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Water stress response after thinning Pinus contorta stands in Montana

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WATER STRESS RESPONSE AFTER THINNING *PINUS CONTORTA* STANDS IN MONTANA

By

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Water Stress Response After Thinning *Pinus contorta* Stands in Montana (49 pp.)

Director: Dr. Steven W. Running SWR

This study compared the leaf water potential of thinned stands of lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) to adjacent controls at three sites in Montana. The even-aged stands had average ages of 48, 58, and 60 years with initial stocking densities of 2000, 2500, and 12,000 stems per hectare, respectively. Each stand was thinned to different units of varying densities in the fall of 1982. Pre-dawn leaf water potential measurements were taken monthly in the summer of 1983 using the pressure chamber technique to determine plant moisture stress differences between the thinned and unthinned stands. Late summer leaf water potential was significantly greater in the thinned stands than in the controls. Furthermore, the increased leaf water potentials were proportional to the basal area removed with the greatest level of thinning exhibiting the greatest water potentials. These water potentials developed in the late summer to levels near those documented in the literature for similar stands even with greater than normal early summer precipitation and soil moisture contents. Measurements of radial increment and height growth of the sample trees in subsequent years will help determine if the phenomenon of thinning shock is related to moisture stress conditions in recently thinned stands.

Acknowledgements

I would like to express my appreciation to all the individuals who helped contribute to the completion of this project. Jeff Graham, Rob Ethridge, Ramakrishna Nemani, Bob Keane, and Steve Running all deserve special thanks for running around in the woods with me in the middle of the night. Thanks to Emily Chesick for boring trees and digging soil pits in the snow; Liz Easterling and Mark Bakeman for helping with the soil analysis and classification; and Dianne Daley for providing the soil moisture data.

Valuable consultation in organizing the project was provided by Roger Hungerford, Jim Faurot, George Briggs, and Bob Pfister. My most sincere appreciation goes to Steve Running, for simultaneously keeping me amused and on the right track.

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INTRODUCTION

Lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) constitutes one of the major timber species harvested in the Northern Rocky Mountains. Pure stands cover millions of hectares in Montana, Idaho, Wyoming, Washington, Oregon, and north into Canada. The serotinous cones allow for reproduction in large numbers after a major disturbance such as fire or clearcutting. The overabundent reproduction may eventually form dense, stagnant stands in later years. Unlike many other conifer species, these stands generally do not become stratified into crown classes. No trees take dominance and outcompete weaker trees, thus naturally thinning the stand to distribute plant requirements to a few healthy individuals (Alexander 1960). Many thousands of hectares are covered with overstocked, middle aged (30 to 70 years) lodgepole pine stands. Trees in these stands are too small to be of commercial sawlog value and are unlikely to grow to a merchantable size.

Prescribed, artificial thinning of overstocked lodgepole pine stands to desired densities is an alternative for the forest land manager. Thinning offers a means for the redistribution of plant requirements to a few trees per hectare (Alexander 1960) allowing for the best possible use of a site for wood production. Commercial thinning is often possible with post and poles as the product (Wellner 1975). Improvements in other forest resources, such as increased rangeland forage (Phillips 1973, Dealy 1975), aesthetic quality, and watershed runoff (Goodell 1952) are possible. Other benefits include increased resistance to mountain pine beetle (Mitchell et al. 1983) and decreased wildfire potential.

Silviculture literature offers many examples of excellent growth response following a first thinning in middle-aged stands (Alexander 1960, Barrett 1961, Gary 1978, Lotan 1967, Dahms 1967 and 1973, Schubert 1971, Seidel 1971). However, individual trees will respond differently to thinning and whole stands may not respond at all, a condition known as "thinning shock" (Staebler 1956). Lane (1963) reported no release in 50-year-old white pine. Yerkes (1960) found that 110-year-old Douglas-fir could not transfer growth capacity to fewer stems through thinning. Crown expansion was reduced in 50-year-old Douglas-fir in Washington (Reukema 1964). Harrington and Reukema (1983) reported on thinning shock in a 55-year-old Washington Douglas-fir plantation. It is difficult to assess the frequency of thinning shock because most reports emphasize favorable responses and discount or ignore unfavorable responses.

Literature pertaining to this specific topic is limited. Thinning shock itself has only been reported as to its occurrence but no literature has been found concerning research into the cause of thinning shock. The water status of the site is a possible explanation but water relations studies of thinned stands are also limited. Sucoff and Hong (1974) reported on work in an 18-year-old red pine plantation. This study showed greater leaf water potential and soil moisture content in the thinned stand than the unthinned stand. Lopushinsky (1975) reported on unpublished data by Seidel in Oregon that thinned lodgepole pine at midday had slightly higher moisture stress than an unthinned plot. Lopushinsky attributed this to increased exposure of the residual trees. The effects of basal area reductions on seasonal soil moisture depletion have been studied more frequently. An increase in soil moisture content following a silvicultural treatment has been reported in lodgepole pine stands (Johnston 1975, Dahms 1971 and 1973, Herring 1968), red pine stands (Bay and Boelter 1963), western larch/Douglas-fir stands (Newman and Schmidt 1980) and ponderosa pine stands (Orr 1968, Helvey 1975).

The growing season in Montana is usually characterized by long periods of little precipitation. Tree growth during dry periods is frequently reduced (Zahner 1968). Other requirements for growth, such as nutrients, radiation, and adequate temperatures, are normally met during the summer months. It is thus reasonable to examine the water relations of a site when first investigating thinning shock. Thinning may improve site water relations by reducing both overall stand transpiring surface area and live root density within the soil, potentially altering water availability for the residual trees. Canopy interception is reduced allowing for a greater amount of rainfall to reach the soil surface. Thinning may also adversely affect site water relations. A reduction in stand leaf biomass would increase the amount of radiation in the lower canopies and could possibly increase canopy temperatures, thus increasing transpirational water loss. Higher radiation loads reaching the ground could also increase soil temperatures and surface evaporation. Therefore, the primary hypothesis for this study was that thinning overstocked, middle-aged lodgepole pine stands in Montana will either improve or adversely effect the water relations of the residual trees from the unthinned stand.

METHODS

Study Areas

Criteria for study area selection were the presence of a control and more than one treatment, middle age with crown closure before thinning, easy access, and sufficiently different from other sites in initial stocking density. The three study areas chosen are refered to as the Lubrecht Experimental Forest, Rattling Gulch, and West Dry Fork. The study areas were thinned in the fall of 1982 under research not originally associated with this study. These thinnings provided an opportunity to measure initial leaf water potential responses in 1983 under this project. One treatment at West Dry Fork was thinned in the spring of 1983 but this was early enough in the growing season so that responses should not have been affected. The Lubrecht site was thinned to three different densities under the Mission Oriented Research Project of the University of Montana School of Forestry. The Rattling Gulch and West Dry Fork sites were thinned to two different densities each by the U.S. Forest Service, Intermountain Forest and Range Experiment Station. Site locations are presented in Figure 1. Photographs showing representative control and one treatment at each site are presented in Figures 2, 3, and 4.

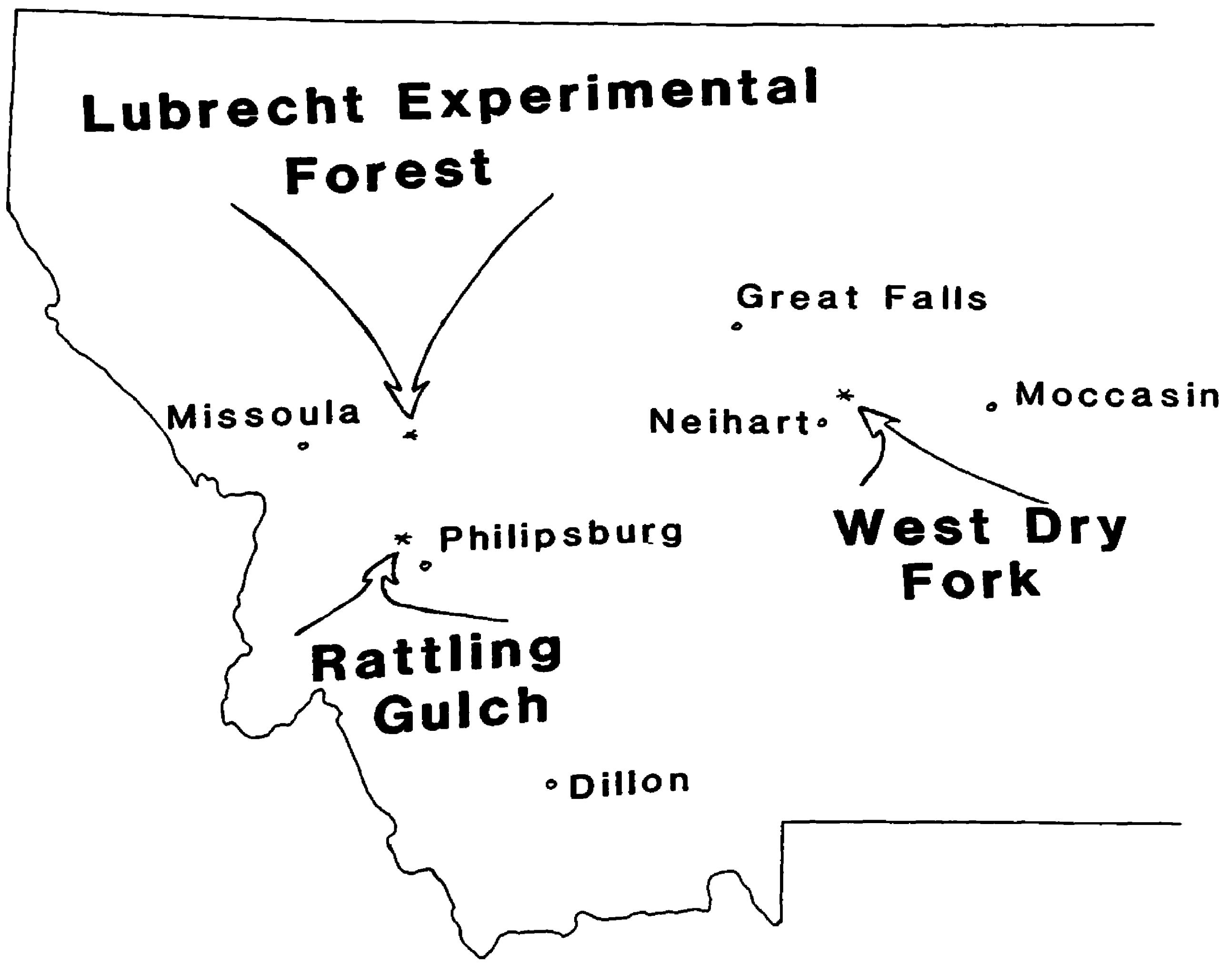


Figure 1. Study site locations.

(A)

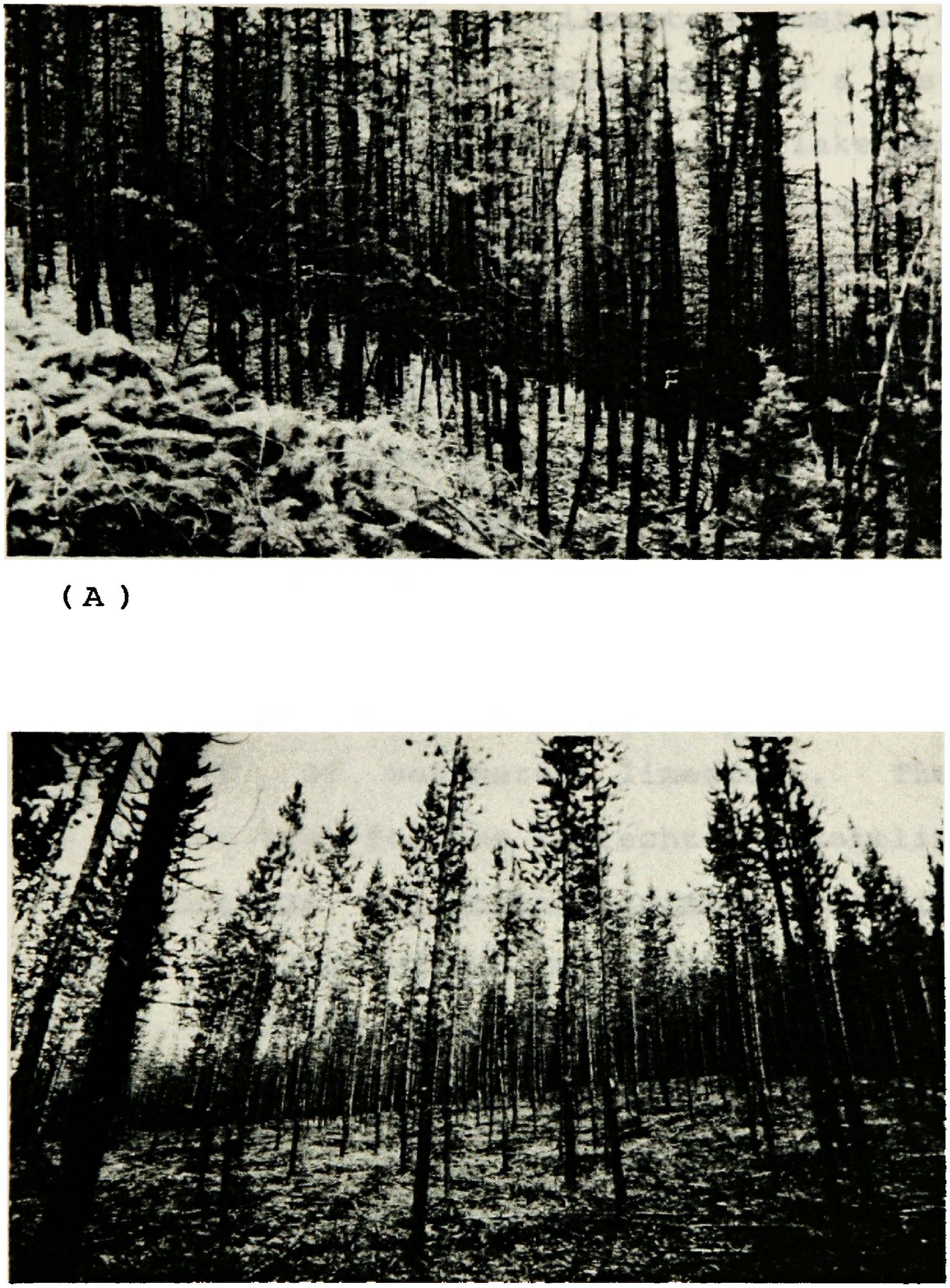
(B)

Figure 2. Lubrecht Experimental Forest. (A) Control. (B) 6.1 meter treatment.

(A)

(B)

Figure 3. Rattling Gulch. (A) Control. (B) 5.3 meter treatment.



(A)

(B)

Figure 4. West Dry Fork. (A) Control. (B) 2.9 meter treatment.

The Lubrecht Experimental Forest is located in the Garnet Range approximately 50 kilometers east of Missoula. The lodgepole pine study area originated from a post-logging fire in 1932. The stand grows on glacial lake sedimentary deposits. The Rattling Gulch site is located on the Philipsburg Ranger District, Deerlodge National Forest. It is approximately 25 kilometers northwest of Philipsburg, Montana in the Upper Willow Creek drainage. The stand grows on a mid-slope alluvial fan. The West Dry Fork study area is located on the Lewis and Clark National Forest in the Little Belt Mountains of central Montana. The site is approximately six kilometers east of Monarch, Montana in the Dry Fork Belt Creek drainage. The stand is on a mid-slope Tertiary deposit of weathered limestone. The climax vegetation habitat type for the Lubrecht and Rattling Gulch sites is *Pseudotsuga menziesii/Vaccinium caespitosum* and West Dry Fork is *Pseudotsuga menziesii/Linnaea borealis* (Pfister et al. 1977). Stand and site characteristics are summarized in Tables 1 and 2, respectively.

Sampling Procedures

Lubrecht has 40 sample trees and Rattling Gulch and West Dry Fork have 30 sample trees each: ten sample trees were selected in each of the treatments or control. Forty samples were determined to be the maximum number possible in

Table 1. Study area stand characteristics.

Feature	Study Area Lubrecht Exp. For.	 Rattling Gulch	 West Dry Fork
Initial Leaf Area Index	5.1	5.5	6.3
Initial Basal Area (sq. m/ha)	29.3	33.5	27.2
Basal Area Reductions (%)	42, 50, 72	33, 66	33, 66
Initial Stocking Density (s/ha)	2000	2500	12,000
Residual Stocking Densities (s/ha)	270, 560 1090	350 900	1210 3600
Average Spacings (meters)	3.0, 4.3, 6.1	3.4, 5.3	1.7, 2.9
Ave. Stand Age	49	60	58

one pre-dawn sampling session. Individual sample trees were chosen primarily for their live crown ratios (LCR). Two contrasting live crown ratio categories were selected for: 55 to 75 percent and 25 to 45 percent. Half of the ten sample trees in each unit fell in one of these categories. Care in sample tree selection was taken to assure that the immediate area around each sample tree consisted of representatively distributed trees of average size and crown

Table 2. Study area site characteristics. Complete soil profile descriptions are located in the Appendix.

	Study Area		
Feature	Lubrecht Exp. For.	Rattling Gulch	West Dry Fork
Elevation (m)	1250	1700	1600
Slope (%)	5 - 15	0 - 10	30 - 35
Aspect	NW	W	NNE
Mean Annual Precipitation (cm)	45	46	50
Mean Min. January Temperature (C)	-13.5	-12.5	-14.4
Mean Max. July Temperature (C)	27.6	26.2	25.4
Soil Subgroup	Typic Eutroboralf	Typic Cryochrept	Typic Cryoboralf

volume so extremes of shading or open areas were avoided. Study site layout and sample tree locations are depicted in Appendices G, H, and I.

Sample tree dimensional characteristics were measured before leaf water potential readings began. Diameter at breast height (DBH, 1.37 m), total height, and the height to the base of the crown were measured using standard forest inventory equipment. Crown width at the greatest point was estimated. The live crown ratio was calculated from the percentage of crown length to total tree height. Increment borings for age and sapwood area were conducted after all leaf water potential measurements were completed. Age was taken at the base. The DBH measurements and length of sapwood on increment borings taken at breast height were used to calculate sapwood basal area. Current year's increment was not great enough to affect calculations. Leaf area index of the stands before thinning were determined using regression equations based on DBH developed by Gholz et al. (1979) in Oregon. Average dimensional characteristics for each LCR category at the three study areas are presented in Table 3.

Pre-dawn leaf water potential measurements were taken four times on a monthly basis beginning in June. All monthly data collection for the three sites were conducted within five days. With the exception of Lubrecht in June, all measurements at a site were taken in one pre-dawn session. Each tree was only sampled once per session and no regard was given to canopy position when the sample twig was removed. A pressure chamber device was used for estimation of leaf water potential using standard techniques (Ritchie and Hinckley 1975). An additional five sample trees of low LCR in the control at Lubrecht were selected for July and August diurnal leaf water potential measurements. These

Table 3. Sample tree dimensional characteristics.

Study Area	n	DBH (cm)	Height (m)	Crown Width (m)	LCR (%)
Lubrecht E.F.					
LCR: >55%	20	20.4	16.1	4.0	62
<45%	20	12.9	14.7	1.8	30
Rattling Gulch					
LCR: >55%	15	18.6	15.7	3.2	62
<45%	15	12.6	14.6	1.3	39
West Dry Fork					
LCR: >55%	15	11.9	10.6	2.2	63
<45%	15	7.1	8.5	1.1	44

alternate sample trees were chosen in order to conserve twigs on the primary sample trees. Diurnal measurements were not taken at Rattling Gulch and West Dry Fork.

Meteorological data were obtained from U.S. Department of Commerce (1984) and Montana Forest and Conservation Experiment Station (1983) publications. Goetz provided unpublished 1983 data for Lubrecht. Precipitation data were selected from weather stations located as near the study areas as possible. A weather station at the Lubrecht Camp is approximately 600 m from the Lubrecht study area. A U.S. Forest Service weather station at Philipsburg is approximately 25 km southeast of the Rattling Gulch site. Another U.S. Forest Service weather station is 13 km north-northwest of Neihart and approximately 5 km southwest of the West Dry Fork site. In addition to precipitation, pan evaporation data were selected from the Moccasin Experiment Station west of Lewistown and Western Montana College at Dillon.

An associated study conducted by other University of Montana School of Forestry researchers concerned seasonal soil moisture depletion at the Lubrecht study site. These data collected can be used in the present study to compare actual soil moisture contents to the tree's ability to utilize soil moisture, as measured by the pre-dawn leaf water potential. Nine neutron probe access tubes were located in each response unit and an adjacent clearcut. Soil moisture by percent volume was measured on a weekly basis from May 1 to November 8, 1983 at six depths ranging from 0.15 m to 1.52 m. Data were not available from July 14 to August 2 due to equipment failure.

Statistical Analysis

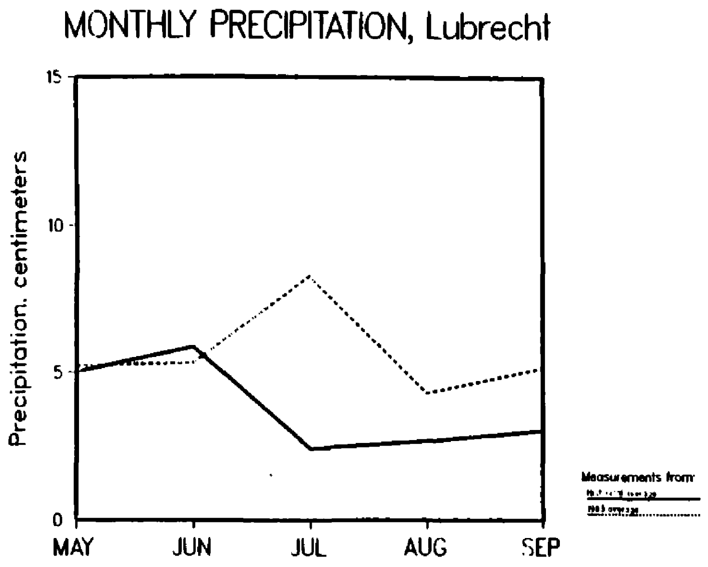
Mean monthly leaf water potentials for each study area response unit were compared for statistical significance. Initial stocking densities, stand age, slope, aspect, elevation, and climatic differences did not allow for contrasts between sites and measurement dates. A one-way analysis of variance with a factorial arrangement of treatments established a pooled variance estimate for individual T-tests between groups. These one-tailed contrasts suggested significance between treatments with the criteria of the greater densities having the least leaf water potential. A two-tailed T-test suggested significance between live crown ratio categories and leaf water potential within each response unit on a given date. Significance was tested at the 95% confidence level. Analysis was conducted using the SPSSx (1983) Batch System.

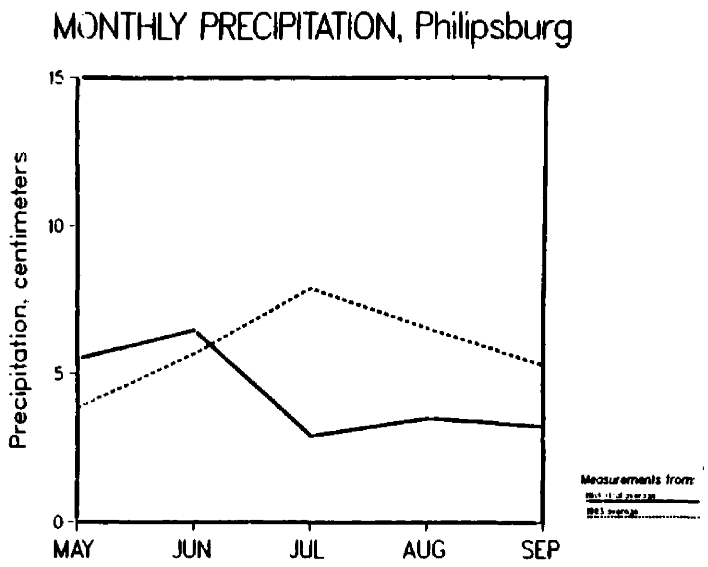
RESULTS

Climate Measurements

May and June total precipitation at all three study sites were relatively normal. The distribution of rainfall in late May and early June, however, was such that little rain fell immediately before the first measurement session. July was uncommonly wet, compared to historical averages, with several periods of intense rainfall at each site. Total precipitation for July was 240% greater than normal at Lubrecht, 170% greater at Rattling Gulch, and 120% greater at West Dry Fork. Total monthly precipitation returned to normal at West Dry Fork in August and September but remained higher at both Lubrecht and Rattling Gulch. Figure 5 summarizes precipitation at the three sites.

Pan evaporation measurements can give a relative indication of the evaporative demand placed on a tree. Radiation, temperature, wind, and humidity affect both evapotranspiration and still water evaporation, but direct correlations cannot be made due to physical differences between the two evaporating surfaces. Seasonal pan evaporation can possibly indicate greater than or less than normal seasonal leaf water potential. A pan evaporator at





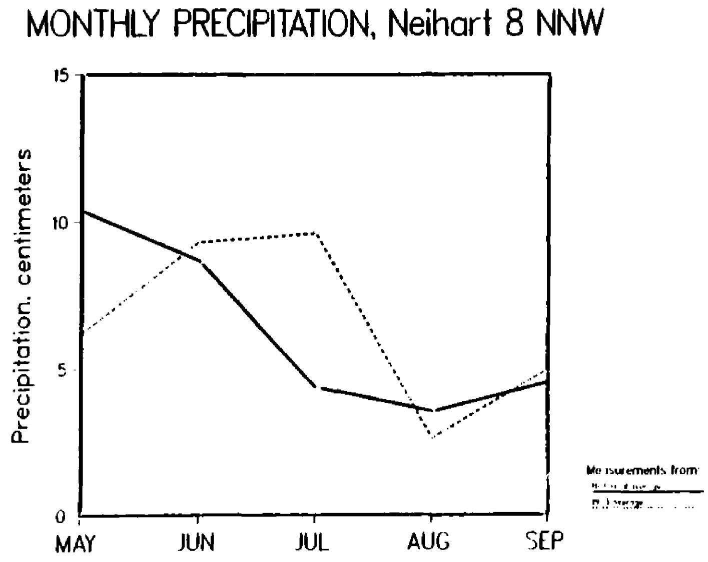


Figure 5. Study area monthly total precipitation. (———) indicates yearly historical average. (- - -) indicates 1983 average.

the Moccasin Experiment Station near West Dry Fork measured consistently lower than normal evaporation throughout the summer. A pan evaporator at Dillon showed evaporation in southwest Montana to be near normal for 1983 except for a lower than normal July.

Leaf Water Potential and Thinning

Pre-dawn leaf water potential at all sites were usually lower in the control than in the treatments. The controls in the late summer were always lower. At least one treatment had significantly greater leaf water potentials than the adjacent control for all measurement dates at each site except for West Dry Fork in June and Lubrecht in July. Statistical analysis is summarized for the three sites in Appendixes A, B, and C.

Leaf water potential in July at the Lubrecht site increased 0.15 to 0.20 MPa from June (Figure 6). All units had statistically similar water potentials in July. The August session showed the greatest difference in water potentials recorded during the study: 0.37 MPa less in the control than the 4.3 meter treatment. Both the 3.0 and 6.1 meter treatments were also significantly greater than the control in August. Leaf water potential in all three treatments decreased from August to September but the control actually increased. Significant differences between

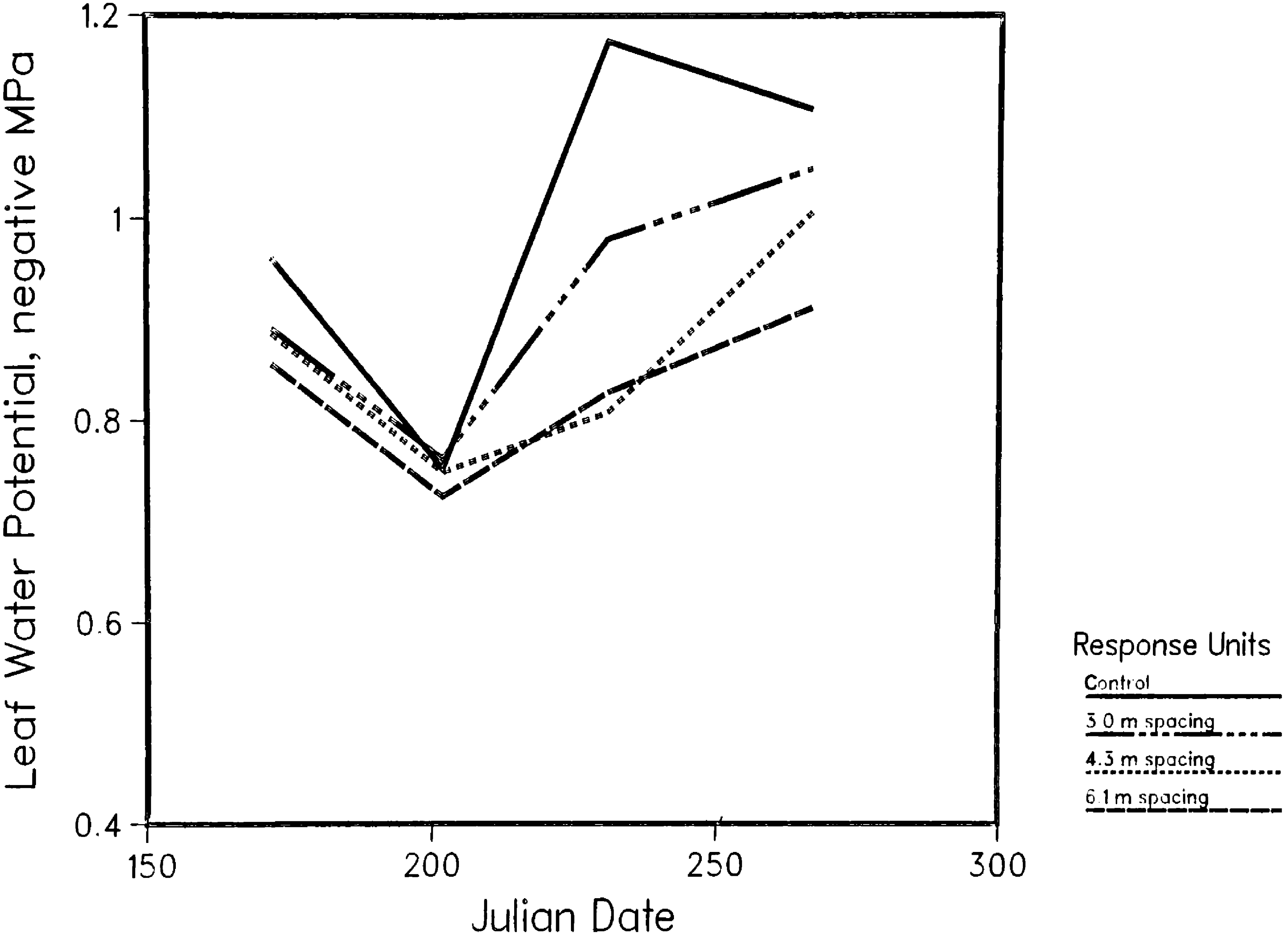


Figure 6. Seasonal leaf water potential by response unit, Lubrecht Experimental Forest.

treatment units always occurred with the treatment that had the least basal area removed having the lowest water potential.

Water potentials in the three units at Rattling Gulch responded similarly throughout the summer. The control and treatment water potentials increased from an unusually low June reading to higher levels in July and August (Figure 7). Leaf water potential, however, decreased dramatically in September. The control water potential was significantly less than the 3.4 meter treatment in every measurement throughout the summer. The greatest difference between these two groups was 0.23 MPa in September. The 3.4 meter treatment had less water potential than the 5.3 meter treatment in all cases. Significant differences between these two groups occurred in June and September. Significant differences between the control and the 5.3 meter treatment only occurred in August and September.

The West Dry Fork site consistently had the most significant differences of the three study areas. No early summer increase in leaf water potential occurred here as did the other two sites (Figure 8). The control decreased water potential markedly in the early summer but increased slightly from August to September. The two treatments remained at about the same water potential as the summer progressed. Except for June when the control was greater

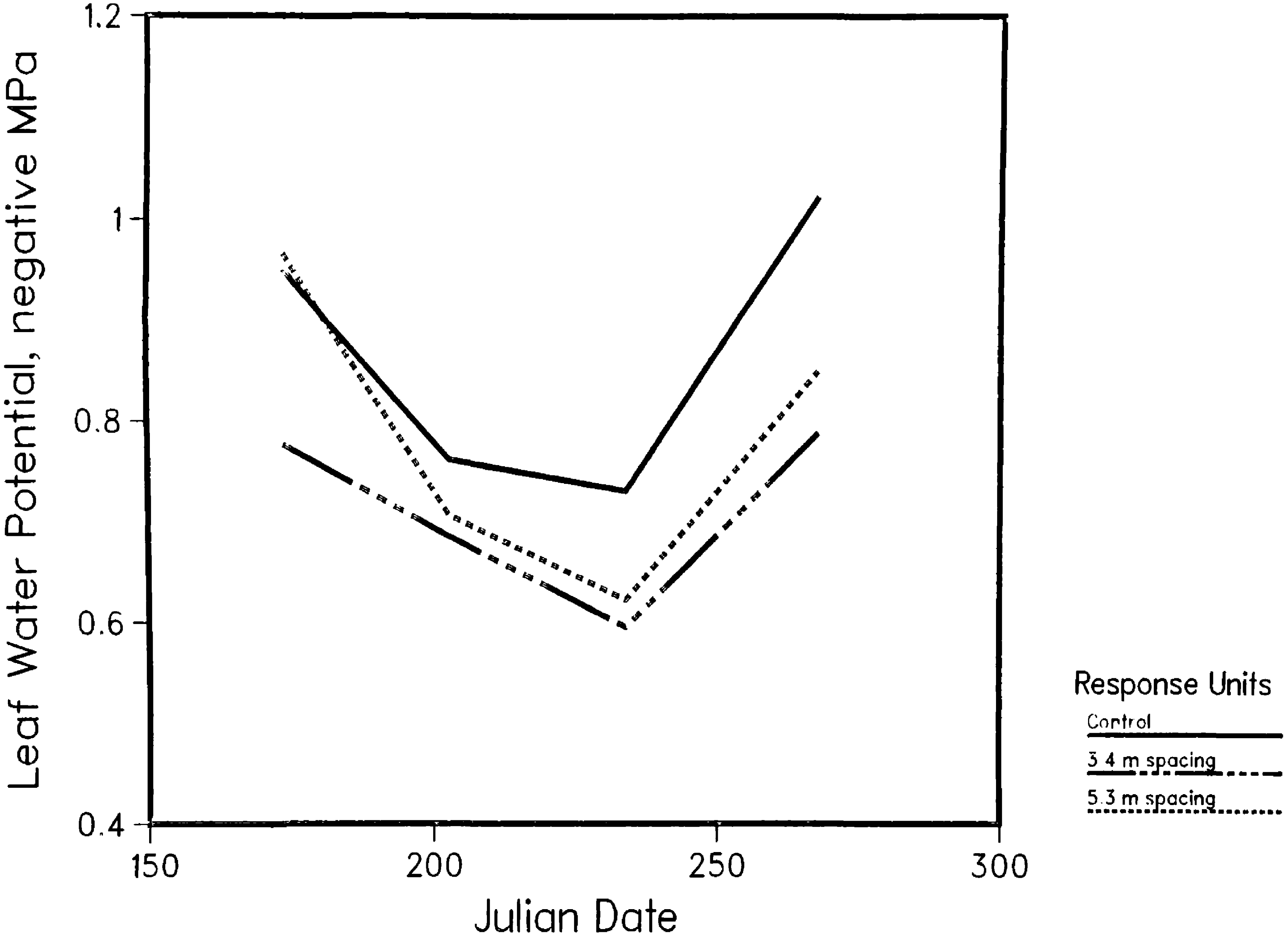


Figure 7. Seasonal leaf water potential by response unit, Rattling Gulch.

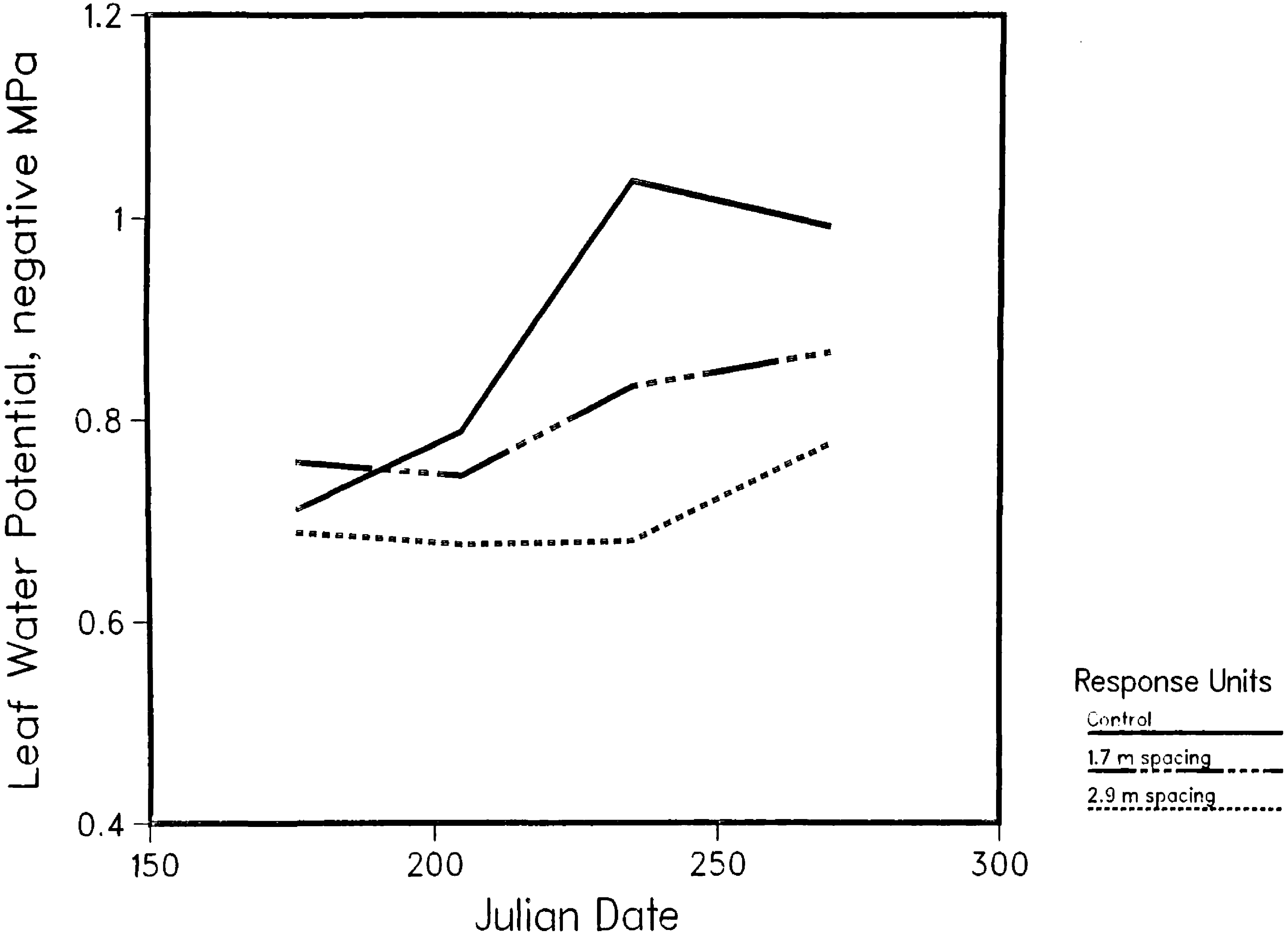


Figure 8. Seasonal leaf water potential by response unit, West Dry Fork.

than the 1.7 meter treatment, all measurements showed water potentials increasing proportional to density. The control had significantly less leaf water potential than both treatments in July, August, and September, except for the 1.7 meter treatment in July. The two treatments were significantly different from each other in all cases.

The live crown ratio does not seem to have had an effect on the pre-dawn leaf water potential. Significant differences between the two LCR categories on a particular date and response unit were few. There were no significant differences at Rattling Gulch. West Dry Fork only had one. The five significant differences at Lubrecht were contradictory. The <45% LCR category sometimes had a greater mean leaf water potential than the >55% LCR category and visa-versa. Statistical analysis is summarized in Appendices J, K, and L.

The two diurnal leaf water potential measurements taken at the Lubrecht Experimental Forest gave fairly similar results. The August pre-dawn water potential was 0.20 MPa less than July but did not decrease as quickly in the late morning. The mid-afternoon minimum was -1.51 MPa in July and -1.63 MPa in August.

Soil Moisture and Thinning

Soil moisture depleted in the upper soil at Lubrecht over the course of the summer was greatest in the control unit (Figure 9). Little soil moisture was depleted at the lower depths from May until September and the clearcut actually accumulated soil moisture at a depth of 1.2 meters. The 4.3 meter treatment had the greatest depletion of all the modified units. The 6.1 meter unit had the least depletion of the forested units. Less depletion occured at 0.15 meters than at 0.30 meters in all cases except the sparsely vegetated clearcut. Informal analysis of soil cores during access tube installation showed tree roots to be concentrated in the 0.25 to 0.75 meter depths.

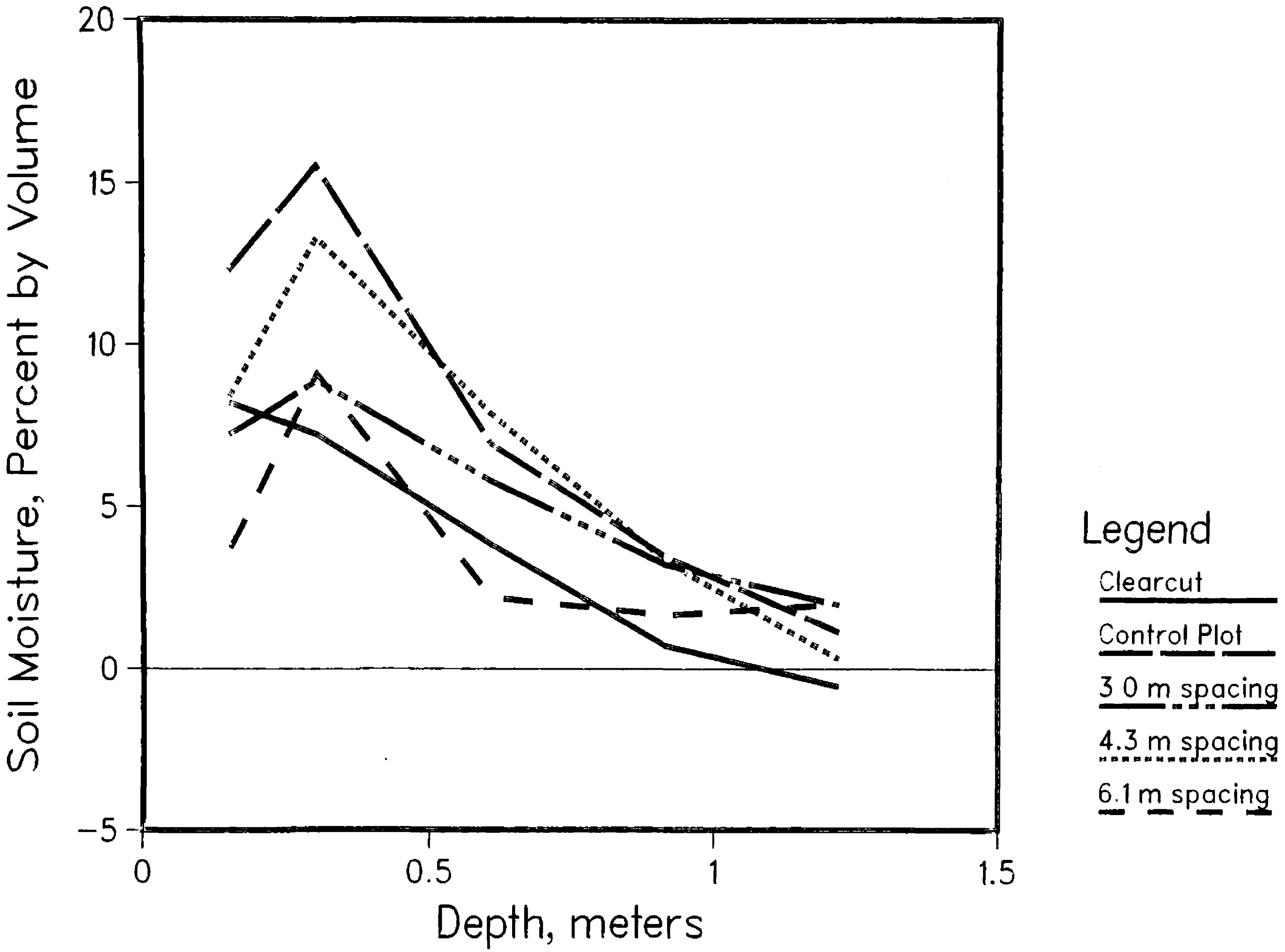


Figure 9. Seasonal soil moisture depletion, Lubrecht Experimental Forest. Measurements taken on May 15 and September 24, 1983.

DISCUSSION AND CONCLUSIONS

I would speculate leaf water potentials measured immediately after thinning in similar stands and sites in years of normal or less than normal rainfall and evaporative demand would probably be significantly different from the results reported here. Overall leaf water potentials would probably be higher in the early summer and progressively decrease through September. I also believe a greater leaf water potential difference between the thinned and unthinned units would exist. The treatments would probably exhibit about the same pre-dawn measurements as my results but the controls would have lower overall water potentials. I make these predictions with some caution, however, since on-site meteorological data were not collected.

The initial stocking density at Lubrecht (2000 s/ha) was relatively light. A forest land manager would probably give this stand low priority in a total forest thinning program. A large number of the trees were already at sawlog size (greater than 16.8 cm). Almost all of the residual trees in the 4.3 and 6.1 meter treatments were of sawlog size. It is interesting that significant differences in leaf water potential developed even under thinnings from a low density stand. This same situation exists at Rattling Gulch. The stand was at 2500 s/ha and about one quarter of the trees were sawlog sized. I suspect that thinning to these same spacings from a stand of greater density would result in even lower leaf water potentials in the control. The West Dry Fork site, however, was a relatively dense stand (12,000 s/ha) but was thinned lightly. A 1.7 meter spacing is less than what forest land managers generally thin to in stands of this age and height. Again, however, significant differences occurred between the control and this high density treatment. The significantly increased leaf water potential in lightly thinned stands or stands thinned from low initial densities indicates the sensitivity of the residual tree's water relations to reduced basal area.

Soil moisture depletion trends at the Lubrecht site are similar to results found in other studies (Bay and Boelter 1963, Dahms 1971 and 1973, Herring 1968, Johnston 1975, Helvey 1975, Newman and Schmidt 1980, and Orr 1968). Response units with the greatest basal area showed the greatest amount of depletion from spring field capacity to late summer. Bay and Boelter (1963) and Newman and Schmidt (1980) sampled soil moisture in a range of depths and found almost equal depletion for all depths down to 1.5 meters. Since the majority of depletion was above 0.75 meters at

Lubrecht, I believe the rooting depth at Lubrecht is shallower than in the soils of the other two studies. The greatest amount of water depleted in the clearcut occurred at the shallowest depth (0.15 meters), indicating the importance of shading in reducing direct solar radiation at the surface. The reason for the large amount of depletion in the 4.3 meter spacing over the 3.0 meter spacing can be attributed to slope positions, side radiation loading from the clearcut, soil differences, and the grid placement of the access tubes (as opposed to carefully placing the tubes in relation to residual trees).

The two most significant factors affecting available soil moisture in thinned stands is canopy interception and transpiring surface area. Standard silvicultural thinnings, similar to those conducted in the study sites, will reduce both of these factors. Under the higher stress conditions of the late summer, control unit leaf water potentials were always lower than the treatments and, except for Rattling Gulch, treatment leaf water potentials increased over the controls proportional to the level of thinning. Therefore, residual soil moisture availability after thinning, as measured by the tree's ability to use soil water, will probably increase proportional to the degree of basal area removed. The lower leaf water potentials in the Rattling Gulch 5.3 meter treatment than in the 3.4 meter treatment cannot be explained.

Zahner (1968) summarized the effects of water stress on the growth of trees. He concluded the rates of cell division and enlargement are reduced when internal water stress is severe enough to cause dehydration and shrinkage of the tissue containing mother cells and derivatives. Assessing "stress" conditions is difficult but comparing pre-dawn leaf water potential measurements to mid-afternoon maximum moisture stresses is possible. Lopushinsky (1975), Running (1980), and Graham (1983) all found mid-afternoon leaf water potential at near stomatal closure to be approximately -1.6 MPa. Reduced stomatal conductance restricts water loss through transpiration but also restricts carbon dioxide gas exchange necessary for photosynthesis. Late summer growth may have been moisture stress limited at each study site's control and the 3.0 meter treatment at Lubrecht. Water stress probably had little effect on growth in all other treatments.

In conclusion, residual lodgepole pine trees were able to immediately utilize increased soil moisture after thinning to avoid moisture stress conditions at three sites in Montana. Furthermore, the decrease in moisture stress was proportional to the basal area removed with the greatest level of thinning exhibiting the highest leaf water potential. Late summer moisture stresses developed in denser units at the three sites even with much greater than normal early summer precipitation. At this time, moisture stress cannot be related to thinning shock. Other factors possibly affecting thinning shock, such as root grafting (Eis 1972) or nitrogen deficiencies caused by large quantities of thinning residues with high C:N ratios (Miller et al. 1976) may be involved. Dimensional analysis of the sample trees in subsequent years will help determine if the time required for release is related to moisture stress after thinning.

APPENDICES

APPENDIX A

Leaf Water Potential Treatment Contrast T-Tests
Lubrecht Experimental Forest
One-tailed, Pooled Variance Estimate
36 degrees of freedom
Ho: There is no leaf water potential difference between the units.
Ha: The denser unit has a lower leaf water potential.

	Statistic		
Contrast	T-value	Prob. value	Significant?
June 21,22 (std. error = 0.034)			
Control - 3.0 m	3.108	0.002	yes
Control - 4.3 m	2.220	0.017	yes
Control - 6.1 m	2.072	0.023	yes
3.0 m - 4.3 m	0.148	0.442	no
3.0 m - 6.1 m	1.036	0.154	no
4.3 m - 6.1 m	0.888	0.191	no
July 21 (std. error = 0.060)			
Control - 3.0 m	-0.531	0.300	no
Control - 4.3 m	0.059	0.477	no
Control - 6.1 m	0.197	0.423	no
3.0 m - 4.3 m	0.256	0.400	no
3.0 m - 6.1 m	0.727	0.236	no
4.3 m - 6.1 m	0.472	0.320	no
Aug. 19 (std. error = 0.056)			
Control - 3.0 m	6.186	0.000	yes
Control - 4.3 m	6.544	0.000	yes
Control - 6.1 m	3.487	0.001	yes
3.0 m - 4.3 m	3.057	0.002	yes
3.0 m - 6.1 m	2.700	0.006	yes
4.3 m - 6.1 m	-0.358	0.362	no
Sept. 24 (std. error = 0.044)			
Control - 3.0 m	4.420	0.000	yes
Control - 4.3 m	2.289	0.014	yes
Control - 6.1 m	1.315	0.099	no
3.0 m - 4.3 m	0.975	0.168	no
3.0 m - 6.1 m	3.106	0.002	yes
4.3 m - 6.1 m	2.131	0.020	yes

APPENDIX B

Leaf Water Potential Treatment Contrast T-Tests
Rattling Gulch
One-tailed, Pooled Variance Estimate
27 degrees of freedom
Ho: There is no leaf water potential difference between the units.
Ha: The denser unit has a lower leaf water potential.

	Statistic		
Contrast	T-value	Prob. Value	Significant?
June 23 (std. error = 0.029)			
Control - 3.4 m	6.061	0.000	yes
Control - 5.3 m	-0.561	0.290	no
3.4 m - 5.3 m	-6.622	0.000	no *
July 22 (std. error = 0.037)			
Control - 3.4 m	2.068	0.024	yes
Control - 5.3 m	1.496	0.073	no
3.4 m - 5.3 m	-0.571	0.287	no
Aug. 22 (std. error = 0.031)			
Control - 3.4 m	4.423	0.000	yes
Control - 5.3 m	3.539	0.001	yes
3.4 m - 5.3 m	-0.885	0.192	no
Sept. 25 (std. error = 0.025)			
Control - 3.4 m	9.486	0.000	yes
Control - 5.3 m	7.002	0.000	yes
3.4 m - 5.3 m	-2.483	0.010	no *

* Did not meet one-tailed requirements.

APPENDIX C

Leaf Water Potential Treatment Contrast T-Tests
West Dry Fork
One-tailed, Pooled Variance Estimate
27 degrees of freedom
Ho: There is no leaf water potential difference between the units.
Ha: The denser unit has a lower leaf water potential.

	Statistic		
Contrast	T-value	Prob. Value	Significant?
June 25 (std. error = 0.017)			
Control - 1.7 m	-2.741	0.006	no *
Control - 2.9 m	1.371	0.091	no
1.7 m - 2.9 m	4.112	0.000	yes
July 24 (std. error = 0.027)			
Control - 1.7 m	1.661	0.054	no
Control - 2.9 m	4.228	0.000	yes
1.7 m - 2.9 m	2.567	0.008	yes
Aug. 23 (std. error = 0.029)			
Control - 1.7 m	6.969	0.000	yes
Control - 2.9 m	12.222	0.000	yes
1.7 m - 2.9 m	5.253	0.000	yes
Sept. 27 (std. error = 0.028)			
Control - 1.7 m	4.415	0.000	yes
Control - 2.9 m	7.620	0.000	yes
1.7 m - 2.9 m	3.205	0.002	yes

* Did not meet one-tailed requirements.

APPENDIX D

Soil Profile Description, Lubrecht Experimental Forest

LOCATION: Section 12 study area, Lubrecht Experimental Forest. Approximately 1050 meters northeast of the southwest corner of Section 12, T13N, R15W.

PHYSIOGRAPHY: Dissected terrace, northeast aspect, 10 percent slope.

PARENT MATERIAL: Tertiary-aged siltstone residuum with a surface mantle of younger lacustrine sediments (probably Glacial Lake Missoula).

DRAINAGE: Well-drained; moderately slow permeability to 150 centimeters and very slow below.

ELEVATION: 1250 meters.

NATIVE VEGETATION: PSME/VACA habitat type.

SOIL CLASSIFICATION: Typic Eutroboralf, fine-silty, mixed, frigid.

PROFILE DESCRIPTION:
Colors are for dry soil unless otherwise noted.

O1	2 - 0 cm	Forest Litter, mostly undecomposed.
A21	0 - 20	Brown (10YR 5/3) silt loam, dark brown (10YR 4/3) moist; weak fine granular structure; soft, very friable, slightly sticky and non-plastic; many very fine, fine and medium roots, common coarse roots; gradual wavy boundary.
A22	20 - 43	Pale brown (10YR 6/3) silt loam, brown (10YR 5/3) moist; weak fine granular structure; soft, very friable, slightly sticky and non-plastic; many very fine, fine and medium roots, common coarse roots; gradual wavy boundary.
A&B	43 - 69	A portion: pale brown (10YR 6/3), brown (10YR 5/3) moist, B portion: brown (10YR 5/3), dark brown (10YR 4/3) moist silt loam; medium subangular blocky structure; slightly plastic; many very fine and fine roots, common medium and coarse roots; moderately thick clay films on ped faces and in pores; gradual wavy boundary.

B2	69 - 97	Pale brown (10YR 6/3) silty clay loam, brown (10YR 5/3) moist; moderate, medium subangular blocky structure; slightly hard, friable sticky and slightly plastic; many fine and very fine roots, common medium and coarse roots; gradual wavy boundary.
B3	97 - 152	Pale brown (10YR 6/3) silt loam, brown (10YR 5/3) moist; weak, medium subangular blocky structure; slightly hard, friable, slightly sticky and nonplastic; common very fine and fine roots; few medium and coarse roots, gradual wavy boundary.
Cr	152	Fractured siltstone with roots and clay films in cracks.

APPENDIX E

Soil Profile Description, Rattling Gulch

LOCATION: Rattling Gulch Study Site, Deerlodge National Forest, approximately 15 kilometers north on FS road No. 88 from state route 348. Approximately 550 meters northeast of the southwest corner, Sec. 4, T8N, R15W, Montana P.M.

PHYSIOGRAPHY: Straight mid-slope, west aspect, 5 - 10% slope.

PARENT MATERIAL: Mixed stream deposited old sediments.

DRAINAGE: Moderately to well drained.

ELEVATION: 1700 meters.

NATIVE VEGETATION: PSME/VACA habitat type. Dominant seral species is PICO with a VACA and CARU dominated understory.

SOIL CLASSIFICATION: Typic Cryochrept, loamy skeletal.

PROFILE DESCRIPTION:
Colors are for moist soil unless otherwise noted.

O	3 - 0 cm	Forest litter, mostly undecomposed.
A1	0 - 5	Very dark brown (10YR 2/2) gravelly loam, brown, (10YR 4/3) dry. Weak granular structure; loose, firm, nonsticky and slightly plastic; clear boundary and pH 5.8.
A3	5 - 22	Dark yellowish brown (10YR 3/6) gravelly loam, light yellowish brown (10YR 6/4) dry. Basically structureless; loose, friable, slightly sticky and plastic; clear boundary and pH 6.2.
B2	22 - 50	Yellowish brown (10YR 5/4) gravelly loam, very pale brown (10YR 7/4) dry. Weak granular structure; loose, firm, slightly sticky and very plastic; gradual boundary and pH 5.4.
B3	50 - 100	Yellowish brown (10YR 5/6) gravelly sandy loam, very pale brown (10YR 5/6) dry. Weak, subangular blocky structure; loose, firm, slightly sticky and plastic; gradual boundary and pH 4.2.

APPENDIX F

Soil Profile Description, West Dry Fork

LOCATION: West Dry Fork Study Site, Lewis and Clark National Forest, approximately 6.5 kilometers east of Monarch on FS road No. 120. Approximately 400 meters east-southeast of the northwest corner of Sec. 6, T15N, R8E, Montana P.M.

PHYSIOGRAPHY: Straight mid-slope, north aspect, 30 - 35% slope.

PARENT MATERIAL: Weathered limestone.

DRAINAGE: Well drained.

ELEVATION: 1650 meters.

NATIVE VEGETATION: PSME/LIBO - CARU habitat type. Dominant seral species is PICO, with a CARU, ASCO, SPBE, and ROAC understory.

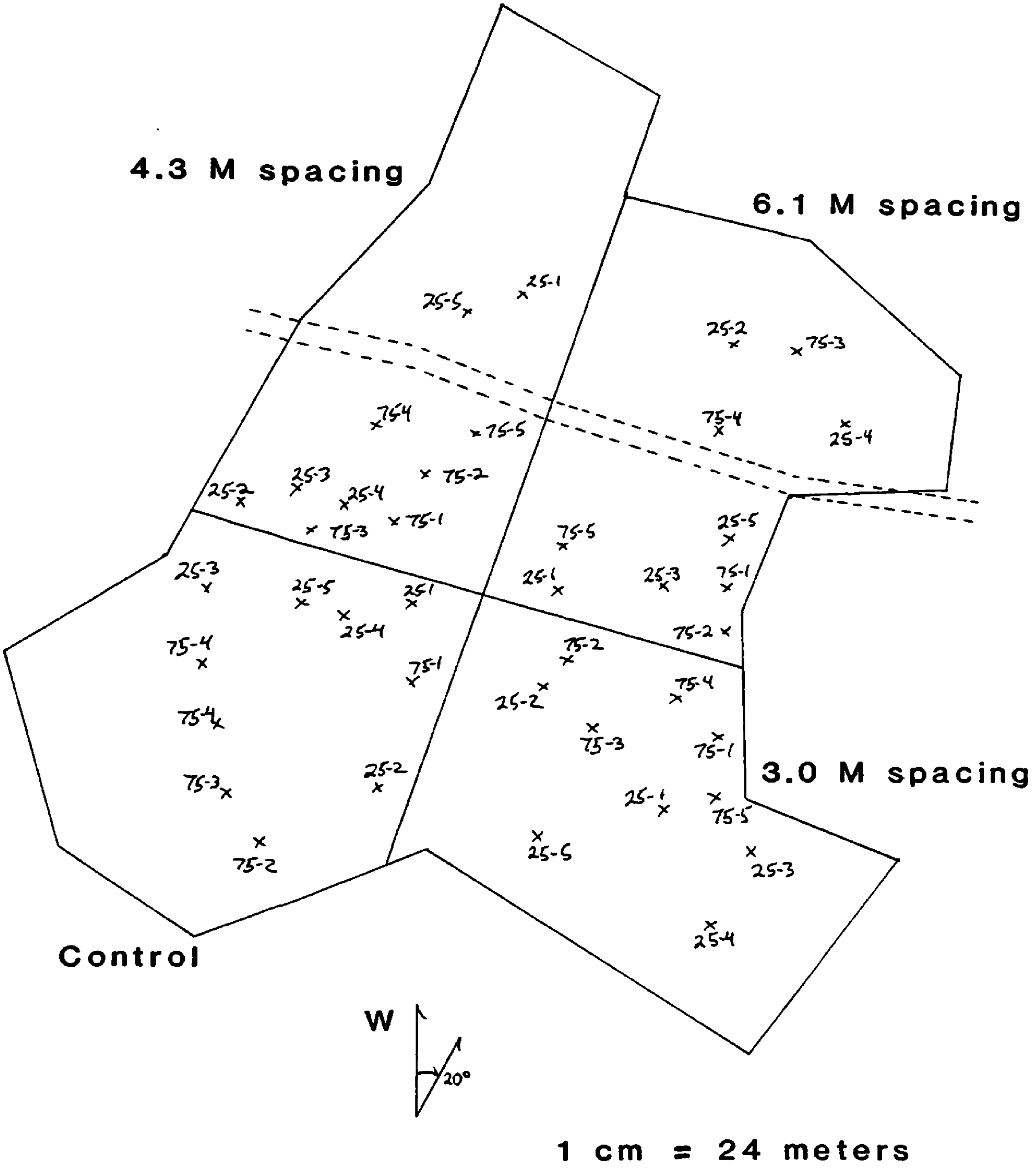
SOIL CLASSIFICATION: Typic Cryoboralf, loamy skeletal.

PROFILE DESCRIPTION:
Colors are for moist soils unless otherwise noted.

Oe	3 - 0 cm	Forest litter, mostly undecomposed.
A1	0 - 3	Dark yellowish brown (10YR 3/4) silty clay loam, dark brown (10YR 4/3) dry. Moderate granular structure; loose friable, sticky and plastic; clear boundary and pH 5.0.
B1t	3 - 7	Dark yellowish brown (10YR 3/6) silty clay, dark yellowish brown (10YR 3/6) dry. Moderate granular structure, loose firm, sticky and plastic; clear boundary and pH 6.5.
B2t	7 - 16	Dark yellowish brown (10YR 3/4) cobbly clay, dark yellowish brown (10YR 3/4) dry. Moderate granular, structure; loose, firm, very sticky and plastic; granular boundary and pH 6.2.
B3ca	16 - 50+	Dark yellowish brown (10YR 3/4) cobbly clay loam, dark yellowish brown (10YR 4/6) dry. Loose, friable, sticky and plastic; very violent effervescence; lower boundary not found and pH 6.8.

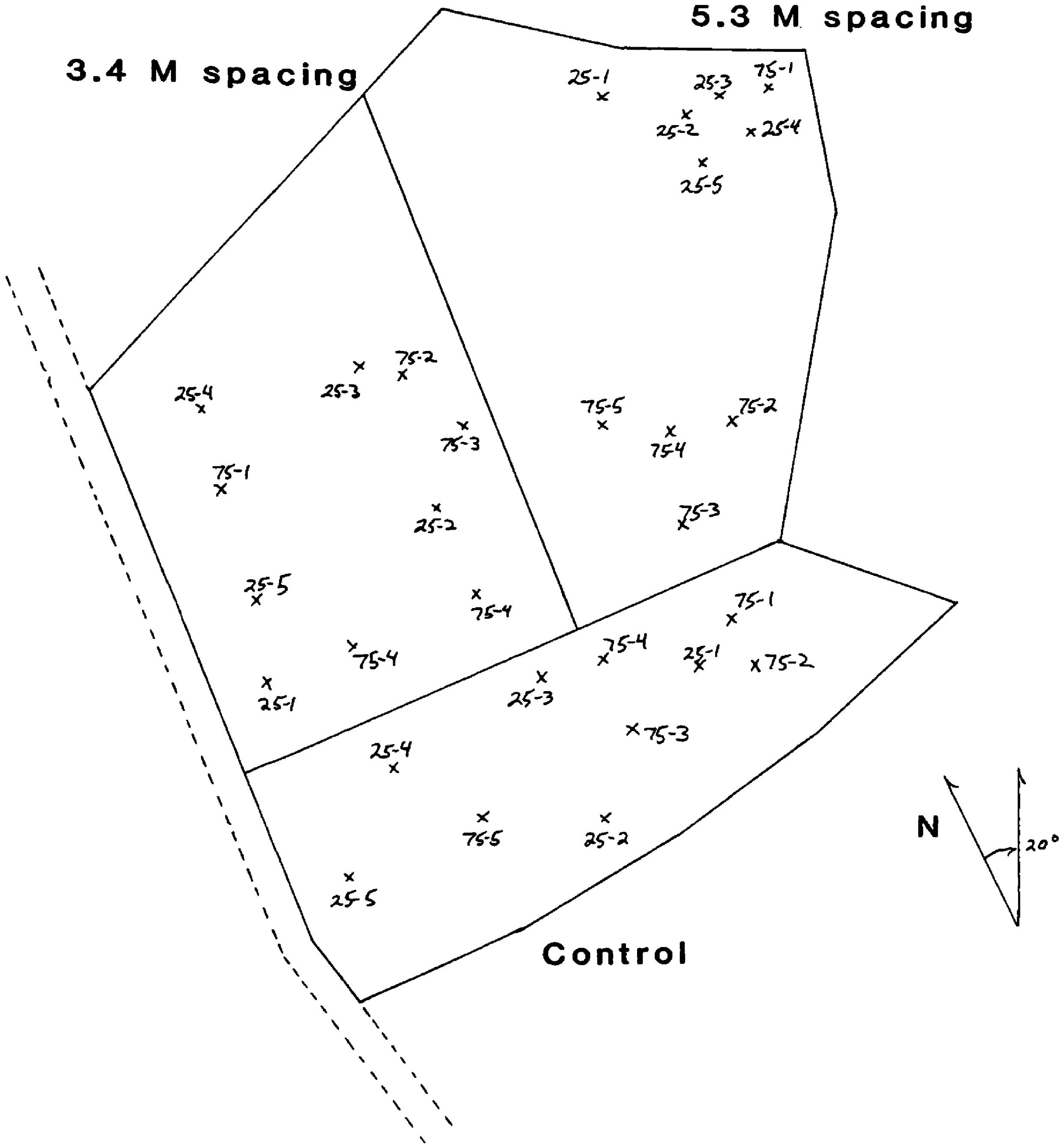
APPENDIX G

Lubrecht Experimental Forest - Study Site Layout and Sample Tree Locations.



APPENDIX H

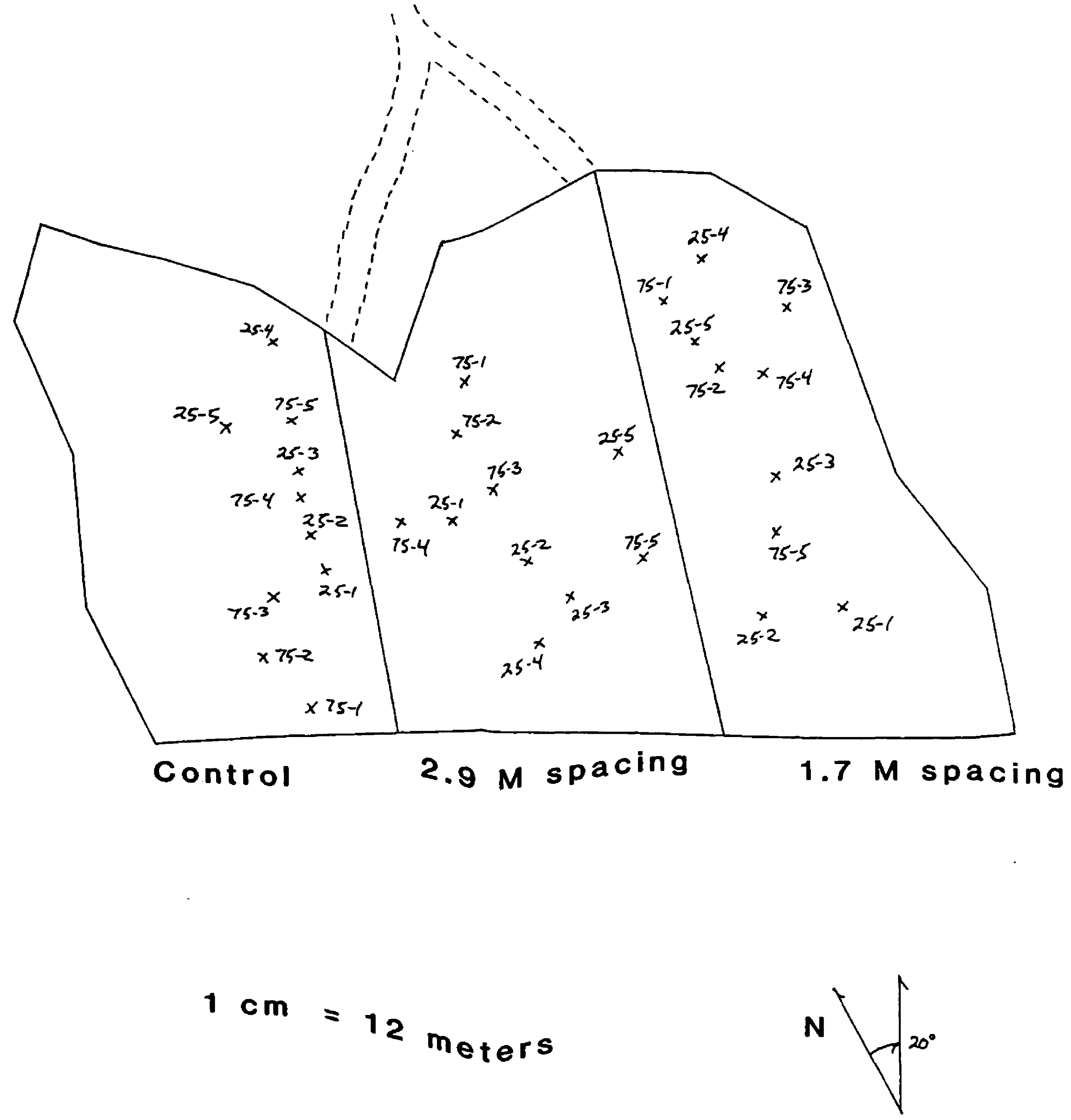
Rattling Gulch - Study Site Layout and Sample Tree Locations.



1 cm = 12 meters

APPENDIX I

West Dry Fork - Study Site Layout and Sample Tree Locations.



APPENDIX J

Live Crown Ratio and Leaf Water Potential T-Tests
Lubrecht Experimental Forest
Two-tailed, Pooled Variance Estimate
8 degrees of freedom
Ho: There is no difference in the leaf water potential of trees of high live crown ratio versus trees of low live crown ratio.
Ha: There is no difference.

	Statistic		
Contrast	T-value	Prob. Value	Significant?
June 21,22			
Control	3.58	0.007	yes
3.0 m spacing	1.13	0.291	no
4.3 m spacing	1.00	0.347	no
6.1 m spacing	-1.57	0.156	no
July 21			
Control	1.44	0.187	no
3.0 m spacing	-0.42	0.684	no
4.3 m spacing	1.68	0.131	no
6.1 m spacing	0.32	0.759	no
Aug. 19			
Control	2.75	0.025	yes
3.0 m spacing	-0.64	0.539	no
4.3 m spacing	0.38	0.717	no
6.1 m spacing	-3.76	0.006	yes
Sept. 24			
Control	2.47	0.039	yes
3.0 m spacing	-0.32	0.760	no
4.3 m spacing	-0.59	0.574	no
6.1 m spacing	-2.41	0.041	yes

Positive T-value indicates a greater >55% LCR mean than the <45% LCR mean.

APPENDIX K

Live Crown Ratio and Leaf Water Potential T-tests
Rattling Gulch
Two-tailed, Pooled Variance Estimate
8 degrees of freedom
Ho: There is no difference in the leaf water potential of trees of high live crown ratio versus trees of low live crown ratio.
Ha: There is no difference.

	Statistic		
Contrast	T-value	Prob. Value	Significant?
June 23			
Control	0.41	0.694	no
3.4 m spacing	0.46	0.656	no
5.3 m spacing	0.23	0.821	no
July 22			
Control	0.74	0.480	no
3.4 m spacing	0.15	0.886	no
5.3 m spacing	0.34	0.740	no
Aug. 22			
Control	1.06	0.320	no
3.4 m spacing	0.89	0.400	no
5.3 m spacing	0.15	0.882	no
Sept. 25			
Control	-0.28	0.790	no
3.4 m spacing	0.81	0.440	no
5.3 m spacing	0.33	0.753	no

Positive T-value indicates a greater >55% LCR mean than the <45% LCR mean.

APPENDIX L

Live Crown Ratio and Leaf Water Potential T-Tests
West Dry Fork
Two-tailed, Pooled Variance Estimate
8 degrees of freedom
Ho: There is no difference in the leaf water potential of trees of high live crown ratio versus trees of low live crown ratio.
Ha: There is no difference.

	Statistic		
Contrast	T-value	Prob. Value	Significant?
June 25			
Control	0.00	1.000	no
1.7 m spacing	-3.13	0.014	yes
2.9 m spacing	0.77	0.462	no
July 24			
Control	-0.06	0.953	no
1.7 m spacing	0.93	0.381	no
2.9 m spacing	-0.43	0.679	no
Aug. 23			
Control	1.03	0.334	no
1.7 m spacing	0.11	0.919	no
2.9 m spacing	-1.10	0.302	no
Sept. 27			
Control	-2.04	0.076	no
1.7 m spacing	1.31	0.228	no
2.9 m spacing	-2.26	0.053	no

Positive T-value indicates a greater >55% LCR mean than the <45% LCR mean.

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