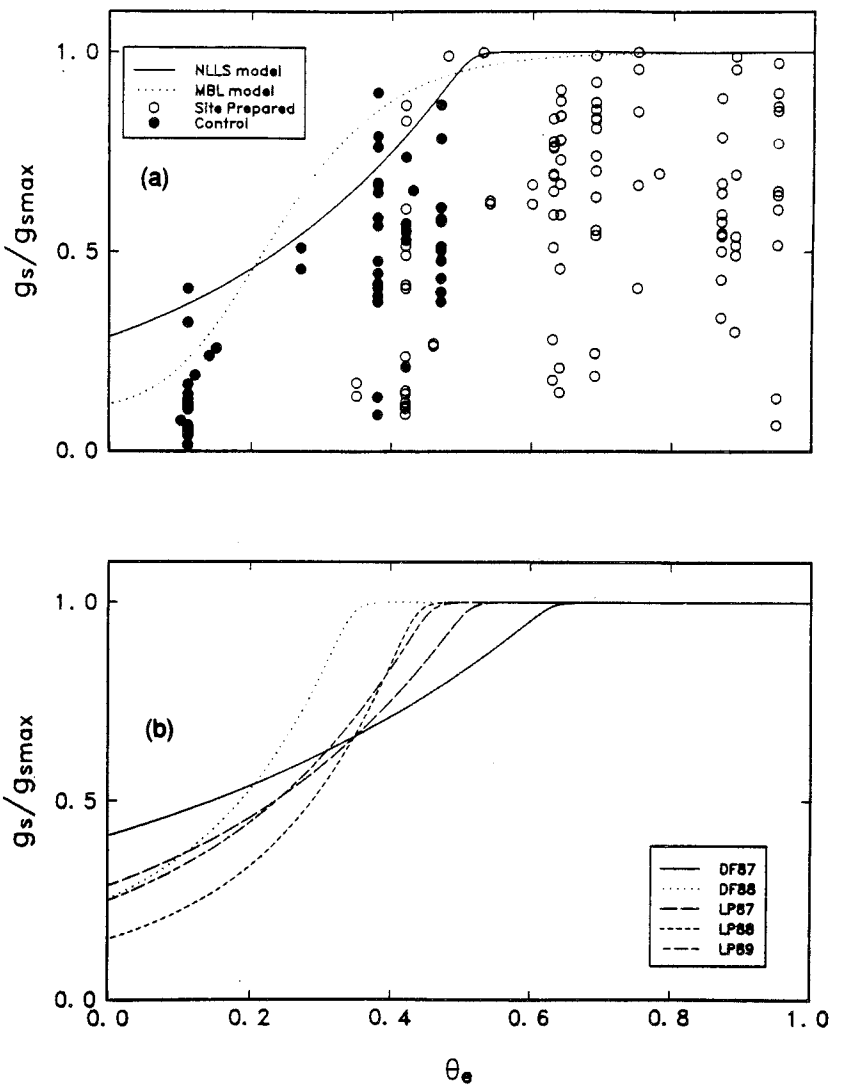

Fig. 3.3. Relationship between relative stomatal conductance (g_s/g_{smax}) and root zone extractable water (θ_e). (*a*) Best-fit MBL and NLLS response functions (Eq. [6]) for the 1987 lodgepole pine data for the control and ripped treatment. (*b*) Best-fit NLLS θ_e response functions (Eq. [6]) for the 1987, 1988 and 1989 lodgepole pine and 1987 and 1988 Douglas-fir data sets.

integrated measure of root zone soil water supply which incorporates site preparation effects (Jones 1990).

6. Seedling Height Air Temperature

NLLS optimization revealed no consistent response of g_s to T_a despite strong boundary line trends for lodgepole pine (Fig. 3.4) and Douglas-fir. Use of T_a in the NLLS models, in addition to D_s/P, R_s and θ_e, did not improve the fit (SEE or R^2) for any of the five data sets. Similarly, residual analysis of the best-fit three term NLLS models (Eq. [3]) for each data set showed no discernible effects of T_a. These results are consistent with many field studies which have found little effect of air temperature on g_s, independent of that on D (Tan et al. 1977; Price and Black 1990; Massman and Kaufmann 1991).

7. Soil Temperature

There were no consistent boundary line relationships between 15 cm soil temperature (T_{s15}) and Douglas-fir or lodgepole pine g_s in any of the data sets. This is not surprising considering that T_{s15} exceeded 10°C in all plots throughout the measurement period while conifer g_s is often not affected by soil temperatures ≥ 7°C (Running and Reid 1980; Carter et al. 1988).

8. Time since Sunrise

Although well-defined boundary line relationships between g_s and t were apparent for lodgepole pine (Fig. 3.5) and Douglas-fir, inclusion of t as an independent variable did not substantially improve the accuracy of the NLLS

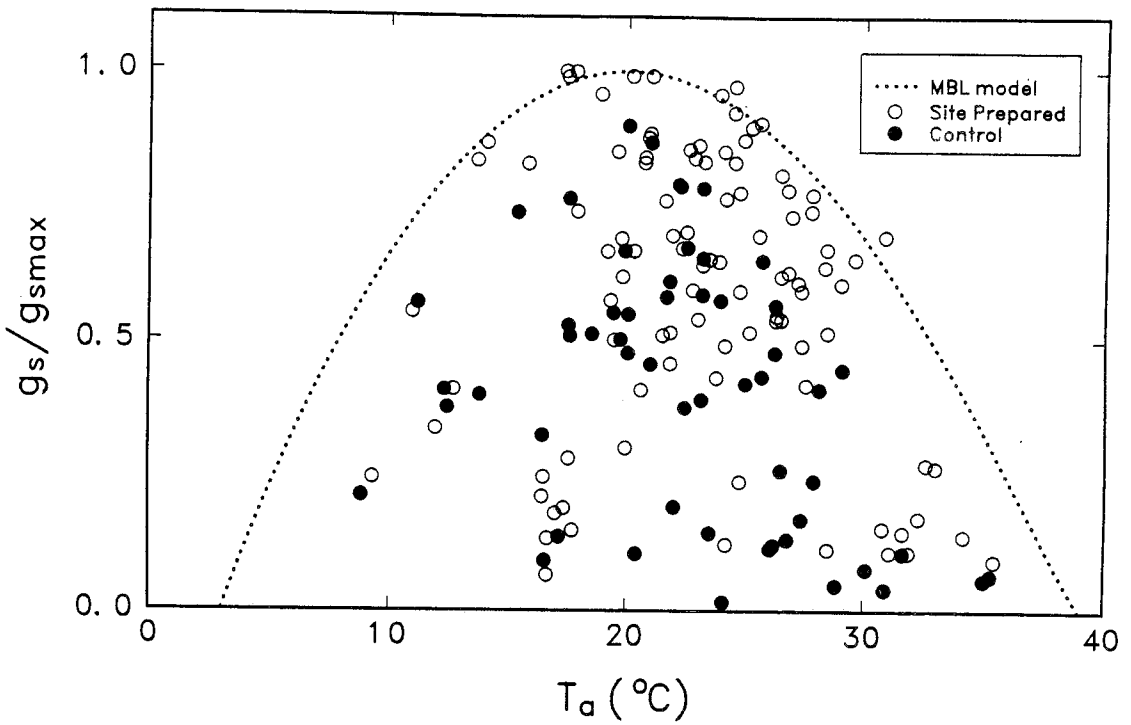

Fig. 3.4. Relationship between relative stomatal conductance (g_s/g_{smax}) and seedling height air temperature (T_a) for the 1987 lodgepole pine data for the control and site prepared plots. Also shown is the best-fit MBL response function for this data set (Eq. [8]). Parameter values are T_L=3, T_H=39, T_O=20 and K_7= 19/17.

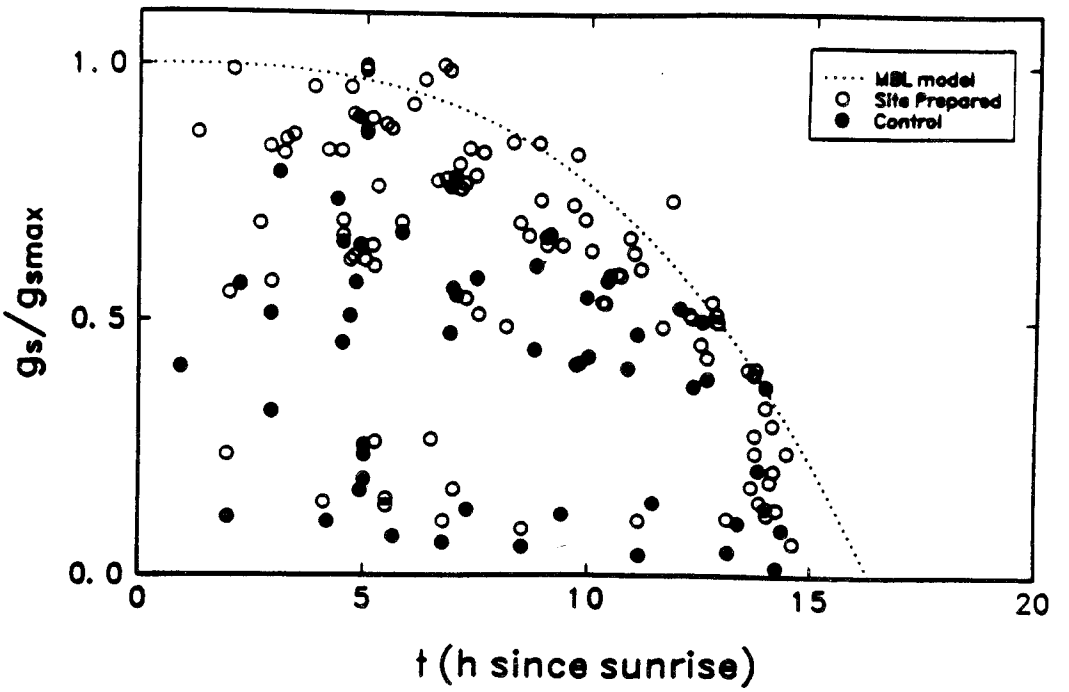

Fig. 3.5. Relationship between relative stomatal conductance (g_s/g_{smax}) and time since sunrise (t) for the 1987 lodgepole pine data for the control and site prepared plots. Also shown is the best-fit MBL response function for this data set (Eq. [9], K_8= 0.0002276).

models for any of the data sets. Residual analysis of these models also showed no readily discernible trends related to t.

B. Phenomenological Models of Stomatal Conductance

The best-fit MBL and LFBL models for each data set were obtained using $g_s/g_{smax} = f_1(R_s)f_2(D_s/P)f_3(\theta_e)f_4(T_a)f5(t)$. In contrast, a simple three term NLLS model (Eq. [3]) consistently provided among the best NLLS fits for all data sets. Use of T_a and t, either solely or in combination, as additional independent variables in the NLLS models explained only 2.2-4.0 % more of the variation in Douglas-fir g_s and only 0.1-1.9 % more of the variation in lodgepole pine g_s than Eq. [3]. Use of fewer than three variables in the NLLS models resulted in much poorer fits to the data sets. For instance, the best two term fit to both the Douglas-fir and lodgepole pine 1987 data sets, $g_s/g_{smax}=f_1(R_s)f_2(D_s/P)$, accounted for about 20% less of the variation in g_s in each data set than did Eq. [3].

The coefficients of determination for the best-fit NLLS models (Eq. [3]) were 4-19% and 4-28% greater for the five data sets than those for the best-fit MBL and LFBL models, respectively. More importantly, the NLLS model provided a relatively unbiased (mean predicted and observed values were similar, b' was close to unity, and $RMSE_s$ was a small fraction of RMSE) and accurate (low RMSE) description of g_s for each data set (Table 3.1). The poorest fits were obtained with the LFBL model, which substantially overestimated the mean observed values for each data set. The mean predicted values for the MBL model usually underestimated the mean observed values, but b' was often close to unity.

These results are consistent with conclusions that growing season conifer stomatal activity is largely controlled by Q_p, soil water availability and D_s/P (Tan et al. 1978; Jarvis et al. 1981; Graham and Running 1984; Massman and Kaufmann 1991) and suggests that these environmental factors act more in a Mitscherlich than a Liebig manner. Reed et al. (1983), in a study of Douglas-fir response to nitrogen and light, concluded that the seedlings reacted to various levels of these two factors in multiplicative fashion. In contrast, Price and Black (1989) found that an LFBL model, using D, R_s, t and root-zone soil water storage, provided a more accurate description of Douglas-fir canopy conductance than an MBL model using the same variables and functions.

Because of its markedly superior performance, further discussion and model testing pertains only to the NLLS model using (Eq. [3]). This model explained 75-84% of the variation in Douglas-fir g_s/g_{smax} and 66-82% of the variation in lodgepole pine g_s/g_{smax}, when used with the data sets for which the model was developed (Table 3.2). Estimating g_{smax} as a parameter rather than setting it as a constant did not substantially improve NLLS model goodness of fit for either species. In most cases estimated values of g_{smax} were within 10% of selected values.

C. Tests of the NLLS Models

1. Predicting g_s in the Ripped Treatment

Parameter values determined with the lodgepole pine 1989 control data were used successfully to predict 1989 lodgepole pine g_s in the ripped treatment (Table 3.3). Mean values of the predicted and observed values were

Table 3.2. Parameter values and associated asymptotic standard errors (SE), mean observed g_s ($\bar{X}$), standard errors of the estimate (SEE) and pseudo R^2 values for the best-fit NLLS model (Eq. [3]) for the five principal data sets (control and ripped treatment combined).

Parameter or Measure	Douglas-fir		Lodgepole pine		
	1987	1988	1987	1988	1989
K_1	0.0129	0.0138	0.0086	0.0129	0.0142
SE (K_1)	0.0013	0.0015	0.0008	0.0021	0.0022
$D_{0.5}/P$	21.239	19.623	30.739	24.557	23.673
SE ($D_{0.5}$)	0.712	0.880	1.121	1.299	1.646
K_2	1.790	1.704	2.688	1.687	1.027
SE (K_2)	0.149	0.159	0.283	0.231	0.143
K_3	0.631	0.346	0.513	0.435	0.457
SE (K_3)	0.050	0.040	0.022	0.024	0.026
K_4	0.017	0.051	0.027	0.051	0.034
SE (K_4)	0.003	0.015	0.004	0.008	0.004
$\bar{X}$	0.391	0.349	0.524	0.312	0.376
SEE	0.0100	0.0095	0.0142	0.0136	0.0197
R^2	0.755	0.837	0.816	0.790	0.658

Table 3.3. Goodness-of-fit of the 1987 and 1988 Douglas-fir (Df), and the 1987, 1988 and 1989 lodgepole pine (Pl) control (CTL) NLLS models to the corresponding ripped treatment data sets. Shown are the treatment sample size (n), the mean observed ($\bar{O}$) and predicted ($\bar{P}$) relative conductance (g_s/g_{smax}) and their associated standard deviations ($SD\bar{O}$ and $SD\bar{P}$), the intercept (a) and slopes (b and b') of the best fit equations $\hat{O}_i = a + bP_i$ and $\hat{O}_i = b'P_i$, and the root mean square error (RMSE) together with its systematic ($RMSE_s$) and unsystematic ($RMSE_u$) components.

Model	$\bar{O}$	$SD\bar{O}$	$\bar{P}$	$SD\bar{P}$	a	b	b'	RMSE	$RMSE_s$	$RMSE_u$
		Df 87, Ripped Treatment, n=104								
Df 87 CTL	0.442	0.198	0.283	0.139	0.096	1.226	1.500	0.192	0.163	0.101
		Df 88, Ripped Treatment, n=52								
Df 88 CTL	0.425	0.213	0.302	0.158	0.062	1.203	1.428	0.159	0.128	0.095
		Df 87-88, Ripped Treatment, n=156								
Df 87,88 CTL	0.436	0.196	0.287	0.152	0.105	1.081	1.365	0.167	0.129	0.107
		Pl 87, Ripped Treatment, n=99								
Pl 87 CTL	0.590	0.269	0.486	0.177	-0.034	1.284	1.221	0.183	0.180	0.158
		Pl 88, Ripped Treatment, n=52								
Pl 88 CTL	0.455	0.232	0.253	0.121	0.108	1.370	1.717	0.262	0.206	0.162
		Pl 89, Ripped Treatment, n=105								
Pl 89 CTL	0.465	0.199	0.463	0.241	0.193	0.587	0.915	0.171	0.099	0.139
		Pl 87-89, Ripped Treatment, n=259								
Pl 87-89 CTL	0.494	0.242	0.459	0.192	0.061	0.942	1.058	0.165	0.036	0.161

similar, the slope of the regression line passing through the origin was close to unity, and the RMSE was relatively low and was largely attributed to $RMSE_u$ rather than $RMSE_s$. This data set provided good comparisons because of the wide range of θ_e as well as R_s and D_s/P values for seedlings in both the control and ripped plots.

Treatment comparisons in 1987 and 1988 resulted in poorer agreement, largely because of incomplete and, for the most part, mutually exclusive coverage of the θ_e variable space in the control versus the ripped treatment (Fig. 3.3a). Thus good comparisons between the control and ripped treatment for Douglas-fir (measured only in 1987 and 1988) were not available. However, when the lodgepole pine data for 1987, 1988 and 1989 were combined, parameter values determined for the control provided good estimates of g_s/g_{smax} in the ripped treatment. The mean observed value was somewhat higher than the mean predicted value, but the slope of the relationship was close to unity, and $RMSE_s$ accounted for only 5% of RMSE.

Residual analysis of the best-fit NLLS models [Eq. 3] for each data set also showed no discernible trends related to site preparation. These results suggest that the impact of ripping on g_s/g_{smax} largely reflected treatment effects on θ_e and D_s/P. During the summer, θ_e was often lower (Chapter 1) and daytime D_s was often higher (Chapter 2) in the control than in the ripped treatment. There was little evidence that stomatal response was affected by changes in other environmental conditions brought about by ripping, such as soil bulk density (Masle and Passioura 1987) or nutrient availability (Chapin III, 1990).

2. Predicting g_s in Other Years

NLLS parameter values developed for the 1988 Douglas-fir data provided a relatively unbiased and accurate description of Douglas-fir g_s in 1987 (Table 3.4), accounting for 63% of the variation in this data set (Fig. 3.6). Use of the 1987 NLLS Douglas-fir parameter values to describe the 1988 data proved less satisfactory; the predicted values tended to underestimate the observed values and $RMSE_s$ comprised a much greater portion of RMSE. The poor fit of the latter model may reflect the 1987 Douglas-fir NLLS θ_e response curve, which differed from those of the other data sets (Fig. 3.3*b*) and may not provide a good representation of general response.

Parameter values developed for the 1988 lodgepole pine data set resulted in reasonable estimates of lodgepole pine g_s for both 1987 (Fig. 3.7) and 1989. Estimates for the 1989 data set were less biased than those for the 1987 data set but accounted for a smaller percentage (pseudo R^2 of 0.60 versus 0.75, respectively) of the variation in the observed values. Parameter values developed with the 1989 lodgepole pine data also provided reasonable estimates (pseudo R^2=0.73) for the 1988 lodgepole pine data set. In contrast, parameter values developed with the 1987 lodgepole pine data set resulted in substantial bias (marked differences between mean predicted and observed values, considerable deviation in b' from unity, and large values of RMSE and $RMSE_s$) in estimates for both the 1988 and 1989 lodgepole pine data sets. This may be accounted for by the 1987 D_s/P and R_s response functions, which differed from those of the 1988 and 1989 data sets (Fig. 3.1*b* and 3.2*b*).

Table 3.4. Goodness-of-fit of the NLLS 1987 and 1988 Douglas-fir (Df), and 1987, 1988 and 1989 lodgepole pine (Pl) models (control and ripped treatment combined) to the same species in other years. Shown are the sample size (n), the mean observed ($\bar{O}$) and predicted ($\bar{P}$) relative conductance (g_s/g_{smax}) and associated standard deviations ($SD\bar{O}$ and $SD\bar{P}$), the intercept (a) and slopes (b and b') of the best fit equations $\hat{O}_i = a + bP$ and $\hat{O}_i = b'P_i$, and the root mean square error (RMSE) with its systematic ($RMSE_s$) and unsystematic ($RMSE_u$) components.

Model	$\bar{O}$	$SD\bar{O}$	$\bar{P}$	$SD\bar{P}$	a	b	b'	RMSE	$RMSE_s$	$RMSE_u$
			Df 87 Data Set, n=160							
Df88	0.391	0.199	0.407	0.193	0.058	0.817	0.934	0.127	0.039	0.121
			Df 88 Data Set, n=102							
Df87	0.349	0.236	0.288	0.099	-0.081	1.494	1.266	0.142	0.092	0.108
			Pl 87 Data Set, n=153							
Pl88	0.524	0.274	0.458	0.209	0.002	1.141	1.144	0.154	0.073	0.136
			Pl 87 Data Set, n=153							
Pl89	0.524	0.274	0.436	0.165	-0.110	1.456	1.234	0.176	0.116	0.133
			Pl 88 Data Set, n=102							
Pl87	0.312	0.231	0.373	0.220	0.000	0.839	0.838	0.154	0.070	0.138
			Pl 88 Data Set, n=102							
Pl89	0.312	0.231	0.329	0.163	-0.094	1.235	1.006	0.119	0.042	0.112
			Pl 89 Data Set, n=209							
Pl87	0.376	0.234	0.476	0.243	0.020	0.748	0.781	0.189	0.117	0.148
			Pl 89 Data Set, n=209							
Pl88	0.376	0.234	0.381	0.241	0.079	0.781	0.928	0.149	0.053	0.139

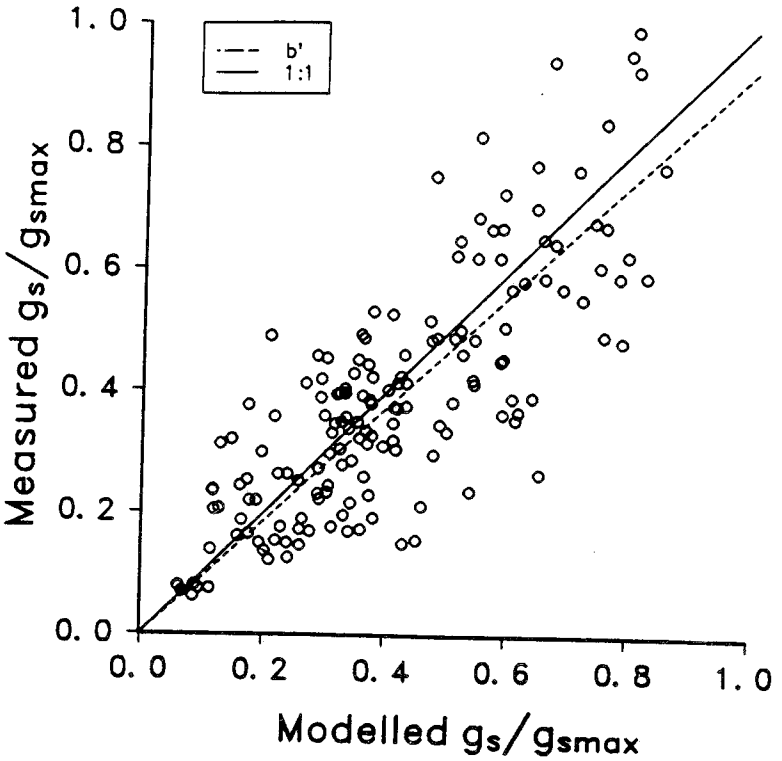

Fig. 3.6. Measured versus modeled relative stomatal conductance (g_s/g_{smax}) for Douglas-fir in 1987 (control and ripped treatment combined). Modeled values were calculated using parameters determined by NLLS (Eq. [3]) for the 1988 Douglas-fir data set. Also shown are the best-fit linear regression line (measured vs modeled data) passing through the origin (b') and the 1:1 line.

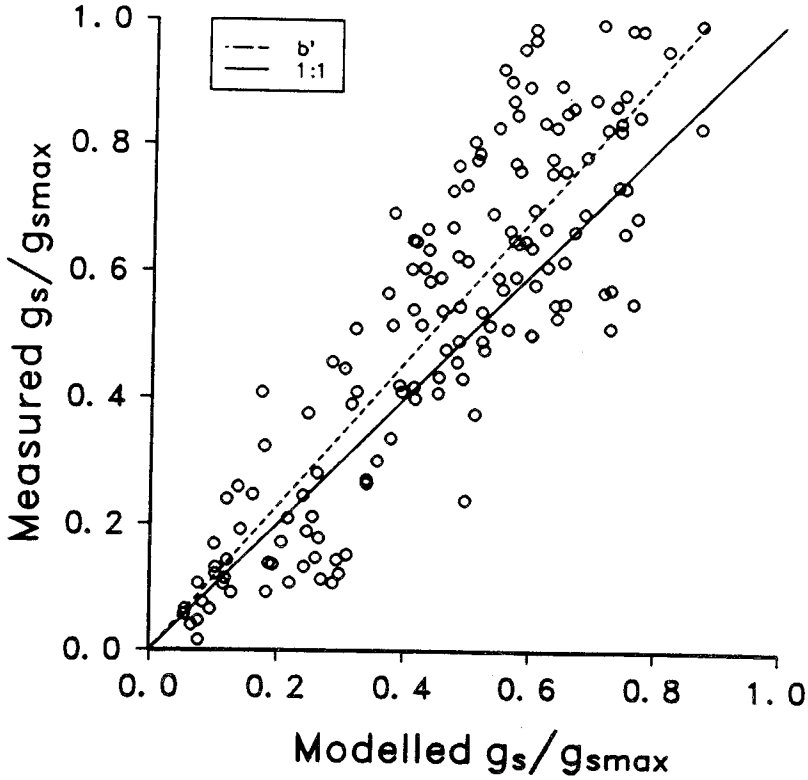

Fig. 3.7. Measured versus modeled relative stomatal conductance (g_s/g_{smax}) for lodgepole pine in 1987 (control and ripped treatment combined). Modeled values were calculated using parameters determined by NLLS (Eq. [3]) for the 1988 lodgepole pine data set. Also shown are the best-fit linear regression line (measured vs modeled data) passing through the origin (b') and the 1:1 line.

3. Predicting Daily Mean Stomatal Conductance and Transpiration Rates

Estimates of G_s and E_{Ad} within 5% of observed values were obtained for all data sets using parameter values determined by NLLS for the same data set as the observed values (Table 3.5). Use of NLLS parameter values determined separately for the 1988 lodgepole pine and Douglas-fir data sets resulted in estimates of G_s and E_{Ad} within 10% of actual values for the respective species in 1987, and for lodgepole pine in 1989. The poorest agreement was obtained with parameter values determined for the 1987 lodgepole pine data set: these resulted in overestimates of G_s and E_{Ad} by 10 - 15% for the 1989 lodgepole pine data set and by 30 - 35% for the 1988 lodgepole pine data set.

IV. CONCLUSIONS

Values of g_{smax} were substantially greater for lodgepole pine than for Douglas-fir in the two years when both species were studied. Stomatal conductance was noticeably lower in the spring, soon after planting, than later in the growing season and showed less response to changes in environmental conditions. However, stomatal responses of the two species during summer and fall to environmental variables such as D_s/P, R_s and θ_e, when normalized against g_{smax}, were usually similar for different years and in both the control and ripped treatment.

The NLLS models provided more accurate and less biased estimates of g_s/g_{smax} for all data sets than did the MBL or LFBL models. A simple three term NLLS model based on response to D_s/P, R_s and θ_e accounted for 75-85% of

Table 3.5. Ratio of modeled to measured mean daily stomatal conductance (G_s) and total daily transpiration rates (E_{Ad}) for Douglas-fir (Df) in 1987 and 1988, and lodgepole pine (Pl) in 1987, 1988 and 1989. Estimated values were calculated from Eq. [3] using parameter values determined by NLLS optimization. Also given is the sample size in days (n) for each data set. Only days after July 1 in which g_s was measured at two hour intervals from sunrise until sunset were used.

Data Set (Measured Values)	n	Model (Estimated Values)	Ratio of G_s modeled/ G_s measured	Ratio of E_{Ad} modeled/ E_{Ad} measured
Df 87	22	Df87	0.995	1.009
		Df88	1.047	1.044
Df88	11	Df87	0.847	0.878
		Df88	1.038	1.027
Pl87	19	Pl87	1.026	1.045
		Pl88	0.909	0.906
		Pl89	0.895	0.913
Pl88	11	Pl87	1.330	1.302
		Pl88	1.053	1.042
		Pl89	1.187	1.214
Pl89	9	Pl87	1.135	1.106
		Pl88	1.015	0.959
		Pl89	0.972	0.959

the variation in g_s/g_{smax} under normal field conditions for the data sets from which the parameters were derived. Use of T_a and t, in addition to D_s/P, R_s and θ_e, did not substantially improve model performance over the three term model. Differences in lodgepole pine g_s/g_{smax} between the control and ripped plots were largely accounted for by differences in θ_e and D_s/P.

Use of the 1988 NLLS models for the two species and the 1989 NLLS model for lodgepole pine resulted in reasonably accurate and unbiased estimates of g_s in other years for the same species. The 1987 NLLS Douglas-fir and lodgepole pine model parameters, however, resulted in more biased estimates of g_s for each species in 1988, and for lodgepole pine in 1989. In most cases, parameter values determined in one year with the NLLS model could be used to predict G_s and E_{Ad} in other years within 10-20% of measured values.

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CONCLUSIONS

During the growing season, root zone soil water content on these grass-dominated clearcuts was lowest at the low elevation site (IDFdk) and highest at the high elevation site (ESSFxc). This corresponded with a trend of decreasing growing season length and evaporative demand with elevation, despite similar rainfall patterns and solar irradiance at all three sites. The largest declines and greatest variations in soil water content occurred in near-surface horizons of the control at the two lower sites, the IDFdk and MSxk. At these two sites, root zone soil water supply in untreated clearcuts probably limits seedling growth throughout the summer months in most growing seasons. At the ESSFxc, root zone soil water content remained greater than 0.22 m^3m^{-3} throughout the growing season and there was little evidence of water use by vegetation at soil depths greater than 50 cm.

Over the four growing seasons studied, soil water potentials at 15 cm (Ψ_{s15}) in the control fell to as low as -0.92 MPa at the IDFdk, -0.68 MPa at the MSxk, and -0.12 MPa at the ESSFxc. These minimum values substantially exceed those generally considered lethal for conifers (-1.5 to -3.0 MPa), and are consistent with the high first growing season survival rates of Douglas-fir and lodgepole pine seedlings at the IDFdk. However, drought stress induced by limited soil water supply at the lower two sites, when augmented by other stresses such as frost damage and winter desiccation, may

contribute substantially to seedling mortality in subsequent years (Black et al. 1991).

During the growing season, root zone soil water content and profile soil water storage at the MSxk resembled that at the IDFdk more than that at the ESSFxc. However, temporal patterns of soil water depletion at the IDFdk and MSxk differed: water deficits developed later in the growing season but lasted longer into the fall at the MSxk. This likely reflected differences in the composition of herbaceous vegetation as well as in microclimate, and may have important silvicultural implications in terms of seedling establishment. Late summer drought may restrict root growth but may also hasten the onset of cold-hardiness, rendering the seedlings less susceptible to late summer frosts (Sakai and Larcher 1987).

At each site scalping, ripping and herbicide site preparation treatments increased root zone and profile soil water content to a similar degree during the summer. The treatments were particularly effective in conserving soil water at the IDFdk and MSxk, and root zone soil matric potentials never fell below -0.15 MPa in any of the treatments at any site. Conservation of soil water was achieved primarily by reducing evapotranspiration through the removal of competing vegetation. Ripping did not increase root zone available water capacity, and the creation of a surface organic mulch did not consistently increase soil water content when compared with bare mineral soil surfaces.

The site preparation treatments also increased drainage losses at all three sites. Calculated drainage losses increased with site elevation, but were similar among the three principal treatments at a given site. Increased

drainage rates following site preparation may accelerate nutrient losses to leaching, and this could reduce stand productivity on coarse textured soils with low nutrient reserves and limited water storage capacities (Smethurst and Nambiar 1989).

Research is now needed to determine the optimum areal dimensions of site preparation treatments from the perspective of both seedling microclimate and nutrition. How large an area must be treated to optimize root zone soil water content, near-surface soil and air temperature regimes, and soil nutrient availability; and what effects will this have on stand establishment, growth and productivity?

Effects of site preparation on the water relations and growth of Douglas-fir and lodgepole pine at the IDFdk largely reflected increased soil water content resulting from the control of competing vegetation. Furthermore, on warm, clear days bare surfaces also tended to have slightly lower seedling height saturation deficits as a result of lower seedling height air temperatures. Treatment effects on other factors, such as air and soil temperature and mineral nutrition, appeared to have relatively little impact on first growing season seedling physiological or growth response. Consequently, while first growing season Douglas-fir and lodgepole pine dry matter production and root collar diameters were greater in the site preparation treatments than in the control at the IDFdk, there was relatively little difference in the growth of either species among the different treatments.

First growing season patterns of Douglas-fir and lodgepole pine stomatal conductance (g_s) and transpiration (E) at the IDFdk were similar in the

control. In the site preparation treatments, lodgepole pine had greater g_s than Douglas-fir, and showed an increase in g_s, leaf area (A) and E over the summer, relative to Douglas-fir. These results suggest that the greatest differences in initial growth rates between the two species on similar sites may occur under favorable growing conditions where soil water is plentiful.

During the spring, g_s as well as E of both species was noticeably lower and showed less response to environmental conditions than later in the growing season. This is a commonly observed phenomenon following outplanting, and reduces seedling water stress at a time when water uptake is restricted by planting stress, root-soil contact resistance and lack of root development (Burdett 1990).

During the summer, lodgepole pine consistently maintained higher twig xylem pressure potential values (Ψ_{tx}) and lower liquid flow resistances (R_{sp}) than Douglas-fir. Despite this, both species appeared well adapted to survive conditions of limited soil water supply. Following the terminology of Turner (1986), lodgepole pine achieved drought tolerance at relatively high plant water potentials (dehydration postponement), and low R_{sp} appeared to be a major factor contributing to this ability. In contrast, Douglas-fir achieved drought tolerance at relatively low plant water potentials (dehydration tolerance), and turgor maintenance mechanisms appear to be an important adaptation of this species (Livingston and Black 1987).

In 1987, there was little relationship between g_s and Ψ_{tx}, whereas in 1988 there was some indication of a g_s-Ψ_{txm} threshold response at Ψ_{txm}<-2.2 MPa for Douglas-fir and at Ψ_{txm}<-1.5 MPa for lodgepole pine. Consistently

strong, direct feedback control of g_s by Ψ_{tx} was not readily apparent from the field measurements.

Burdett (1990) suggested that in many instances seedling establishment primarily reflects the interaction between and interdependence of root growth and photosynthesis, as mediated by plant water status (i.e., Ψ_{tx} and its effect on g_s). While seedlings of both species in this study had greater root egress, g_s, E and biomass production in the site preparation treatments than in the control, the lack of consistently strong g_s-Ψ_{tx} relationships suggests that interactions between root growth and photosynthesis may have been regulated as much by R_{sp} and direct root-shoot communication as by hydraulic feedback mechanisms involving Ψ_{tx} (Davies and Zhang 1991).

First growing season stomatal responses of Douglas-fir and lodgepole pine seedlings to environmental variables such as D_s, solar irradiance (R_s) and root zone extractable water (θ_e), when normalized using the seasonal mean maximum conductance (g_{smax}) for each species, were similar in different years and in both the control and ripped treatment.

A multiplicative model employing non-linear least squares optimization of response functions to individual environmental variables (NLLS) provided more accurate and less biased models of g_s for both species than did a multiplicative model or a limiting function model, each based on boundary line functions fitted by eye to individual environmental variables. The poorest fits were obtained with the limiting function model, suggesting that stomatal response behaved more in a multiplicative (Mitscherlich) manner than in a limiting factor (Liebig) manner.

A three term NLLS model based on response to D, R_s and θ_e provided a simple and reasonably accurate description of g_s/g_{smax} for both species. Inclusion of seedling height air temperature and time since sunrise as environmental variables, in addition to D, R_s and θ_e, did not substantially improve model performance.

In most cases the NLLS models developed for a given species in a particular year resulted in relatively precise and unbiased estimates of g_s/g_{smax}, mean daily stomatal conductance (G_s) and daily transpiration flux densities (E_{Ad}) in other years for the same species. In some instances, however, this was not the case and this was attributed to poorly defined response functions for a particular year.

Each of the site preparation treatments used in this study alters the seedling environment in unique ways and may have different long-term effects on the survival and growth of the two species. For example, the herbicide treatment produced substantial increases in soil water content, but often resulted in lower minimum seedling height temperatures than scalping or ripping (Black et al. 1991). On droughty, frost-prone sites such as the IDFdk, this treatment would be well suited for establishing frost-hardy species such as lodgepole pine, but not frost-sensitive species such as Douglas-fir.

From a biological perspective, the choice of site preparation treatment is complicated by treatment effects on factors such as nutrient availability, mycorrhizal development and the virulence of pathogens, as well as on various components of the physical environment. As the stand develops and the soil surface is increasingly shaded by the developing

canopy, microclimatic differences between treatments will be moderated while nutritional demands will increase. Thus the greatest treatment benefits in terms of microclimate should occur within a few years of planting, while treatment effects related to nutrient supply may not be fully manifested for several decades (Morris and Lowery 1988). It remains to be seen whether treatments which primarily ameliorate the seedling microclimate or those which primarily enhance soil nutrient availability provide the greatest long-term benefits in terms of stand development.

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APPENDIX I

MEASUREMENT OF WATER CONTENT, BULK DENSITY AND COARSE FRAGMENT CONTENT IN FOREST SOILS

Water Content, Bulk Density, and Coarse Fragment Content Measurement in Forest Soils

R. L. Fleming, T. A. Black,* and N. R. Eldridge

ABSTRACT

Measurement of soil physical properties in forest soils is often complicated by coarse fragments. In this study, a two-probe gamma-density gauge was used in a stony forest soil (Typic Boralf) to determine water content, bulk density, and coarse fragment content, and to calibrate a neutron moisture meter. Laboratory and destructive field procedures for gamma-density gauge calibration and a correction factor for actual tube separation distance were developed. The gamma-density gauge could be readily calibrated and provided good field estimates of water content, bulk density, and coarse fragment content in 5-cm vertical increments. Satisfactory neutron meter field calibrations incorporating soil density effects were obtained using gamma-based water content measurements. However, differences in soil composition and water content in the sampling volume of the two instruments may confound neutron meter calibration. To overcome this, the use of additional gamma tube installations, a back-scattering soil density meter, or soil excavations were considered. The gamma-density gauge was used to determine site preparation effects on soil physical properties and soil water withdrawal in the seedling root zone.

THE MEASUREMENT of bulk density and soil water content in forest soils is often complicated by large, spatially variable coarse fragment contents. Root zone water content is an important factor governing establishment, growth, and succession on many forested sites (Waring and Schlesinger, 1985). In British Columbia, a substantial research effort has been directed at developing silvicultural procedures to restock backlog cut-over areas. As part of this research, we have used gamma attenuation and neutron moderation techniques to examine the effects of site preparation treatments on seedling root zone (upper 30 cm of soil) water content, total soil bulk density, and fine soil (soil material ≤2 mm in diameter) bulk density.

Gamma attenuation can provide repeated nondestructive measurements of total soil bulk density and water content in depth increments as small as 2.5 cm (de Vries, 1969; Bertuzzi et al., 1987). The well-defined measurement region of the two-probe gamma-density gauge, which remains constant regardless of water content, is advantageous in stony soils where soil water content varies substantially with coarse fragment content (Baker and Lascano, 1989). Changes in water content at a particular location can be measured if the total and fine soil bulk density does not change during the period of interest.

In contrast, the neutron moderation technique permits rapid measurements of soil water content of much larger volumes (McHenry, 1963; Haahr and Ølgaard, 1965). Hydrogen is primarily responsible for the thermalization of fast neutrons. Thus neutron meter count rates depend largely on free soil water (water driven off by drying at 105 °C), but are also influenced by constitutional H (bound water), total soil bulk density, and the thermal neutron absorption and scattering characteristics of the soil constituents (Marais and Smit, 1962; Ølgaard and Haahr, 1968; Greacen et al., 1981; Wilson and Ritchie, 1986). This has important implications for interpreting neutron meter measurements in stony forest soils.

The calibration and use of neutron meters to measure water content in soils with sizable coarse fragment contents is problematic (Lal, 1979). This is a result of (i) the effects of coarse fragment content and bulk density on neutron counts (Ølgaard, 1965; Couchat, 1973; Greacen et al., 1981), (ii) the scale of heterogeneity in soil physical properties within given soil strata at a particular site, (iii) difficulties with destructive sampling and gravimetric determinations in stony soils (Reinhart, 1961; Flint and Childs, 1984a), (iv) the effect of water content on the volume sampled by the neutron meter (Ølgaard, 1965; Wilson, 1988), and (v) the greater response of the neutron meter to regions close to the probe within the sampling volume (Kasi et al., 1983).

The objectives of this study were to (i) develop a procedure for using a dual-probe gamma-density gauge to measure root-zone total- and fine-soil bulk densities, coarse fragment content, and water content in stony forest soils, (ii) develop a technique for the field calibration of a neutron meter in these soils using a gamma-density gauge, and (iii) apply these techniques in reforestation research.

METHODS

Site Description and Experimental Layout

The experimental site is 40 km west of Kamloops at an elevation of 1220 m in the Interior Douglas-fir (IDFdk) Biogeoclimatic Subzone (Thompson Plateau–Very Dry Montane Interior Douglas-fir variant) of southern British Columbia (Mitchell et al., 1981). The soil, a Typic Boralf (Orthic Gray Luvisol; Canada Soil Survey Committee, Subcommittee on Soil Classification 1978) formed on glacial till, consists of 20 to 30 cm of gravelly to cobbly silt loam overlying a more compact gravelly to cobbly clay loam of similar mineralogical composition. Coarse fragments of volcanic origin (primarily olivine basalt and basalt andesite) ranging from 2 to 500 mm in diameter occupy on average 20 to 35% of the mineral soil volume. A thin organic layer (4–6 cm) with a xeromor humus form covers the mineral soil. The site is level and well drained. The previous lodgepole pine (*Pinus contorta* Dougl.)–Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] stand was clear-cut in 1982, and the area is currently dominated by pine grass (*Calamagrostis rubescens* Buckl.).

Site preparation treatments were carried out from 1986 to 1989 and included herbicide, scalping, trenching, and ripping, as well as a control. Our study was largely confined to measurements made in the ripping treatment and the control. Ripping was conducted in two stages. First, the top 5 to 10 cm of soil, including the organic horizons, were sheared off with

R.L. Fleming, Forestry Canada, Ontario Region, Box 490, Sault Ste. Marie, ON, Canada P6A 5M7; T.A. Black, Dep. of Soil Science, Univ. of British Columbia, no. 139 MacMillan Building, 2357 Main Mall, Vancouver, BC, Canada V6T 1Z4; and N.E. Eldridge, Faculté de Foresterie et Géomatique, Université Laval, Sainte-Foy, Québec, Canada, G1K 7P4. Received 3 Dec. 1991. *Corresponding author.

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the straight blade of a Caterpillar D7 crawler tractor. Then several overlapping passes were made with 20-cm-wide hydraulically controlled flanged ripper teeth mounted immediately behind the pads of the crawler tractor (Coates and Haeussler, 1987). This resulted in ripper tooth paths spaced 0.3 to 0.5 m apart that penetrated the soil to a depth of about 50 cm. The ground was subsequently leveled with hand tools. Treatments were laid out in large blocks (≥5 by 10 m) so that the soil and aerial environment near the middle of each plot was relatively unaffected by adjacent treatments.

Within plots, pairs of thin-walled aluminum access tubes (5.1-cm o.d.) for the two-probe gamma-density gauge were installed vertically in holes initially dug with a power auger and undersized bit, and enlarged with a hand auger. Several attempts were often required to obtain holes of sufficient depth (35 cm) because of the high coarse fragment content. The prescribed tube spacing for each pair was 25.2 cm (inside edge to inside edge). Despite the use of a parallel access hole guide, small deviations in the prescribed tube spacing (less than ±4 cm) often occurred. However, in all cases the tubes fit snugly and required little packing at the surface. One tube of each pair was designated for neutron meter measurements.

Measurement Theory and Procedures

Gamma attenuation and neutron moderation measurements were made with a two-probe density gauge (5 mCi ^{137}Cs source, NaI scintillation detector; Model 2376, Troxler Electronic Laboratories, Triangle Park, NC) and a hydroprobe (He 3 detector and ^{241}Am–Be source; Model 503, Campbell Pacific Nuclear Corp., Martinez, CA), respectively.

Gamma Attenuation

With the dual-probe gamma-density gauge, the source and detector are lowered vertically to selected depths down parallel aluminum access tubes. Mineral particles, organic matter, and water in the soil attenuate the gamma beam. To determine water content from scintillation counts, the density of mineral soil and organic matter must be known.

Theory. The intensity of transmitted monochromatic, primary gamma radiation (I) through a soil from the source to the detector of a two-probe gamma-density gauge can be expressed as (van Bavel et al., 1957)

$$I = \frac{I_{O\Lambda}}{(x + 2r)^2} \exp[-x(\mu_s\rho_b + \mu_w\rho_w\theta)] \qquad [1]$$

where μ_s and μ_w are the mass attenuation coefficients (m^2 kg^{-1}) for dry soil and water, respectively, ρ_b is the total soil bulk density in the sampled volume (kg m^{-3}), ρ_w is the density of water (1000 kg m^{-3}, although slightly temperature dependent), θ is the volumetric water content (m^3 water m^{-3} bulk soil), r is the radius of the access tubes (m), x is the distance (m) through the soil between the two tubes, and $I_{O\Lambda} = I_O \exp[-x(\mu_a\rho_a + \mu_{Al}\rho_{Al})]$, where I_O is the radiation intensity (count rate) at the source, μ_a and μ_{Al} are the mass attenuation coefficients (m^2 kg^{-1}) for air and Al, respectively, and ρ_a and ρ_{Al} are the average densities (kg m^{-3}) of air and Al across the distance $x + 2r$. Since in the present configuration $\mu_a\rho_a + \mu_{Al}\rho_{Al}$ is three orders of magnitude less than $(\mu_s\rho_b + \mu_w\rho_w\theta)$, $I_{O\Lambda}$ may be regarded as a constant for small variations in tube spacing.

The radiation intensity $I_{O\Lambda}$ is related to that transmitted through a magnesium bar spanning the two tubes (I_{Mg}) as follows:

$$I_{Mg} = \frac{I_{O\Lambda}}{(x_s + 2r)^2} \exp(-x_s\mu_{Mg}\rho_{Mg}) \qquad [2]$$

where μ_{Mg} is the mass attenuation coefficient for Mg, ρ_{Mg} is the density of Mg (≈1200 kg m^{-3}), and x_s is the standard separation distance between the inside edges of the two tubes in the magnesium bar (25.2 cm). The value of I at this standard separation distance is given by

$$I_s = \frac{I_{O\Lambda}}{(x_s + 2r)^2} \exp[-x_s(\mu_s\rho_b + \mu_w\rho_w\theta)] \qquad [3]$$

Dividing Eq. [3] by Eq. [2] gives

$$I_s = KI_{Mg} \exp[-(a_s\rho_b + a_w\rho_w\theta)] \qquad [4]$$

where $K = \exp(x_s\mu_{Mg}\rho_{Mg})$ and a_s $(=x_s\mu_s)$ and a_w $(=x_s\mu_w)$ are the attenuators (m^3 kg^{-1}) for soil and water, respectively. Since $\theta = w\rho_b/\rho_w$, where w is the soil mass wetness (kg water kg^{-1} dry soil), Eq. [4] can also be written as (van Bavel et al., 1985)

$$I_s = KI_{Mg} \exp[-\rho_b(a_s + a_w w)] \qquad [5]$$

Determination of Calibration Parameters. Because of differences in source-detector geometry and electronic discrimination, it is recommended that two-probe gamma-density gauge instruments be calibrated individually (Coppola and Reiniger, 1974; van Bavel et al., 1985). This involves the determination of K, a_s, and a_w in Eq. [5].

The value of K was determined by measuring the counts with a Mg standard (I_{Mg}) and with varying numbers of evenly spaced Plexiglas plates (6.5 by 6.5 by 1.19 cm thick) placed normal to the source-detector path (x = 25.2 cm) between the tubes (cf., Gurr, 1962; Reginato and van Bavel, 1964; Fritton, 1969). The slope of the linear least-squares regression line relating the natural logarithm of standardized counts (I/I_{Mg}) to the density of Plexiglas in the sampled volume (ρ_p) gave the attenuator for Plexiglas (a_p) (Fig. 1). The value of K calculated from the intercept of this line was 16.5603 (r^2 = 0.9994). Densities <650 kg m^{-3} were avoided because of potential counting errors due to instrument resolving time (Fritton, 1969; Gardner et al., 1972).

The attenuator values a_s and a_w were determined using a vertically oriented steel cylinder 25.2 cm long and 9.8 cm in diameter filled with various densities of water or soil (i.e., material mass/cylinder volume). A range of water densities

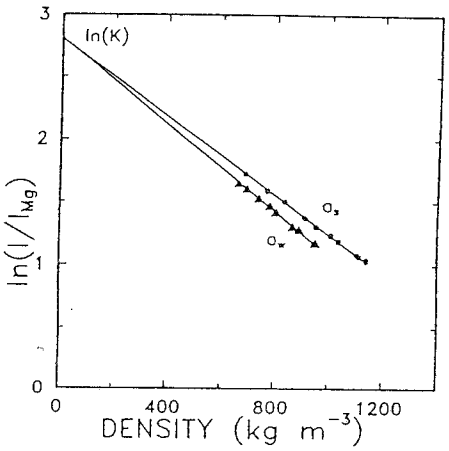

Fig. 1. Determination of K [$K = \exp(x_s\mu_{Mg}\rho_{Mg})$] and the gamma attenuators for soil (a_s) and water (a_w) from the linear relationship between standardized gamma counts and material density (kg specified material m^{-3} sampling volume).

was obtained by filling the cylinder to various levels, while a range of soil densities was achieved by varying both the level and degree of packing of oven-dried fine soil. The slope of the least-squares linear regression of the natural logarithm of standardized counts (adjusted to account for attenuation [using a_p] by the 0.45-cm-thick Plexiglas base of the cylinder) vs. the density of each material provided values for a_s and a_w (Fig. 1). In both cases, the value of K, obtained as described above, was included in the regression data set. Values obtained were $a_w = 0.00172$ m^3 kg^{-1} ($r^2 = 0.9998$), and $a_s = 0.00156$ m^3 kg^{-1} ($r^2 = 0.9997$). The values of K and the attenuators are similar to those reported by van Bavel et al. (1985).

To test the reliability of the calibration procedures, readings were taken in the middle of a 21 by 33 by 56 cm water-filled trough, following Rawitz et al. (1982). The resulting calculated density (1017 kg m^{-3}) was 2% higher than the actual value. The ability of the gauge to resolve changes in water content was then examined by filling the cylinder with moist fine soil from the field site. Several readings were taken, the soil was subsequently oven dried in the cylinder and reweighed, and readings were taken again. The calculated change in water content, 0.6264 kg, was within 0.6% of the value measured gravimetrically.

Count Correction for Tube Separation. Correcting dual-probe gamma-density gauge readings for a nonstandard tube separation distance at the measurement depth is necessary for accurate measurements of water content and bulk density (Rijtema, 1969; Bertuzzi et al., 1987). This involves converting the actual count rates to count rates at a standard separation distance (corresponding to the separation distance of the Mg standard).

By manipulation of Eq. [1], [2], and [3], the value of I_s corresponding to the value of I for $x \neq x_s$ (i.e., for the same value of θ) can be calculated from

$$I_s = I_{Mg}\left[\frac{I(x + 2r)^2}{KI_{Mg}(x_s + 2r)^2}\right]^{(x_s/x)} \qquad [6]$$

where I is given by Eq. [1]. This equation was used to correct all measured values of I following destructive sampling between gamma tube pairs.

Field Measurement of Bulk Density, Coarse Fragment Content, and Water Content. Equation [5] can be rewritten to given an expression for determining the total soil bulk density:

$$\rho_b = [\ln(KI_{Mg}/I_s)](a_s + a_w w) \qquad [7]$$

where w is measured gravimetrically. When the total soil bulk density remains constant, this value can then be used to determine θ during the growing season from Eq. [4], rewritten as

$$\theta = \left(\frac{(KI_{Mg}/I_s) - \rho_b a_s}{\rho_w a_w}\right) \qquad [8]$$

where ρ_b is obtained from Eq. [7]. Furthermore, the volumetric coarse fragment content, S, can be determined from

$$S = \left(\frac{\rho_b m_s}{\rho_s(m_s + m_f)}\right) \qquad [9]$$

where ρ_s is the particle density of the mineral fraction, ρ_b is obtained from Eq. [7], and m_s and m_f, the mass of coarse fragments and fine soil, respectively, are obtained by destructive sampling.

Measurements for each tube pair were carried out in the following manner: first, six 1-min readings were taken in the Mg standard, then consecutive 1-min readings were taken at 2.5-cm vertical increments in the soil to a maximum depth of 35.5 cm, and, finally, six 1-min readings were again taken in the standard.

Excavation to determine w, m_s, m_f, S, ρ_b, ρ_{bf} (fine soil bulk density, kg fine soil m^{-3} fine soil), and θ involved the removal of 25.2-cm-long by 10-cm-wide by 5-cm-deep rectangular soil volumes between the access tubes. These samples were stored in sealed polyethylene bags at 2 to 4 °C. The samples were subsequently weighed, oven dried at 105 °C for 48 h, and then reweighed and sieved to determine w, m_f, and m_s. These values were then used to calculate ρ_b, S, and θ, both volumetrically and from Eq. [7], [8], and [9] using gamma-density gauge measurements taken immediately prior to excavation.

Neutron Probe Calibration

The source and detector of the neutron meter are contained within a single cylindrical probe which is lowered vertically down aluminum access tubes to selected soil depths representing the mid-point of the source location within the probe. In the soil, the fast neutrons emitted by the source are slowed, principally by H atoms, and back-scattered thermal neutrons are counted by the detector. Calibration is affected by soil density and composition as well as water content.

Theory. Two field calibration equations for neutron meters that account for soil density effects are (Greacen and Schrale, 1976)

$$\theta = A + B\rho_b^{-0.5}n + C\rho_b \qquad [10]$$

and (Vachaud et al., 1977)

$$\theta = D + (E\rho_b + F)n + G\rho_b \qquad [11]$$

where n is the neutron meter count ratio (counts/standard counts), A, B, C, D, E, F, and G are constants, and the effects of bound water are included in the right-hand side of the equations. Equation [10] is similar to the square root correction method of Greacen and Schrale (1976), which may be written as

$$\theta = H + In' \qquad [10b]$$

where H and I are constants, $n' = n(\rho_{bs}/\rho_b)^{0.5}$, ρ_b is the total soil bulk density associated with n, and ρ_{bs} is a selected standard total soil bulk density (e.g., the mean total soil bulk density of the soil layer). The intercept H incorporates the effects of bulk density on bound water.

From the above equations it is apparent that S, through its influence on ρ_b, will affect both the slope and intercept of the calibration equation. The θ–n relationships for replicate tubes from the same soil layer may be confounded if ρ_b, and thus S, for the sphere of importance of each tube is not considered. For a given tube and depth, there should be a near-linear relationship between θ and n, provided ρ_b remains constant. If ρ_b changes appreciably with θ (the sphere of importance of the neutron meter varies with θ) the calibration may be affected. As well, for a given ρ_b and S, differences in the distribution of coarse fragments within the sphere of importance may also affect count rates (Couchat, 1973). Correction for these last two sources of error in field calibrations is difficult and will not be considered here.

Field Procedures and Calculations. We used a procedure similar to that outlined by Lasçano et al. (1986) to obtain neutron meter field calibrations with the two-probe gamma-density gauge. The latter instrument provided estimates of both θ and ρ_b. Two calibrations were obtained for the control: one for the upper soil horizons and one for the more compact lower horizons. As well, a separate calibration was developed for

the upper horizons of the ripped treatment because of its contrasting bulk density and surface conditions.

Neutron meter measurements were made at the 19- and 34-cm depths in the designated tube of each gamma pair. These measurements were made concurrently with two-probe gamma-density measurements at weekly to biweekly intervals throughout the growing season. At each depth, neutron count rates were taken during a 30-s interval. Prior to and following these sets of readings, eight 30-s standard counts were taken with the meter in a designated position on its transport case.

Gamma attenuation estimates of volumetric water content and total soil bulk density were averaged for a 10-cm depth interval centered at the 19-cm depth and for a 5-cm depth interval down to the 34-cm depth for neutron probe calibration. Gamma readings below 35 cm were not usually available because the stony, compact soil limited the depth to which tubes could be inserted.

Linear least-squares regression using θ, ρ_b, and n were then carried out. Increasing the depth interval for which gamma-density gauge readings of water content were averaged (i.e., to a 15- or 20-cm interval about the 19-cm depth) generally did not improve the standard errors or coefficients of determination, or significantly change the slopes of the calibration equations. Regressions were determined for individual tubes and for combinations of tubes for a given depth and treatment.

Good neutron meter field calibrations are most readily developed using a wide range of soil water contents (Greacen et al., 1981). This was best achieved in the control, where the pine grass cover provided a substantial seasonal soil water drawdown. The control was particularly effective in this regard when used in conjunction with a shelter to exclude rain. In contrast, water contents at the 34-cm depth in the ripped treatment did not vary sufficiently during the growing season to develop accurate calibrations of this type.

In 1989, four neutron access tubes in each of the ripped and control treatments were excavated at different times during the growing season to destructively determine total and fine soil bulk density and volumetric water content immediately after neutron readings were taken. A cylinder of soil 15 cm high, 10 cm in radius, and coaxially centered at the midpoint of the neutron meter access tube (providing a soil sample of $\approx$4700 cm^3) was removed at both the 19- and 34-cm depths. These samples were stored and analyzed using procedures similar to those outlined above for destructive sampling around the gamma tubes. Volumes excavated were determined by the volume displacement technique using dry sand. Large coarse fragments were sometimes encountered lying partially within the sampling volume. In these cases, the proportion that lay within the sample volume was estimated visually after delineation on the fragments in situ with a felt marker. The resulting data were used to verify the calibration equations obtained using the two-probe gamma-density gauge.

A mineral soil particle density of 2650 kg m^{-3} was used in all calculations for both the fine fraction and coarse fragments. The mean particle density of coarse fragments in the 2- to 5-mm-diam. class determined by the pycnometer method with kerosene (Blake and Hartge, 1986) was 2671 kg m^{-3}. Mean particle densities of coarse fragments in the 2- to 5- and 5- to 15-cm-diam. classes, determined by the submersion method (Blake and Hartge, 1986), were 2645 and 2651 kg m^{-3}, respectively.

RESULTS AND DISCUSSION

Effect of Tube Spacing on Gamma Measurements

The derived correction factor for tube spacing (Eq. [6]) was verified experimentally with gamma-density gauge measurements taken at x = 25.2, 32.3, and 39.4 cm in water. In each case, standard counts were taken in a magnesium block at a spacing of x = 25.2 cm. The estimated I_s at 25.2 cm exceeded the actual value by only 0.84% when x = 32.3 cm, and by 1.14% when x = 39.4 cm. Detector resolving time probably contributed to these slight overestimates.

Small deviations in tube spacing can have a large impact on gamma-density gauge count rates. Expected counts for different tube spacings were computed from Eq. [6], assuming a total soil bulk density of 1600 kg m^{-3} and a gravimetric water content of 0.15 kg kg^{-1}. Using these values, the errors in calculated total soil bulk density (Eq. [7]) and water content (Eq. [8]) arising from differences between actual (25.2 cm) and assumed source-detector distances are presented in Table 1. Deviations of 3 cm from the assumed tube separation distance resulted in a systematic bias of about $\pm$300 kg m^{-3} in the calculated total soil bulk density, and about $\pm$0.045 m^3 m^{-3} in the calculated volumetric water content. Bertuzzi et al. (1987) also reported sizable errors in calculated bulk density, using a length-specific calibration, as a result of small deviations in tube spacing.

The effects of deviations from the assumed tube spacing on estimates of total soil bulk density, volumetric coarse fragment content, and volumetric water content are illustrated in Fig. 2 for one of the tube pairs from the control. The actual separation distance of the gamma tube pair was 26.4 cm at the surface and 28.6 cm at a depth of 30 cm, compared with an assumed separation distance of 25.2 cm throughout. Consequently, error in the three variables increased with depth when actual tube spacing was not accounted for, resulting in substantial error for the lower part of the profile. Rawitz et al. (1982) also reported substantial errors in field dry density estimates at depth with this instrument when relatively small angular deviations in tube spacing were encountered.

In forest soils, large roots and course fragments make it difficult to install parallel access tubes a fixed distance apart for gamma-density gauge measurements. However, if deviations in tube spacing and alignment are calculated from the angular deviation of each tube and the distance separating the top and the bottom of the two tubes, theoretical corrections can be made for variable path lengths to provide accurate estimates of bulk density and water content. Use of gravimetric sampling to cal-

Table 1. Effect of actual tube separation distance on calculated bulk density and volumetric water content (Eq. [6]) with the dual-probe gamma-density gauge, assuming a separation distance of 0.252 m. Measurement at the correct tube separation distance yields a reference bulk density of 1600 kg m^{-3} and water content of 0.240 m^3 m^{-3}.

Actual separation distance	Calculated bulk density	Calculated water content
m	kg m^{-3}	m^3 m^{-3}
0.202	1084	0.163
0.212	1190	0.179
0.222	1295	0.194
0.232	1398	0.210
0.242	1500	0.225
0.252	1600	0.240
0.262	1699	0.255
0.272	1797	0.270
0.282	1895	0.284
0.292	1991	0.299
0.302	2086	0.313

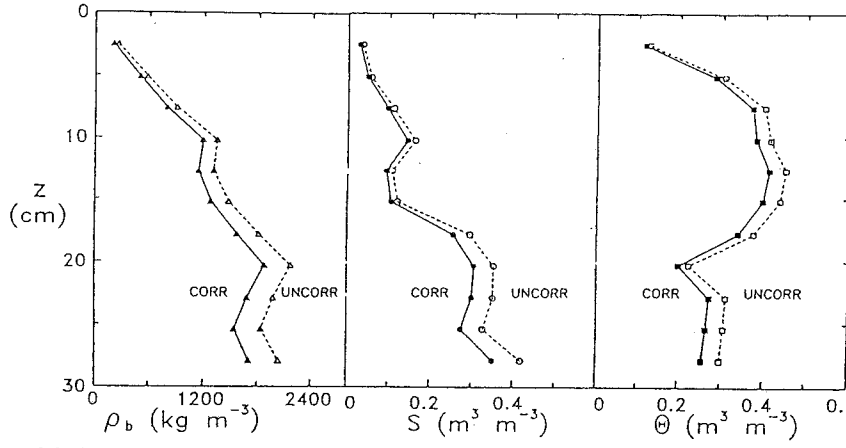

Fig. 2. Effect of deviations in tube spacing on two-probe gamma-density gauge estimates with depth (z) of (a) total soil bulk density (ρ_b), (b) coarse fragment content (S), and (c) volumetric water content (θ) in a control plot, uncorrected (using assumed tube spacing of 25.2 cm throughout) and corrected for actual tube separation distance of 26.4 cm at the surface and 28.6 cm at a depth of 30 cm.

culate deviations in gamma tube spacing, instead of excavation and direct measurement, as proposed by Rijtema (1969), is difficult in stony, heterogeneous soils.

Measurement of Bulk Density and Coarse Fragment Content by Gamma Attenuation

There was generally good agreement in total soil bulk density estimates obtained using gamma-density gauge readings (Eq. [7]) and destructive sampling for a given depth (Fig. 3). The dual-probe gamma-density gauge appeared capable of accurately detecting changes in total soil bulk density with depth. In 70% of the cases examined in this study (six or seven depth increments from each of six gamma tube pairs installed in different site preparation treatments), the two estimates differed by <200 kg m^{-3}. In these cases, there was no discernible pattern of discrepancy between the two methods. In a few instances, however, there were large discrepancies and in these cases gamma-density gauge estimates of bulk density were usually larger than those obtained with destructive sampling.

Differences in bulk density estimates with these two methods were attributed mainly to inaccuracies in the estimation of the volume removed for destructive sampling and to real differences in the bulk densities of the volumes actually measured with the two techniques. Destructive sampling was complicated by large coarse fragments that fell partially within the sample volume. A tendency to overestimate the volume actually removed by destructive sampling or underestimate the contribution of coarse fragments that lay partially within the destructive sampling volume could account for the large discrepancies that sometimes occurred. As well, the volume destructively sampled at each depth was two to three times greater than that measured by the gamma-density gauge. The coarse fragment content, and thus the total soil bulk density, within the volume sampled by the two methods could be substantially different.

Comparisons of coarse fragment content estimates also showed close agreement between those determined by

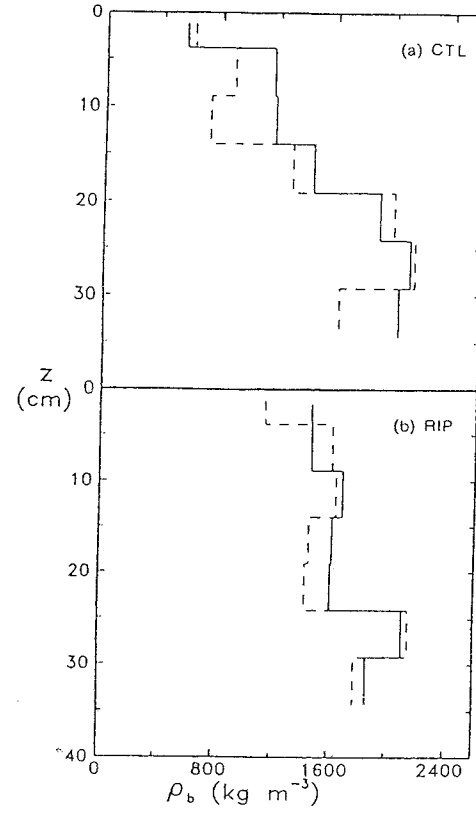

Fig. 3. Comparison of total soil bulk density (ρ_b) with depth (z) estimated by destructive volumetric sampling (dashed line) and by gamma attenuation (solid line) for an individual gamma tube installation in (a) the control plot and (b) the ripped plot.

gamma attenuation from Eq. [7] and [9] and excavation (Fig. 4). In 75% of the cases, volumetric coarse fragment contents estimated using the two methods agreed to within 0.045 m^3 m^{-3}. As can be seen from Eq. [9], this is the result of good agreement between the two methods in the measurement of total soil bulk density.

The gamma-density gauge was used to investigate the effects of ripping on total and fine soil bulk density and coarse fragment content in the seedling root zone. Great variability both within and between individual seedling root zone total soil bulk density profiles is evident for the control and ripped treatments 1 yr after site preparation (Fig. 5). Coefficients of variation ranged from 0.11 to 0.13 for both total and fine soil mean root zone bulk density, and from 0.21 to 0.36 for mean root zone coarse fragment content, in both treatments. Mean total and fine soil bulk densities in the ripped treatment were usually higher in the upper 10 cm of the profile, but slightly lower below 20 cm than those in the control. Low near-surface total soil bulk densities in the control reflected both the higher organic content and reduced coarse fragment content in the surface horizons. In contrast, the original 5- to 10-cm-thick surface horizons, including the organic horizons, had been scraped away when the plots were ripped.

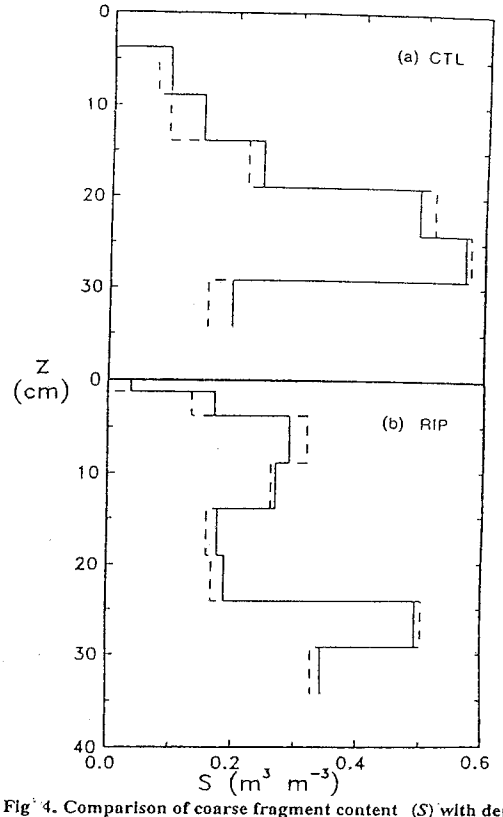

Fig. 4. Comparison of coarse fragment content (S) with depth (Z) estimated by destructive volumetric sampling (dashed line) and by gamma attenuation (solid line) for an individual gamma tube installation in (a) the control plot and (b) the ripped plot.

Measurement of Water Content using Gamma Attenuation

There is increasing interest in the use of site preparation techniques to improve soil water supply in the seedling root zone (Lanini and Radosevitch, 1986; Newton and Preest, 1988; Spittlehouse and Childs, 1990). The gamma density probe was used to compare the depth and time variation in volumetric water content in control and ripped plots during a 3-wk drying period in July 1987 (Fig. 6). There were large decreases in θ in the upper portions of the profile in both plots but reductions in θ were much less pronounced at greater depths in the ripped than in the control plot. The continued decrease in θ at depth in the control plot was probably due to the steady rate of transpiration by the deep-rooted pine grass (Adams et al., 1991). Consequently, there were higher soil matric potentials below 5 cm in the seedling root zone in the ripped plot as the drying period progressed.

Neutron Probe Calibration Using Gamma Attenuation

Gamma-based volumetric water content measurements were plotted against neutron count data (Fig. 7a). Strong linear relationships between θ and n for individual tubes were particularly apparent in the control plots, probably because the large seasonal variation in θ provided a wide range of θ–n values (mean r^2 of 0.93 for the 19-cm depth and 0.89 for the 34-cm depth in the control). Evidently, the neutron probe closely tracked changes in soil water content as measured by the two-probe gamma-density gauge. However, differences in the resulting intercepts and, to a lesser degree, slopes of these relationships for different tubes from a given depth and treatment were also evident. These were attributed to differences in ρ_b and S among the tubes.

Calibration equations were tested using the combined data for each of the control and the ripped plots at 19 cm. These two data sets provided a range of soil water contents and had the most comprehensive gamma-based estimates of ρ_b and θ. Volumetric water content was chosen as the dependent variable following Vachaud et al. (1977), Parkes and Siam (1979), and Haverkamp et al. (1984).

Regression results from Eq. [11] using ρ_b were unsatisfactory. Some of the independent variables were highly intercorrelated and usually one or more of the partial regression coefficients was not significant ($P > 0.10$). The term $\rho_b n$ was deleted because it was the least significant variable. This is consistent with Vachaud et al. (1977) and indicates a greater sensitivity of the intercept than the slope of the calibration equations to total soil bulk density as influenced by coarse fragment content (Couchat, 1973; Lal, 1974). The modified equation was written as

$$\theta = J + Kn + L\rho_b \qquad [11b]$$

where J, K, and L are constants. This equation, with $L = 0$, has commonly been used in neutron calibration (Greacen et al., 1981).

The use of Eq. [10], [10b], or [11b] improved the relative precision and the coefficients of determination of the neutron meter calibration for both treatments over

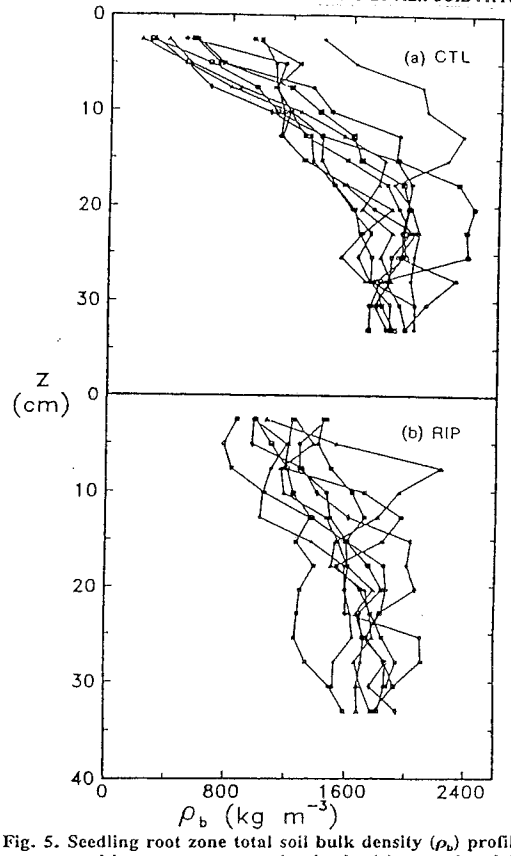

Fig. 5. Seedling root zone total soil bulk density (ρ_b) profiles measured by gamma attenuation in the (a) control and (b) ripped plots. Each profile represents measurements from a different tube pair. Ripping removed the surface 5 to 10 cm of the original soil profile, including the organic horizons. Depth (Z) is measured from the soil–atmosphere interface in both plots.

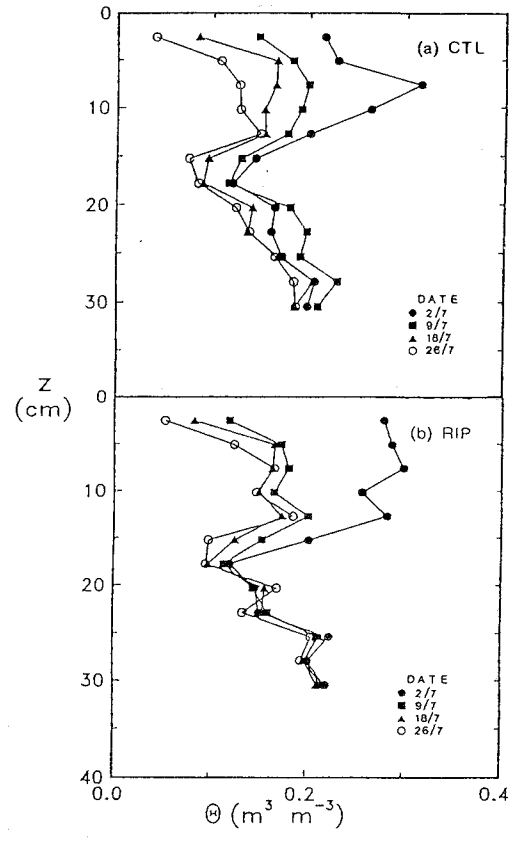

Fig. 6. Profiles of seedling root zone water content (θ) with depth (Z) during a 3-wk drying period in July 1987 for an individual gamma tube installation in (a) the control and (b) the ripped plot.

that of the simple linear model involving θ and n (Eq. [11b] with $L = 0$) (Table 2). This can be seen by comparing Fig. 7b, which uses the square root correction method (Eq. [10b]), with Fig. 7a, which uses Eq. [11b] with $L = 0$. All but one of the eight single-point θ measurements obtained through destructive sampling of the 15-cm-high by 10-cm-radius cylinders of soil around individual neutron meter access tubes (cf., Fig. 7b) fell within the 90% confidence interval of the predicted θ derived from Eq. [10], [10b], and [11b].

A similar proportion of the total variation in θ was accounted for by Eq. [10] and [11b] in both treatments, and by Eq. [10], [10b], and [11b] in the control (Table 2). For the ripped treatment, Eq. [10b] explained less of the total variation in θ and had a higher standard error of the estimate than Eq. [10] or [11b]. From a theoretical perspective, each of these empirical models has limitations; Eq. [11b] ignores the effect of bulk density on the slope of the calibration curve, while, according to Wilson and Ritchie (1986), the fractional power appearing in Eq. [10] and [10b] "is a surprise and difficult to understand on the basis of the way neutrons interact with matter".

Occasionally density-corrected data (θ–n') for a particular tube diverged from similar data from other tubes for the same treatment and depth. This was largely ascribed to inaccurate estimates of S and thus ρ_b, w, and θ for the sphere of importance of the neutron meter. This could result from errors in the determination of these variables within the gamma path or from conditions within the gamma path being unrepresentative of the larger volume measured by the neutron meter.

With regard to the first problem, the soil volume excavated between the gamma tubes to determine w, m_s, and m_f destructively was, as described above, two to three times larger than the volume actually measured by gamma attenuation. Depending on the exact location and orientation of coarse fragments within this larger volume, S and thus ρ_b and w in the volume measured by the detector could differ substantially from the values determined by destructive sampling.

With regard to the second problem, estimates of θ, ρ_b, and S associated with a given neutron meter measurement were obtained from gamma attenuation readings taken adjacent to but covering only a small fraction of the volume sampled by the neutron meter. Depending on the location and distribution of large coarse frag-

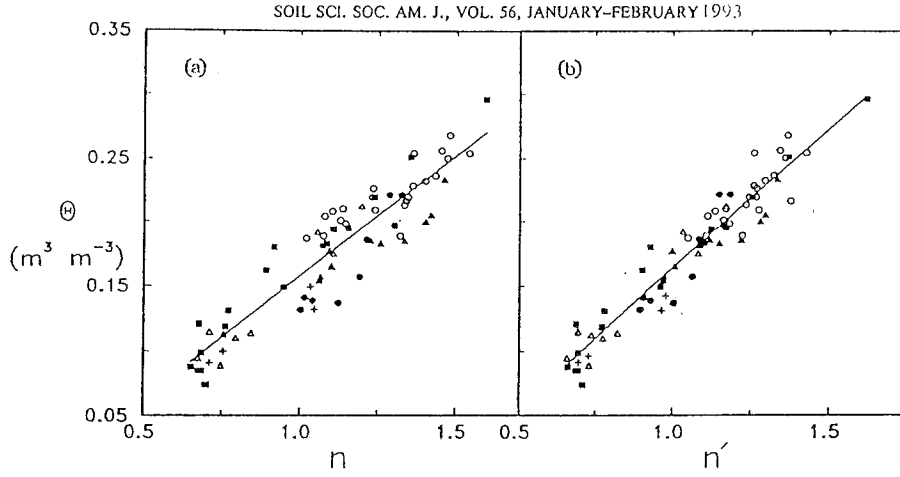

Fig. 7. Comparison of volumetric soil water content (θ) vs. (a) unadjusted (n) and (b) bulk-density-adjusted (n') neutron meter count rates at 19 cm for individual tubes in control plots. Measurements from a given tube pair are represented by the same symbol. The line through the data represents the best-fit least-squares linear regression for all data points combined. Also shown are four calibration points (+) obtained by destructive sampling using a 15-cm-high by 10-cm-radius cylinder of soil around each of four different neutron tubes to determine the water content within the sphere of importance.

ments, these gamma-based estimates for the sphere of importance of the neutron meter could contain sizable errors.

Given that $\theta = (1 - S)\rho_{bf}w_f/\rho_w$, the ratio ($\beta$) of θ in the gamma-density gauge (γ) and neutron meter (n) sampling volumes is $(1 - S_\gamma)/(1 - S_n)$. This assumes (i) ρ_{bf} and w_f show much less spatial variability than S, and (ii) θ is held entirely by the fine soil fraction, a reasonable assumption for relatively unweathered, nonporous coarse fragments (Coile, 1953; Flint and Childs, 1984b). Consequently Eq. [11b] with $L = 0$ would become $\theta = \beta J + \beta Kn$. Thus differences in coarse fragment content between the respective volumes sampled by gamma attenuation and neutron moderation can affect both the slope and intercept of the neutron calibration through their influence on θ. This is separate from and in addition to the effects of such differences on fast neutron scattering and absorption.

Using more gamma installations around each neutron tube would improve the accuracy of gamma-based estimates of S, ρ_b, and θ, but could be difficult to install and time-consuming to sample. The use of a gamma back-scattering density meter in conjunction with the neutron meter would provide concurrent estimates of soil density and water content at a given depth for each tube (Greacen and Hignett, 1979). However, this would not provide direct estimates of S, and differences in the spheres of importance of the two instruments should be consid-

Table 2. Regression equations and associated statistics for combined neutron calibration data from individual tubes for the different equations used for each treatment.

Treatment and depth	Equation	Intercept or variable†	Coefficient value	Standard error	Student's T statistic	F ratio	Adjusted R^2	Standard error of estimate
Control, 19 cm (n = 68)	[11b] $L = 0$	J	−0.031	0.011	−2.77	373	0.847	0.020
		n	0.189	0.010	19.31			
	[11b]	J	0.086	0.016	5.46	424	0.927	0.014
		n	0.217	0.008	28.74			
		ρ_b	−8.36‡	9.84§	−8.50			
	[10]	A	−0.032	0.017	−1.93	372	0.925	0.014
		$n\rho_b^{-0.5}$	8.968	0.315	27.46			
		ρ_b	−1.43‡	9.13§	−2.14			
	[10b]	H	−0.055	0.008	−6.53	809	0.923	0.014
		n'	0.220	0.008	28.45			
Ripped, 19 cm (n = 55)	[11b], $L = 0$	J	−0.075	0.037	−2.04	48	0.466	0.043
		n	0.209	0.030	6.93			
	[11b]	J	0.215	0.032	6.64	146	0.843	0.023
		n	0.163	0.019	8.25			
		ρ_b	−1.49¶	1.32‡	−11.3			
	[10]	A	0.125	0.041	3.03	150	0.846	0.023
		$n\rho_b^{-0.5}$	5.389	0.639	8.43			
		ρ_b	−8.76‡	1.70‡	−5.15			
	[10b]	H	−0.072	0.019	−3.87	184	0.772	0.028
		n'	0.196	0.014	13.57			

† Uppercase letters refer to intercept values for Eq. [10], [10b], and [11b]; n is the neutron meter count ratio; $n' = n(\rho_{bx}/\rho_b)^{0.5}$; ρ_b is the total soil bulk density; and ρ_{bx} is a selected standard total soil bulk density.
‡ × 10^{-5}
§ × 10^{-6}
¶ × 10^{-4}

ered. Another approach would be to excavate the approximate sphere of importance for the neutron meter for each reading depth to independently determine S, ρ_b, and θ at the same time as the gamma tubes are excavated. If neutron readings were taken immediately before excavation, this data (representing one point on the calibration curve) could also be used to verify or adjust the intercept of the calibration equation.

Consideration should also be given to the number of sampling points (tubes) needed to provide mean water content values within a required precision (Vauclin et al., 1984). For stony soils, the volume sampled by the neutron meter may be relatively small in relation to the scale of heterogeneity in coarse fragment content, total and fine soil bulk densities, and water content within a given soil layer. Thus readings from a number of tubes may be required to obtain reasonably accurate estimates of average water content for a particular depth at a given time.

CONCLUSIONS

The two-probe gamma-density gauge was used effectively to measure profiles of θ, ρ_b, and S in forest soils. It provided good measurements of these variables for small volumes in vertical increments of 5 cm. Gauge readings were effectively converted to measurements of ρ_b, θ, and S by determining, at the end of the experiment, the actual tube spacing, the mass wetness (w) and the mass ratio of coarse fragments to coarse fragments plus fine soil $[m_s/(m_s + m_f)]$ for the gamma path length without measuring the volume of the sample. The instrument is particularly useful for studies of near-surface silvicultural treatment effects, such as ripping, on soil bulk density and water content.

The complex, highly variable matrix of many stony forest soils complicates neutron meter calibration. Use of a two-probe gamma-density gauge enabled calibration to be done at actual bulk densities and coarse fragment content distributions found at the field location. Gamma attenuation measurements provided repeated nondestructive measurements of θ with time within the neutron probe sphere of importance, as well as estimates of ρ_b. The rapidity of gamma measurements allowed several tubes to be used to construct mean calibrations for specific treatments and depths that accounted for both θ and ρ_b. It also avoided the difficulties associated with volumetric determinations of θ and ρ_b by excavation where large coarse fragments were present. However, the soil volume sampled by the two-probe gamma-density gauge is much smaller than and not entirely contained within that sampled by the neutron meter. In stony soils, differences in coarse fragment content in the sampling volume of the two instruments may occur and could lead to biased estimates of the slope and intercept of the neutron calibration. Further work is needed to refine field techniques for rapidly measuring ρ_b and S in soils with large coarse fragment contents and to incorporate their effects in neutron meter calibrations.

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APPENDIX II

DETERMINATION OF ROOT ZONE SOIL WATER POTENTIAL USING IN SITU PELTIER-COOLED THERMOCOUPLE PSYCHROMETERS

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DETERMINATION OF ROOT ZONE SOIL WATER POTENTIAL USING IN SITU PELTIER-COOLED THERMOCOUPLE PSYCHROMETERS

I. INTRODUCTION

Thermocouple psychrometry provides a rapid, non-destructive means of inferring the water potential of the liquid phase of a soil (Ψ_s) from *in situ* measurements of the relative humidity (*RH*) of the vapor phase in equilibrium with it (Rawlins and Campbell 1986). Under isothermal conditions Ψ_s values between -0.10 MPa and -7.00 MPa can be accurately determined with *in situ* Peltier-cooled thermocouple psychrometers (TCPs) (Savage and Cass 1984). However, temperature gradients within the thermocouple cavity or between the cavity and the surrounding soil can produce substantial errors in estimates of Ψ_s.

At shallower soil depths in open clearcuts large temperature gradients pose a severe constraint to the use of TCPs (Wiebe et al. 1977; Savage and Cass 1984). One means of addressing this problem is to make *in situ* TCP measurements during periods of the day when temperature gradients are minimized (Wiebe and Brown 1979; Savage and Cass 1984; Brown and Chambers 1987). This Appendix outlines the effects of commonly occurring root zone

temperature gradients on TCP outputs, and indicates how soil temperature and zero offset measurements can be used to select diurnal TCP readings which are least affected by these gradients.

II. THEORY OF OPERATION

Peltier-cooled thermocouple psychrometers are used to determine the dry bulb temperature (T) and the wet bulb temperature depression ($\Delta T = T - T_w$, where T_w is the wet bulb temperature) of the soil water vapor. T is commonly measured with a copper-constantan thermocouple while T_w is commonly measured with a chromel-constantan thermocouple, the measurement junction of which is first Peltier-cooled below the dew point to form a wet bulb. The output voltages generated by these two thermocouples determines T (°K) and ΔT, and these values are used with the psychrometric equation to calculate the soil water vapor pressure:

$$e = e_w - (\rho c_p R_v T/\lambda)\Delta T \tag{1}$$

where e_w is the saturation vapor pressure at T_w, ρ is the density of the soil air, c_p is the specific heat of the soil air, R_v is the gas constant for water vapor, and λ is the latent heat of vaporization of water.

Eq. [1] can be rearranged to give an explicit expression for *RH* (e/e_o)(Campbell 1979):

$$e/e_o = 1-[(s+\gamma)/e_o]\Delta T \tag{2}$$

where e_o is the the saturation vapor pressure at ambient temperature, s is the slope of the saturation vapor pressure curve, and γ is the thermodynamic psychrometer constant ($\rho c_p R_v T/\lambda$ or $Pc_p/\varepsilon\lambda$, where P is the atmospheric pressure and ε is the ratio of the molecular weight of water vapor to that of dry air). It is assumed that ΔT is small enough that $e_o - e_w \cong s\Delta T$, and that the ratio of vapor flow resistance to that of sensible plus radiant heat flow resistance approaches unity. The term $(s+\gamma)/e_o$ in Eq. [2] is temperature but not pressure dependent.

The soil water potential (Ψ_s) is related to *RH* by the Kelvin equation:

$$\Psi_s = (R_v T)\ln(e/e_o) \tag{3}$$

In soils e/e_o is usually >0.95 and $\ln(e/e_o)$ can be approximated by e/e_o-1. Combining Eq. [2] and Eq. [3], and using this approximation (Campbell 1979):

$$\Psi_s = -R_v T[(s+\gamma)/e_o]\Delta T \tag{4}$$

Thus Ψ_s is a linear function of both ΔT and T. However, the likely magnitude of measurement errors in T associated with copper-constantan thermocouples (<1 °K) have little effect on estimates of Ψ_s (Campbell 1979).

The effect of measurement errors in ΔT on estimates of Ψ_s may be described by:

$$\delta\Psi_s = \delta(\Delta T)d\Psi_s/d\Delta T \tag{5}$$

and, from Eq. [4]:

$$\delta\Psi_s = R_v T[(s+\gamma)/e_o]\delta(\Delta T)) \tag{6}$$

For instance, at 20°C, $R_v T[(s+\gamma)/e_o]$ = 12.21 MPa $^\circ K^{-1}$, and an error of 0.1 °C in ΔT will result in an error of 1.221 MPa in Ψ_s. Thus small errors in ΔT may cause large errors in Ψ_s.

With TCPs, ΔT is measured using the voltage produced by the wet bulb depression of the chromel-constantan measurement junction located in the middle of the shield cavity, when referenced to the chromel - copper and constantan - copper reference junctions at the base of the TCP. This is used to approximate ΔT of the surrounding soil. Large errors in the determination of Ψ_s can arise because of differences in temperature between the sensing or reference junctions and the surrounding soil. Other sources of error include error or drift in the zero setting and electronic noise (Campbell 1979).

III. EXPERIMENTAL METHODS

The effects of thermal gradients on *in situ* TCP readings were investigated using groups of TCPs set out at depths of 5, 15 and 30 cm in

the control plot within the rainout shelter at the IDFdk site (Appendix III). The TCPs (J.R.D. Merrill Specialty Equipment, Logan UT, 74 Series Screen Cage Psychrometers) were first individually calibrated at 20 °C in a temperature-controlled water bath using calibration chambers (Merrill Specialty Equipment, Part #81-500) and NaCl solutions corresponding to osmotic potentials of -0.45, -0.90 and -1.79 MPa (Brown and Collins 1980). Calibration coefficients for each TCP were then obtained using the calibration model of Brown and Bartos (1982).

Groups of TCPs were installed in the rainout shelter by excavating a narrow pit 40 cm deep with a smooth vertical face on one side. Individual TCPs were inserted horizontally at least 15 cm into this face, at the required depths, in holes created with a metal rod of similar diameter as the TCPs (Merrill and Rawlins 1972). Before backfilling with soil, several coils of lead wire from each TCP were placed in the excavated pit slightly below the level of insertion. This reduced thermal gradients near the sensor and prevented water from running down the wire to the TCP (Brown and Chambers 1987).

Hourly TCP readings were taken with Campbell Scientific Inc., Logan, UT, Model A3497 TCP Cooling Current Interfaces attached to a Campbell Scientific Inc., Model CR7X data logger. The TCP reference temperature and zero offset (the temperature difference between the sensing junction and the two reference junctions (Brown and Bartos 1982)) were first recorded. A 4.5 mA current was then used to cool the sensing junction for 10 s, and this was followed immediately by 10 consecutive readings of ΔT (*in* μV) at 1.4 s

intervals. Each reading represented the mean of five differential measurements with the zero offset subtracted.

IV. RESULTS AND DISCUSSION

Diurnal TCP temperature, zero offset and ΔT readings are presented for two days in 1988, one near the beginning of August before rain was excluded from the shelter, and one near the end of August following three weeks of imposed drought. The first day (August 4) was clear and warm in the morning but cloudy in the afternoon, with a peak in hourly solar irradiance of 950 W m^{-2} and screen height air temperature of 25 °C at 12:00 h. The upper 10 cm of the soil profile had been wetted by 12.0 mm of rain on August 1, but prior to this, less than 7 mm of rain had fallen since July 6. The second day (August 22) was a cloudless, warm day with a peak in solar irradiance of 825 W m^{-2} and a maximum hourly screen height air temperature of 24°C. Rainfall had been excluded from the shelter since August 2.

1. Soil Temperature and Zero Offsets:

Diurnal soil temperature amplitudes and the magnitude of zero offsets were greatest near the surface and decreased with depth on both days. On August 4, soil temperatures at the three depths converged around 9:00 h (PST), and for a brief time were within 0.3 °C of each other (Fig. A2.1). In comparison, zero offset magnitudes for the three depths on this day converged to near zero around 8:00 h (Fig. A2.2). Although temperature

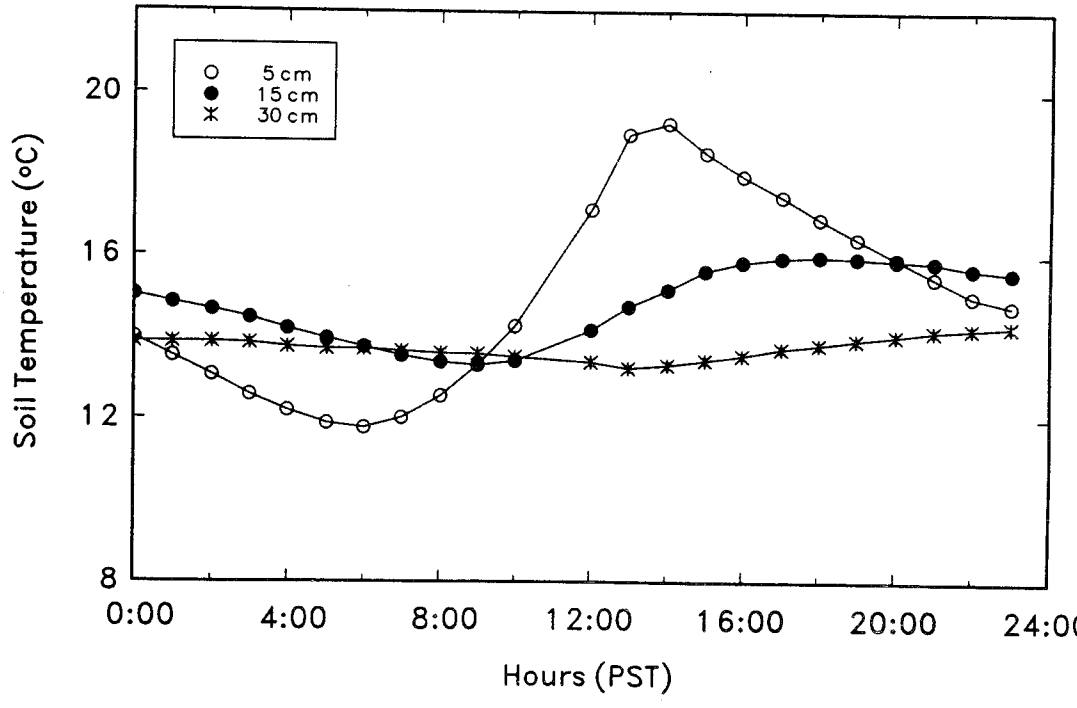

Fig. A2.1. Mean hourly TCP soil temperature measurements at the 5, 15 and 30 cm depths in the control plot in the IDFdk rainout shelter on August 4, 1988.

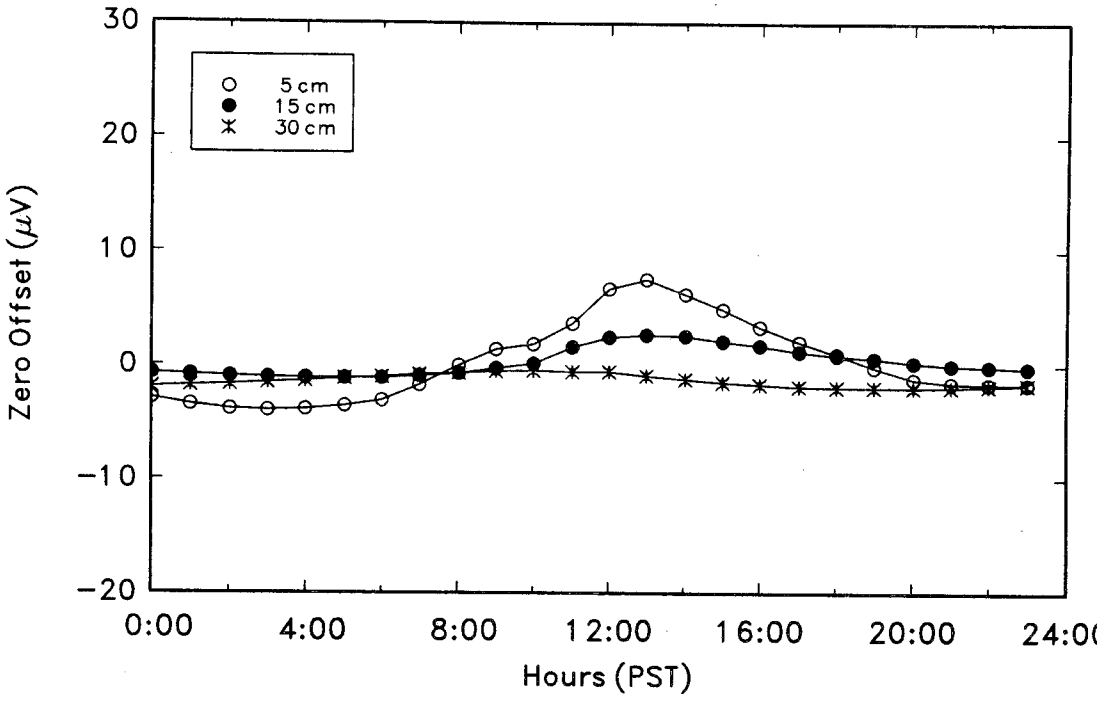

Fig. A2.2. Mean hourly TCP zero offset measurements at the 5, 15 and 30 cm depths in the control plot in the IDFdk rainout shelter on August 4, 1988.

differences between depths were also reduced late in the day (between 20:00 and 24:00 h), temperature and zero offsets did not converge as they did at 9:00 h.

On August 22, temperatures at the 5 cm depth converged with those at the 15 cm depth around 9:00 h, and shortly afterwards with those at the 30 cm depth (Fig. A2.3). In contrast, temperatures at the 15 cm depth converged around 11:00 h with those at the 30 cm depth. Similarly, the lowest zero offset magnitudes at the 5 cm depth occurred about 2.5 h earlier in the morning than did those at the 15 and 30 cm depths (Fig. A2.4). On this day, minimum zero offset magnitudes were attained 1.0 - 1.5 h before temperatures for the corresponding depths converged. Temperatures at the three depths also approached one another between 21:00 and 24:00 h, but did not converge as they had earlier in the day. Zero offsets at the three depths converged near zero around 16:00 h, when there were large temperature differences between depths, but not between 21:00 and 24:00 h.

Evidently, minimum soil temperature gradients are likely to occur at different times of day, depending on measurement depth, soil characteristics, atmospheric conditions and day length (Stathers et al. 1985).

2. Wet Bulb Temperature Depression and Inferred Soil Water Potentials

On August 4, the largest diurnal variations in ΔT were found at the 15 cm depth (Fig. A2.5), despite much larger diurnal variations in temperature at the 5 cm depth (Fig. A2.1). Because of a wetting front, Ψ_s was considerably higher at 5 cm than at 15 cm. Other studies have also reported much greater

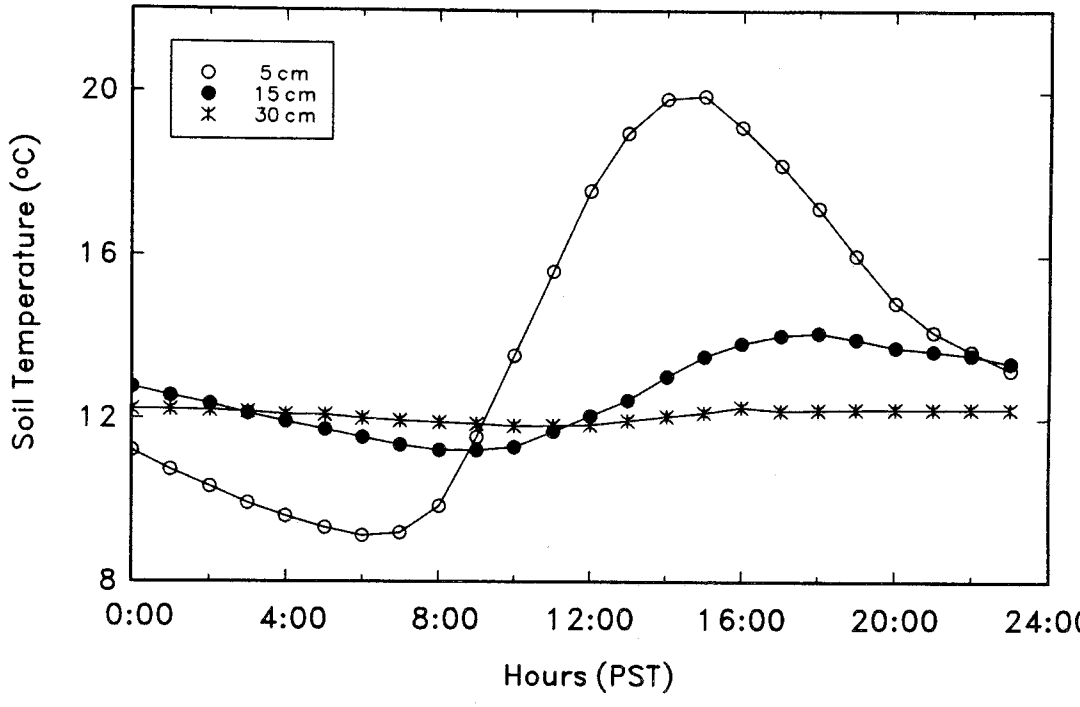

Fig. A2.3. Mean hourly TCP soil temperature measurements at the 5, 15 and 30 cm depths in the control plot in the IDFdk rainout shelter on August 22, 1988.

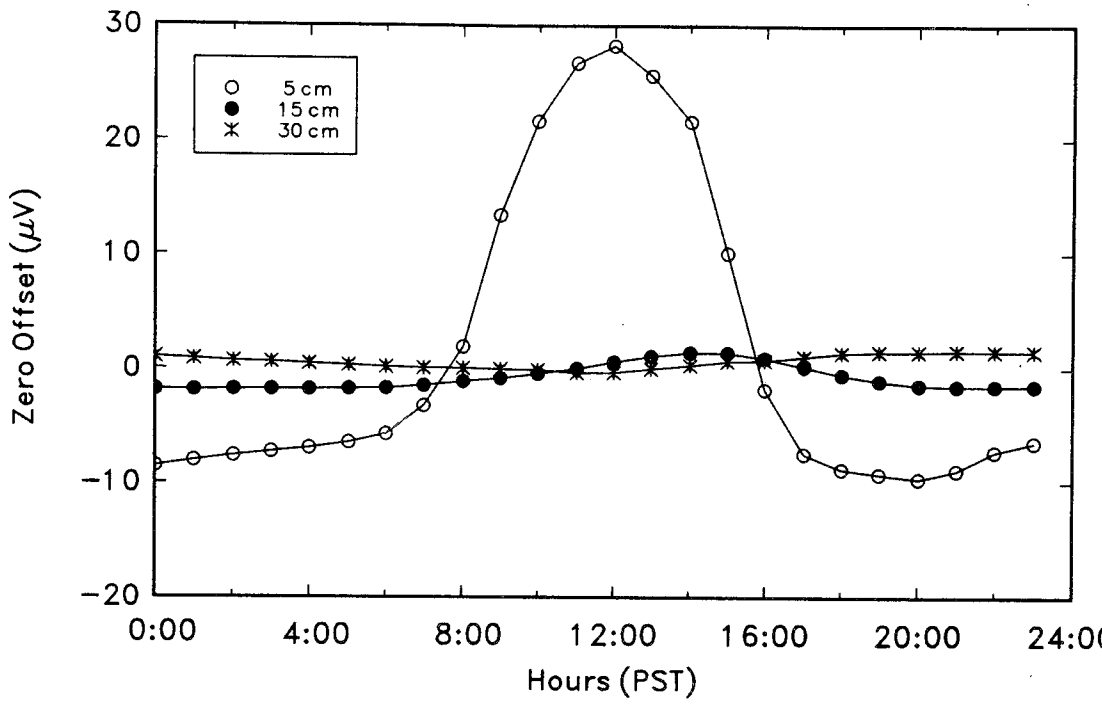

Fig. A2.4. Mean hourly TCP zero offset measurements at the 5, 15 and 30 cm depths in the control plot in the IDFdk rainout shelter on August 22, 1988.

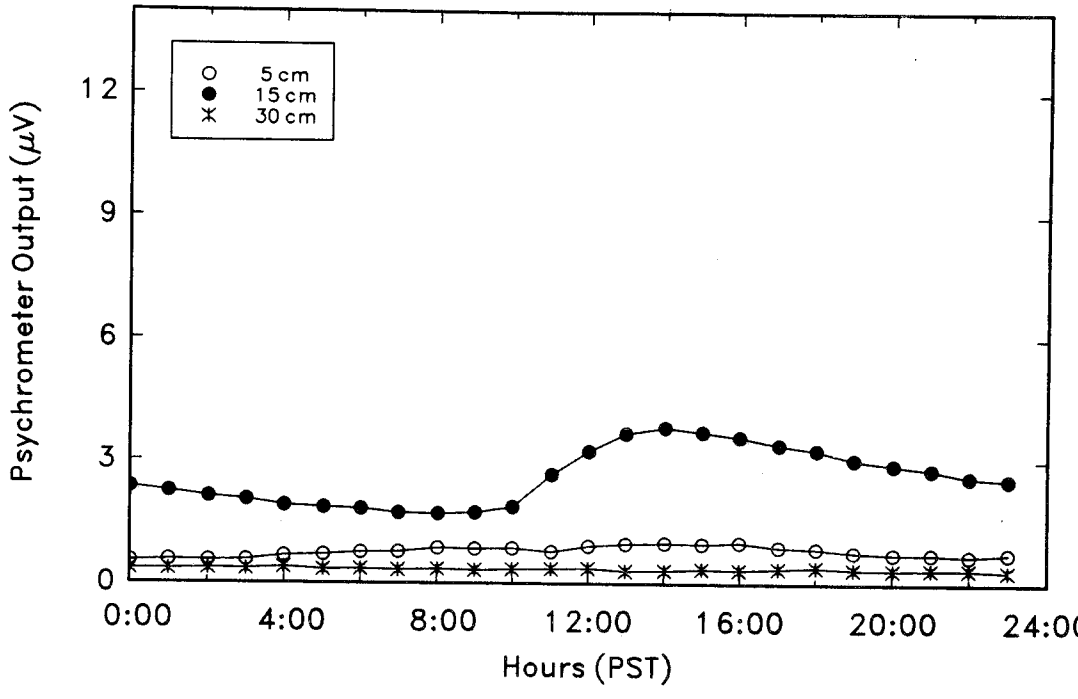

Fig. A2.5. Mean hourly TCP wet bulb depression (ΔT) measurements at the 5, 15 and 30 cm depths in the control plot in the IDFdk rainout shelter on August 4, 1988.

effects of temperature gradients on ΔT measurements at low Ψ_s (Brown and Bartos 1982; Brown and Chambers 1987). This may be attributed to: 1) substantial diurnal changes in Ψ_s at low Ψ_s resulting from vapor movement induced by temperature gradients (Campbell and Gardner 1971; Campbell 1985); 2) greater physical disruption of water and heat flow patterns by the sensors at low Ψ_s (Campbell 1979); and 3) greater effects of temperature gradients on condensation and drying within the TCP shield at low Ψ_s (Wiebe and Brown 1979).

On August 22, the largest diurnal variations in TCP ΔT measurements occurred at the 5 cm depth (5-13 μV), followed by the 15 cm depth (4.0-5.3 μV) and then the 30 cm depth (2.0-2.2 μV)(Fig. A2.6). Some of this variation results from the temperature dependence of ΔT measurements, which is often corrected for using (Savage and Cass 1984):

$$\text{Correct } \Delta T \text{ Value } (\mu V) = \text{Actual } \Delta T \text{ Value } (\mu V)/(0.325 + 0.026T_s(^\circ C)) \qquad (7)$$

where T_s is the soil temperature.

However, use of Eq. [7] together with the maximum and minimum diurnal 15 cm soil temperatures, accounted for only 11% of the difference between the maximum and minimum ΔT values recorded at this depth on August 4, and 20% of the difference recorded on August 22.

These results demonstrate that TCP estimates of Ψ_s can vary greatly during the day because of thermal gradients, even when recommended methods of calibration, installation and measurement (including subtraction of zero offset readings) are followed. The wide diurnal variation in zero offset and

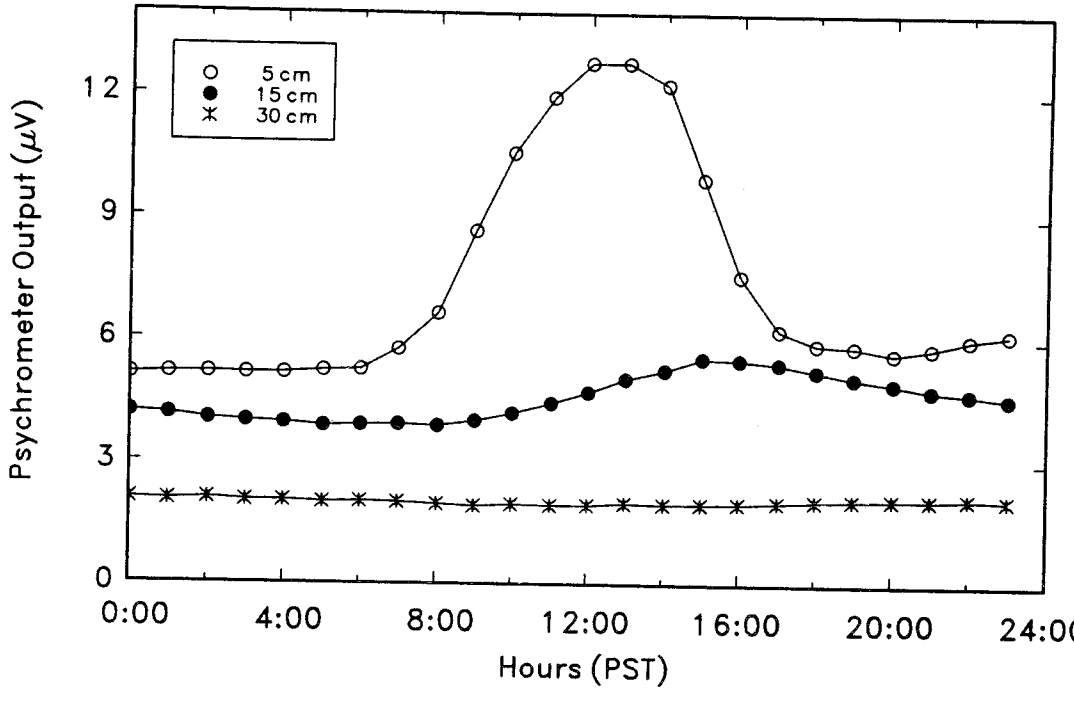

Fig. A2.6. Mean hourly TCP wet bulb depression (ΔT) measurements at the 5, 15 and 30 cm depths in the control plot in the IDFdk rainout shelter on August 22, 1988.

ΔT values at 5 cm on August 22 suggests that, even with automated measurement systems, accurate measurements of Ψ_s at this depth may be difficult to obtain. On clear days, there is only a short period when thermal equilibrium is approached at this depth, and its occurrence varies with factors such as day length, solar irradiance and soil water content. In addition, thermally induced condensation or evaporation within the TCP shield, and differences in the rate of heat versus water vapor transport across the TCP shield (Rawlins and Campbell 1986) may confound attempts to measure Ψ_s at this depth during the short periods of relative isothermality. Nighttime measurements of ΔT at this depth appear much more stable (Fig. A2.6) but concurrent large nighttime zero offsets (Fig. A2.4) are cause for concern.

At depths ≥ 15 cm, automated, simultaneous recording of TCP temperature, zero offset and ΔT measurements at regular intervals throughout the day likely offers an effective means for selecting appropriate ΔT measurements. The accuracy of measurements should increase with depth because diurnal soil temperature amplitudes, and consequent effects on thermally induced vapor movement, and on heat and vapor exchange between the TCP and the soil, will decline.

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APPENDIX III

A RAINOUT SHELTER TO STUDY SEEDLING RESPONSE TO DROUGHT AND SITE PREPARATION

APPENDIX III

A RAINOUT SHELTER TO STUDY SEEDLING RESPONSE TO DROUGHT AND SITE PREPARATION TREATMENT

I. INTRODUCTION

Field research to evaluate the effects of drought on soil processes and plant response is often confounded by randomly occurring rainfall events. Removable rainout shelters of various designs are commonly used in agricultural research to address this problem (Foale et al. 1986), but have rarely been employed in silvicultural research. These shelters control water supply while maintaining appropriate diurnal and seasonal fluctuations in soil and aerial microclimates (Ritchie 1987).

In this study a rainout shelter was constructed on a backlog clearcut site in the Interior Douglas-fir (IDFdk) Biogeoclimatic Subzone (Mitchell et al. 1981) to examine the effects of drought and site preparation on soil water supply, soil hydraulic characteristics, and seedling water relations and growth. This Appendix describes the design and layout of the shelter and the instrumentation used to monitor microclimate and seedling response.

II. DESIGN AND LAYOUT

The rainout shelter was constructed in May, 1988 and protected a study area of 5.0 x 3.5 m. It consisted of a wooden frame with a central beam 1.5 m high which bisected the long axis of the shelter, and two shorter beams (0.5 m high) running along the long axis on either side of the shelter (Fig. A3.1). Ten removable 1.2 x 2.4 m coverings were constructed of translucent corrugated fiberglass attached to wooden frames of nominal 5 x 10 cm stock that were then held in place on the beams by supports and ropes. When the coverings were in place, they overlapped the ends of the study area by 0.5 m and the sides of the study area by 0.3 m. There was a 30 cm gap for ventilation along each side of the shelter between the coverings and the soil surface, and a larger, triangular-shaped gap at either end.

To prevent subsurface lateral flow or root extension from the surrounding vegetation, the perimeter of the shelter was excavated and subsequently backfilled after a polyethylene lining (0.15 mm thick and 0.7 m in depth) was installed. Plastic gutters were placed on the outside beams on either side of the shelter to divert water running off the coverings into two tanks, each 2 m in diameter and 35 cm deep.

The corrugated fiberglass coverings were removed and stored near the rainout shelter when there was no immediate threat of rain. Thus the plots were subjected to ambient air temperatures, solar irradiance and wind speeds, for the most part, minimizing differences in microclimate caused by the shelter itself (Legg et al. 1978; Dugas and Upchurch 1984). It took

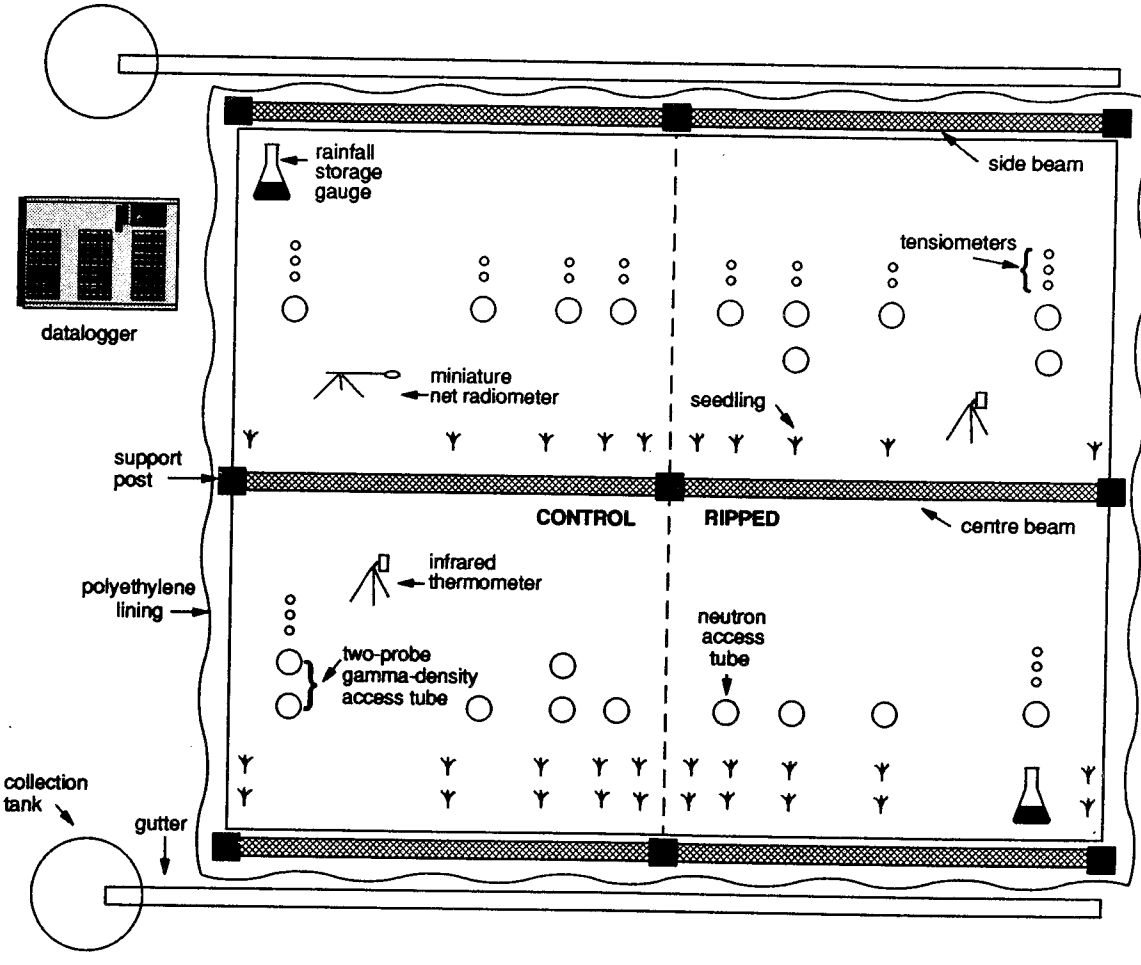

Fig. A3.1. Layout and instrumentation for the rainout shelter constructed at the IDFdk site near Fehr Mountain.

approximately 15 min to place the coverings on the rainout shelter and an additional 15 min to secure them.

The long axis of the study area was bisected by the border between a ripped site preparation treatment (Chapter 1) and an untreated control (Fig. A3.1). The control plot (2.5 x 3.5 m) was a continuous area of untreated native vegetation, largely pinegrass (Calamagrostis rubescens Buck.), while the ripped plot (also 2.5 x 3.5 m) had been uniformly ripped (Chapter 1) in the fall of 1987. The exclusion of rain from these two plots resulted in gradients in soil water potential across the long axis of the study area (Fig. A3.2), permitting study of seedling response to different levels of soil water potential and extractable soil water under otherwise similar conditions. The lowest soil water potentials were found in the control while the highest soil water potentials were found in the ripped portion, >1 m from the border between the two plots (the plot border).

In the spring of both 1988 and 1989, the ripped plot was loosened with shovels to a depth of about 25 cm and then leveled with rakes. At the same time, roots of vegetation were severed with a spade to a depth of 40 cm at the plot border. Boardwalks 30 cm high and 20 cm wide were constructed both inside and outside the shelter so that shelter coverings, access tubes and instruments could be installed and used without disturbing the surface of the plots.

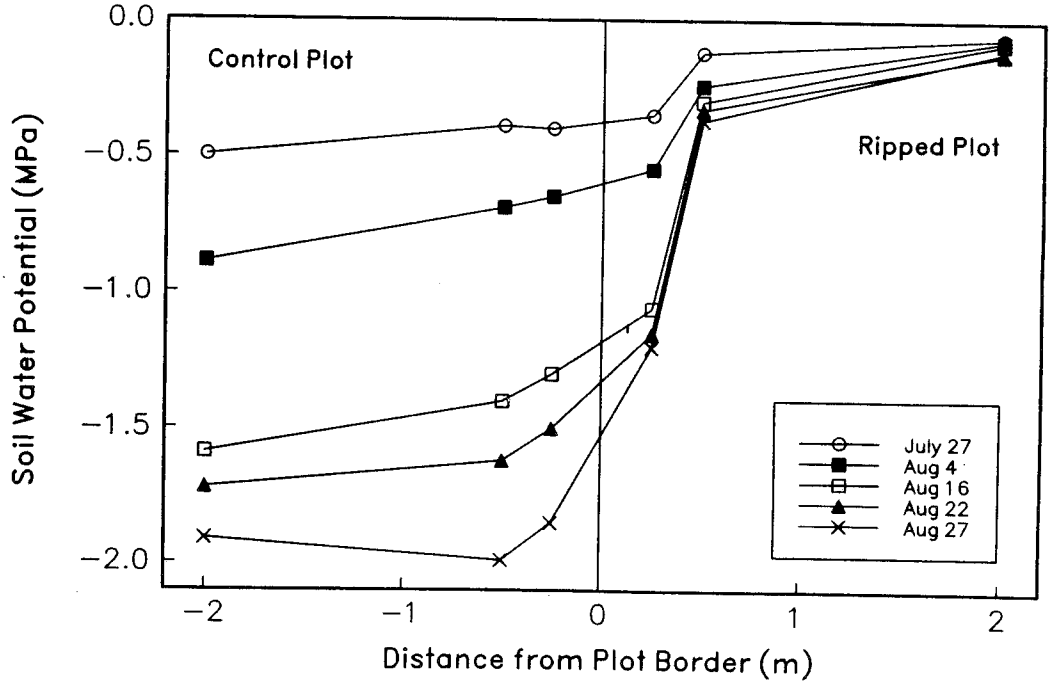

Fig. A3.2. Soil water potential at 15 cm in the rainout area for selected periods in the summer of 1989. Measurements were made with thermocouple psychrometers, and where appropriate, tensiometers, 0.25, 0.50 and 2.0 m from the plot border in both the control and ripped plots. Rain was excluded from the rainout area from July 5 to August 31, 1989.

III. MEASUREMENTS

1. Soil water content

Two transects of neutron meter access tubes were established across each plot within the rainout area, allowing duplicate measurements of water content at distances of 0.25, 0.5, 1.0 and 2.0 m in each direction from the plot border (Fig. A3.1). For comparison, two additional transects of neutron meter access tubes at similar spacings were established across a similar plot border between a control and a ripped treatment adjacent to but outside the rainout shelter. Weekly measurements of soil water content, centered at the 19 and 34 cm depths, were made in each access tube using a neutron meter (Campbell Pacific Nuclear Corp., Martinez, CA, Model 503 Hydroprobe with an Am 241-Be source and He 3 detector). Additional measurements were made at the 49, 64 and 79 cm depths in the control and ripped plots, 2.0 m from the plot border, using deeper neutron meter access tubes.

Soil water content in the top 30 cm was also measured in 2.5 cm increments in both plots, 0.5 and 2.0 m from the plot border, with a dual-probe gamma-density gauge (Troxler Electronic Laboratories Inc., Triangle Park, NC, Model 2376 Two Probe Density Gauge with a 5 mCi Cs 137 source and NaI scintillation detector). For this purpose, additional access tubes were inserted 25.2 cm away from but parallel to neutron meter access tubes at the appropriate distances from the border. Further details on access tube installation, and neutron meter and gamma-density gauge calibration and use are found in Chapter 1 and Appendix I.

2. Soil water potential

Soil water potential (Ψ_s) was measured with thermocouple psychrometers (TCPs) and tensiometers. Duplicate groups of TCPs (J.R.D. Merrill Specialty Equipment, Logan UT, 74 Series Screen Cage Psychrometers) were installed at depths of 5, 15 and 30 cm in the control and ripped plots near neutron meter access tubes located 0.25, 0.5 and 2.0 m from the plot border. Automated hourly readings were made with these TCPs using Campbell Scientific Inc, Logan, UT, Model A3497 TCP Cooling Current Interfaces attached to a Campbell Scientific Inc. Model CR7X data logger. Further details on TCP calibration, installation and measurement techniques are outlined in Appendix II.

Pairs of tensiometers, constructed according to the design of Marthaler et al (1983), were installed at depths of 15 and 30 cm in each plot near neutron meter access tubes located 0.25, 0.5, 1.0 and 2.0 m from the plot border. These were read with a pressure transducer (Soil Measurement Systems, Tucson, AZ, Model SW-010 Tensimeter) and provided measurements of Ψ_s >-80 kPa. Tensiometers and TCPs were also installed at the 45 and 90-cm depths, 2.0 m from the border in both plots.

3. Unsaturated hydraulic conductivity

Measurements of sorptivity and steady-state water flow rates were taken at depths of 10 and 30 cm in the control and ripped plots with a CSIRO Disc Permeameter (A.L. Franklin PTY. Ltd., Brookvale, New South Wales). Five or six measurements were made at a given depth in each plot at water supply potentials ranging from -0.07 to -0.91 kPa, and used to calculate

unsaturated hydraulic conductivities ($K(\Psi_s)$) following Perroux and White (1988).

4. Soil temperature

Soil temperatures were determined with TCPs at the distances and depths outlined above. Additional integrated hourly measurements of soil temperature were made with thermistor probes (Fenwall Electronics, Framingham, MA, UUT-51J1 thermistors potted in Armstrong C7 epoxy, configured as in the Campbell Scientific Inc., Logan, UT, Model 101 thermistor probe) installed at depths of 5 and 15 cm in the control and ripped plots, 0.25, 1.0 and 2.0 m from the plot border. Thermistors were also placed at depths of 45 and 90 cm in each plot, 2.0 m from the plot border.

5. Other measurements of the physical environment

Two infra-red thermometers (Everest Interscience Inc., Fullerton, CA, Model 4000A) with a 60° field of view were used with a Campbell Scientific Inc., Logan, UT, Model CR7X data logger to determine half-hourly mean surface temperatures for selected periods in the control and ripped plots. These instruments were mounted on tripods 50 cm above the surface, giving a viewing area of about 2,600 cm^2. Surface albedos for the ripped and control surfaces were determined at different times during several cloudless days with a Dome Solarimeter (Lintronics, UK, Model M/188) held 50-70 cm above the surface.

IV. SEEDLING OUTPLANTING

In May of 1988 and 1989, equal numbers of one-year-old lodgepole pine (Pinus contorta Dougl.) 2-12 plug seedlings and one-year-old Douglas-fir (Psuedotsuga menziesii (Mirb.) Franco) 3-13 plug seedlings were planted in 10 rows across both plots, 0.15, 0.3, 0.6, 1.2 and 2.4 m from the plot border. These seedlings were periodically sampled to determine diurnal and seasonal patterns of transpiration, stomatal conductance and xylem pressure potential, as a function of treatment and distance from the border. Individual seedlings were subsequently harvested to determine biomass, leaf area and rooting characteristics.

Results from this study were analyzed by Scott (1991) and will be the subject of a future report.

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