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Title Soil and Growth Studies in Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] Stands Near Molalla, Oregon

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In 1957 three Douglas-fir stands (15-, 25-, and 40-year-old age classes) were selected on a tree farm in the Cascade foothills of northwestern Oregon to study factors affecting site productivity. Soil-moisture, soil-temperature and seasonal radial-growth pattern measurements were made with a Colman moisture meter and a dial gauge dendrometer on thinned and unthinned subareas.

Soil temperatures were significantly increased by thinning in each stand. This effect decreased with soil depth and increased with increasing intensity of thinning. Root distribution studies eight years after thinning showed that a heavily thinned stand had relatively few roots in the lower profile between the remaining trees, in contrast to the complete distribution throughout the profile in the unthinned subareas. This would indicate less overall soil-moisture depletion with thinning since the available soil-moisture levels measured within the fully rooted zone were not significantly different for the

various thinning treatments.

As expected radial growth increased significantly with increasing intensity of thinning. The amount and proportion of late season growth tended to increase with increasing thinning intensity although the observed differences were not statistically significant. Late season growth, however, was significantly increased by increasing crown position (intermediate to dominant) regardless of thinning treatment.

Irrigation of selected trees at a ridgetop area extended the spring maximum radial growth rate throughout most of the summer. On comparable non-irrigated trees growth retardation was detectable in the range of one-half to one atmospheres of soil-moisture tension. Growth cessation occurred when soil-moisture-tension values reached the two to five atmosphere range. Irrigation of trees in a young hillside bench stand slightly increased radial growth rate during the first two years, but decreased growth in relation to non-irrigated trees during the next two years apparently as a result of excess irrigation.

Fertilization with high rates of nitrogen and phosphorus fertilizers increased the late season radial growth of irrigated and non-irrigated trees in both stands. The late season response is attributed to a dwindling supply of mineralized soil nitrogen in the late summer and early fall. Irrigation and fertilization combined gave approximately additive increases in radial growth which ranged from 35 to 60 percent.

It is hypothesized that potential radial growth (except for short periods at the start and end of the growing season) is equivalent to the maximum spring rate. Departures from this maximum result from deficiencies in moisture, mineral nutrient elements, or heat. Thus the maximum growth rate is proposed as an important characteristic, reflecting the potential carbohydrate productive capacity of the crown when raw material levels exceed rate limiting supplies.

The fertility status of each research area was assessed by various means including soil chemical and physical analyses, sampling and chemical analyses of forest floor and litter fall material and pot fertility tests. The relative ranking of these areas in terms of fertility was consistent with their site index or productivity rating. Monterey pine and Douglas-fir seedling test plants grown on the potted soils from the different horizons in each profile responded to nitrogen, phosphorus, and sulphur additions. In field tests nitrogen fertilization stimulated radial growth of Douglas-fir whereas phosphorus fertilizer at high application rates resulted in a growth depression.

SOIL AND GROWTH STUDIES IN DOUGLAS-FIR [*Pseudotsuga menziesii* (Mirb.) Franco] STANDS NEAR MOLALLA, OREGON

by

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SOIL AND GROWTH STUDIES IN DOUGLAS-FIR [*Pseudotsuga menziesii* (Mirb.) Franco] STANDS NEAR MOLALLA, OREGON

INTRODUCTION

The underlying premises of sustained yield management of forest lands are protection, reproduction, and growth. After the first two conditions have been satisfied, growth becomes a critical factor in profitable operation of the forestry enterprise. The maximizing of growth with consideration of utility and costs is a fundamental objective. Success in attaining this objective is often limited by understanding of the biological complex which is the forest and of its relationship to its physical environment. In Europe foresters have accumulated three centuries of experience in forest growth management. In addition a wealth of information has developed there in the field of forest science through observation, study, and experimentation. This serves to enlighten the forester as to the nature and behavior of the system which he seeks to control. The benefits of such knowledge and understanding are obvious.

The history of sustained yield forestry in the Pacific Northwest is a very brief one. Although National Forests have been in existence for more than a half century, initial policy was one of protection and preservation. Only in the last several decades has the emphasis for the National Forests switched from classical conservation to active management. Early in the 1940's private industry under the leadership of Colonel W. B. Greeley (77, p. 158-164) began to organize for perpetual forest production. The "tree farm" program of private industry which emerged under the auspices of the organization, American Forest Products Industries, Inc., was in sharp contrast to their traditional liquidation policies.

Regional research in forest science is likewise a very recent activity which has not accumulated pertinent information to an extent sufficient to provide much overall understanding of the regional forest ecology. Thus the silviculturalist has been forced to borrow heavily from outside knowledge and experience especially from Europe. Despite its deceptive similarities the Douglas-fir Region is not the same environmental system familiar to European ecologists. Subtle but important differences exist which make extrapolation of European knowledge of detailed relationships between plants, soils, and climate a hazardous practice.

For extensive forest management thus far practiced, the lack of a comprehensive understanding of regional site factors has not been critical. However, the age of intensive forest management is now very close at hand, particularly for private industry. Old-growth stands under private ownership are being cut out rapidly in the Pacific Northwest and within a few years, operations on industrial timberlands will be confined to young stands. Since the size of the sustainable cut will be more than ever limited by the growth rate of these young stands, much interest has been focused within industry on maximizing and sustaining that growth in usable forms.

Yield tables formed from regional data on natural stands (127, p. 1-74) are not adequate for sustainable cut calculations for intensively managed stands in a specific area. Recognizing this fact, Baisinger (9) in 1953, proposed a program of forest production research designed to meet the future needs of Crown Zellerbach Corporation for information on the potential of managed stands. The primary approach was a network of pilot management study areas distributed over the different tree farms, among the different age classes and species. The initial areas were established in 25- and 40-year-old Douglas-fir stands on the Clackamas Tree Farm east of Molalla, Oregon. An additional research area was established in 15-year-old Douglas-fir on the same tree farm to study techniques of increasing seed production of a high elevation stand.

One evaluation method applied to these study areas was, of course, a mensurational comparison of the various thinning regimes (including an unthinned control subarea) at each location. Another method utilized was a detailed study of soil moisture, soil fertility, soil temperature, and seasonal tree growth patterns. The latter project, the topic of this thesis, was initiated and carried out by the author as a Research Forester with Crown Zellerbach Corporation. The study was designed to provide fundamental information about important local site factors affecting tree growth and their interaction with stand treatment. As the work progressed, the effects of irrigation and fertilization on growth patterns were explored. Pot studies with conifer test plants were also made to assess soil fertility relationships. In this thesis the results and implication of these soil and growth studies will be discussed.

LITERATURE REVIEW

Soil Moisture and Thinning

The vital role water plays in all phases of a plant's physiological activites has been well known for some time. It is not particularly surprising, therefore, that growth of forest trees is profoundly influenced by supply of moisture in the soil. Likewise, the forest has an appreciable influence on soil moisture. Fricke (as cited in Craib, 43, p. 9-10) found increasing soil moisture and seedling survival when plots beneath a Scotch pine (Pinus sylvestris L.) stand were trenched to cutoff the overstory roots. Craib (43, p. 49-58) found a similar increase of soil moisture with trenched plots placed under a white pine stand. Aaltonen (as cited in Craib, 43, p. 13-14) reasoned that root competition for moisture and nutrients strongly influenced spatial arrangement of trees.

Artificially altered spatial arrangements or thinnings have been found to affect soil-moisture patterns. In New England after a detailed study in white pine (Pinus strobus L.) and Scotch pine plantations, Adams (1, p. 82) concluded that thinning resulted in higher available soil-moisture levels during dry periods. Investigation by Adams and Chapman (2, p. 8-16) of the soil-moisture regimes of 28-year-old jack pine (Pinus banksiana Lamb.) and Norway pine (Pinus resinosa Ait.) plantations spaced initially from two by two feet up to eight by eight feet reveal the same, but less clearcut, trends of increased soil-moisture contents with increased spacing distances.

In south Arkansas, Zahner and Whitmore (217) found a decreased rate of soil-moisture depletion with removal of all but widely spaced loblolly pine (Pinus taeda L.) trees in a young plantation. They concluded that incomplete utilization of the site by remaining tree root systems was primarily responsible. This contention has been further supported by the findings of Douglass (56) that during soil-moisture depletion in a thinned 16-year-old loblolly pine plantation in South Carolina, the soil-moisture content was highest midway between, and lowest adjacent to, the remaining trees. In southeastern Arkansas, Bassett (13, p. 87-94) found that openings caused by thinning in 30-year-old loblolly pine stands were significantly more moist throughout the first growing season after cutting than the soil under the trees surrounding the opening. Harms (89, p. 1-16) however, found no significant difference in available soil moisture between different spacings of a six-year-old slash pine (Pinus elliottii Englem. var. elliottii) plantation in the middle coastal plain area of Georgia. Diameter growth rate, however, was strongly correlated to available moisture for all spacings. McClurkin (129) showed that rates of soil-moisture depletion were markedly lower for thinned 19-year-old shortleaf pine (Pinus echinata Mill.) plantation stands in northern Mississippi than for the unthinned plots.

In Minnesota, Hansen (87, p. 56-63) found greater soil moisture under thinned 37-year-old jack pine the first year, but more soil moisture under the unthinned stand the following season. Della-Bianca and Dils (50) showed on soils derived from glacial sands in lower Michigan that as the growing stock level in 40-year-old red pine decreased, the soil moisture at a given date during the depletion phase increased. On similar soils in Wisconsin decreased rates of soil-moisture depletion resulted from heavily thinning a 15-year-old plantation stand of red pine (52, 81). Another study on sandy soil by Bay and Boelter (16) showed slightly higher available soil moisture with a 60 square feet basal area stocking of 90-year-old red pine in contrast to that of a 140 square feet basal area.

Albert (5) measured soil moisture under control and thinned stands of 20- to 25-year-old pine in Germany and found higher levels under the thinned stand during the depletion period. Russian workers (157, p. 16-20; 176) have also noted that thinning decreased total soil moisture consumption by ash, aspen, oak, and pine trees for a number of years.

In the Pacific Northwest André (8, p. 35-48) observed no appreciable difference in rate of moisture depletion for different thinning intensities in 22- to 45-year-old Douglas-fir on the western slopes of the Willamette Valley near Salem, Oregon. Moisture use by sapling ponderosa pine (*Pinus ponderosa* Laws. var. *ponderosa*) increased with increasing density in a spacing study on pumice soil in central Oregon (12, p. 1-22).

It may be generally concluded that thinning does decrease soil-moisture depletion. The fact that this effect decreases with time is a result of rerooting of the unutilized soil volume by remaining trees or by subordinate vegetation. As thinning intensity increases (or stand density decreases) the rate of soil-moisture depletion decreases. Root distribution appears to be the most important factor involved. The total transpiring needle surface would of course be decreased by thinning, but the exposure of this surface as well as that of the soil to higher levels of radiation and increased air movement should tend to increase moisture loss with thinning. In the top layer of soil under thinned stands of forest trees higher rates of moisture depletion have been observed than in comparable unthinned stands (176). Increased evaporation through increased exposure to insolation and greater air circulation in the thinned stand is the logical explanation. The fact that this trend is generally overridden by the decrease in transpiration loss attests to the relative order of importance of the two opposing effects.

Soil Temperature and Thinning

In most cases soil temperatures have been found to increase as a result of thinning. Ronge (as cited in Braathe, 22, p. 63) found June-July temperatures 6.7°F. higher at the four-inch level and 5.7°F. higher at the eight inch level for heavily thinned plots of 120-year-old pole stands of Norway spruce (Picea excelsa Link) in north Sweden. In a similar situation Angstrom (as cited in Braathe, 22, p. 63) observed a maximum temperature 3.5 - 5.5°F. higher with the heavy thinning. In old spruce stands of central Norway, Mork (as cited in Braathe, 22, p. 63-64) found in the top half inch of soil a temperature difference of 3.5°F. after removal of 18 percent of the volume corresponding to 24 percent of the trees. In Russia, Savina (157, p. 20-22) noted slightly higher growth-period temperatures and slightly lower fall temperatures as a result of thinning treatments in 20- to 25-year-old pine. Bournebusch (21, p. 90) measured soil temperatures under various thinning regimes of a 60-year-old red spruce plantation in an elaborate Danish thinning study. The differences in temperature for the July measurement at 20 cm. were less than 1°C. In Minnesota Hansen (87, p. 52-56) observed significantly higher soil temperatures under thinned jack pine stands. In lower Michigan thinning of 32-year-old red pine resulted in a similar trend of increasing temperature with decreasing stand density (50). These differences, however, were not statistically significant. André (8, p. 48-49) failed to detect temperature differences due to thinning in a 22-year-old Douglas-fir plantation in western Oregon.

In general, investigators observed that the nearer the temperature measurement point to the soil surface the greater the growing-season-temperature difference due to thinning. Likewise as thinning intensity increased the temperature differences between the thinned and unthinned stand tended to increase.

Root Distribution and Thinning

Several thinning studies have included descriptions of root distribution. Zahner and Whitmore (217) examined root distribution in a loblolly pine stand that had been radically thinned at an early age. They estimated the rate of root expansion of the 10-year-old plantation trees from the soil-moisture-depletion patterns, and in addition excavated and diagrammed lateral roots from selected trees in each treatment class. The original cut in the wide spacing treatment left 10 percent of the area effectively rooted; at the end of the second growing season 30 percent was more or less fully occupied; at the end of the third year 60 percent; and after five years the top two feet of soil was completely utilized by the 100 crop trees per acre. Root excavations indicated that their longest lateral roots were twice that of the control trees just two and a half years after thinning. Bassett (13, p. 121) concluded from moisture depletion patterns that thinning of 30-year-old loblolly pine to a basal area of 130 square feet allows complete closure of roots after one growing season. Thinning to lower basal areas of 85 and 55 square feet, however, left considerable soil unrooted after the first season. Adams and Chapman (2, p. 26-28) examined root systems of jack pine plantations with spacing ranging from two by two feet to eight by eight feet. Halfway between jack pine crop trees there was downward penetration of the lateral roots which in the opinion of the authors occurred when competition in the upper soil horizon became intense.

Dendrometer Growth Patterns

Instruments which precisely measured slight dimensional changes in tree bole radii or circumference are called dendrometers. MacDougal (120, p. 1-10) reviews the early development of these devices in some detail and has obtained voluminous growth observations with recording dendrometers or dendrographs of his own design (119, p. 1-256; 120, p. 1-240). There are several types of dendrometers in current use. One is a dial gauge dendrometer originally suggested by Reineke (146) and subsequently improved by Daubenmire (46). The base for the gauge is supported by three wood screws fixed in the tree while its spindle bears on a small plate attached to the trunk outside the cambium. Band dendrometers with a vernier scale are used to indicate changes in circumference (86, 187). These work well where close agreement to diameter tape measurement is desired. Bormann and Kozlowski (20) compared dial gauge and band dendrometers on eastern white pine in New Hampshire and concluded that the band, though less mechanically accurate, gives an average radial growth thus eliminating variation between individual radii. Young (211) suggested measuring more than one radius or sampling a large number of trees upon which to base an estimate of error.

Dendrometers have been extensively used to describe seasonal growth patterns of trees (17; 18; 33; 45; 47; 49, p. 1-12; 58; 62; 75; 79; 88; 100; 109; 128). Dendrometer growth comparisons have been made to show the effect of defoliation (53; 118, p. 24-29; 119, p. 104-129; 152); to test the association of growth with climatic variables (48, p. 464-475; 54; 65, p. 778-785; 67, p. 705-720; 68, p. 334-359; 145, p. 1-362; 165; 198, p. 52-66); and to compare release treatments, thinning intensities, or growing stock levels (13, p. 1-158; 15; 29; 50; 78, p. 1-58; 98, p. 1-83; 129; 169, p. 353-369; 198, p. 52-66; 217). Dimensional increases cannot always be attributed to growth. Haasis (80, p. 1-103) and MacDougal (120, p. 21-30) have established the fact that the swelling and shrinking of the tree bole results from rehydration and dehydration of the conducting elements of the stem brought about by a shift in balance between transpiration and absorption. Continuous recording of tree growth (69; 120, p. 21-30) shows that the tree typically reaches its daily minimum in the afternoon which corresponds to its greatest moisture deficit. Its daily maximum on the other hand is in the early morning when moisture deficits are the least.

Growth and Soil Moisture Availability

Available soil moisture has been defined as the amount of water a soil contains between field capacity and its permanent wilting point. Field capacity is usually defined as the moisture content at which drainage of moisture from soil becomes quite slow in contrast to an initially rapid flow. Permanent wilting percentage, the lower limit of soil-water availability, is the soil-moisture content at which plants wilt and do not recover turgidity in a humid atmosphere. Richards and Weaver (151) showed a close association of soil-moisture-tension values of 15 atmospheres with permanent wilting percentages determined with test plants.

It was originally concluded by Briggs and Shantz (24; 25; 26; 27, p. 20-37) that permanent wilting percentage was the same for all plants. Veihmeyer and Henrickson (185; 186; 187, p. 285-304; 188, p. 243-268) studied the question further and decided on the basis of field and greenhouse experiments that soil moisture was equally available for absorption, growth, and transpiration throughout the available range. Both points of view have been conclusively refuted by numerous studies reviewed in Hagan et al. (84), Marshall (123, p. 55-61), Slatyer (164, p. 585-636), and Stanhill (166). They generally concluded that permanent wilting percentage is a function of the plant and the climate as well as the soil, and that soil moisture is not equally available in the range of 0 to 15 atmospheres tension.

Russell (156) examined the nature of the evidence for and against equal availability of soil moisture and made a case for better experimental techniques in resolving the question. Kramer and Kozlowski (106, p. 499-504) tend to favor the explanation that the degree of climatic stress affects the conclusions regarding the relative availability of soil moisture. High climatic stress values reduce growth at low tension values but under low climatic stress conditions high soil-moisture-tension values may be approached without appreciably affecting growth. Also involved is the matter of root distribution and root concentration. Hagan (83) points out that deep permeable soils may allow root expansion into moist zones while the soil around the bulk of the root system may be held at high tension values. Thus determination of absorption, growth, and transpiration when related to the soil-moisture-stress levels measured where the root system is well established would appear to support the concept of equal availability. The ability of the plant to grow and extend its root system is also involved. Kramer and Coile (105) concluded that soil water made available solely by root growth could be adequate for the normal moisture requirements of winter rye (Secale cereale L.). Likewise root concentration plays an important role. Plants with sparse root systems have growth affected at lower soil-moisture tensions than those with dense systems (83). Differential root concentrations may lead also to differential rates of moisture depletion (6, p. 975-988; 180; 184).

The growth of forest trees has been shown to be affected by moisture relations in a manner similar to other types of plants (108). White (202) however, points out that the wilting point for many xerophytic tree species would probably be substantially below that obtained by sunflower (Helianthus annuus). The demonstration of just such a capability of ponderosa pine seedlings by Fowells and Kirk (63) supports this hypothesis. If this species was accepted as typical one might expect growth inhibiting effects for forest trees at only rather high soil-moisture tensions. Zahner and Whitmore (217) however, found that growth of loblolly pine ceased when only about half of the available soil water was utilized to an average tension of about three atmospheres. Bassett (13, p. 137) in another study concluded: "diameter increase of loblolly pine is slowed appreciably when moisture throughout the 0 to 12 inch layer is held at an average tension greater than 0.5 atmospheres". Prolongation of soil-moisture availability extended the duration of shortleaf pine diameter growth (129) though the increased rate of growth throughout the period seemed to be the chief benefit of thinning. In red pine, growth of an unthinned plantation stand ceased when one third of the total available soil moisture remained (50). Bay and Boelter (16) could not detect growth influences by soil moisture on 90-year-old red pine, probably because frequent rainfall during the growth period to a large extent effectively eliminated drought conditions. DeVries and Wilde (52) observed growth retardation in 17-year-old red pine plantations when soil moisture had been depleted to a value which corresponded to field capacity in the sandy soil.

It does not seem likely, therefore, that soil moisture can be equally available for forest tree growth through the 0 to 15 atmosphere tension range. Quite the contrary, growth retardation effects have been recorded at surprisingly low tension values. The current point of view seems to be that available moisture as a soil constant is a useful but oversimplified concept. A more sophisticated picture permits consideration of both the plant and climate in soil-moisture and plant-growth relationships.

Growth and Irrigation

There has been little irrigation practiced in forest situations even for research purposes. Kraus and Bengtson in a 1960 review on the use of irrigation in forestry (107) found several dozen papers half of which related to irrigated plantations. A portion of the remaining was concerned with seed production and of those dealing with mature trees only that of Paul and Marts (141, p. 784-796) was adequately designed to evaluate growth. Over a three year period in this study, radial growth and percent summerwood of irrigated 100- to 250-year-old longleaf pine (Pinus palustris Mill.) increased 77 percent and 124 percent respectively above the average of the previous 14 years. Control trees had 17 percent more growth and 24 percent more summerwood for the three years after treatment initiation as compared to the 14 years prior to treatment. Irrigation and fertilization combined gave 81 percent more radial growth and 134 percent more summerwood respectively. Zahner (216) found that irrigation applied in the third through the fifth growing season doubled the amount of radial growth of loblolly pine during this period, but the amount of summerwood remained unchanged.

Fielding and Millet (60, p. 26-28) watered 25-year-old Monterey pine (Pinus radiate D. Don) in growth studies at Canberra. The three-year-diameter growth at dbh. (diameter breast height) was 22.7 mm. compared to 7.4 mm. for the control trees. At Harvard's Black Rock Forest 75-year-old hardwoods responded significantly in basal area growth to irrigation treatments (173). Mosher (138) found 90-year-old ponderosa pine in eastern

Washington to respond in diameter growth to irrigation alone and in combination with nitrogen fertilization. Zahner (214) described a number of other irrigation studies which were underway in 1958. To date, however, no diameter growth information has been published with the exception of a wood-formation study of five-year-old loblolly pine (216). Use of industrial waste water for forest irrigation has been reported in recent years (116; 125, p. 227-239; 132; 154). The primary concern of these studies has been the effect of excessively large amounts of moisture on forest vegetation.

Growth and Fertilization

Foresters have recently focused a great deal of interest on the possibilities of site amelioration by fertilization so successfully practiced in agriculture. A number of interesting studies concerned with the mineral nutrition of tree seedlings grown in sand or solution culture have established a substantial requirement similar to, but in general somewhat less than that of other crop plants (3; 64, p. 95-112; 72; 135, p. 1-135; 144; 177, p. 1-16; 178, p. 1-66; 195). Attempts to quantify nutrient cycles and nutrient drain in older trees (140, p. 75-88; 148, p. 1-95) indicate that under intensive forest management, losses from the site will be appreciable and means of effective additions must be considered.

Reviews of world and regional literature on forest fertilization

(126, p. 1-111; 163, p. 1-35; 193, p. 1-50; 204, p. 1-305) have been published in the last decade and work in this field has subsequently proliferated. Much of this has been directed towards the problems of afforestation and regeneration. Some of the studies with mature trees have been primarily to evaluate effects of fertilization on seed production (51, 159, 168, 201). Long-term-European-forest-fertilization studies have proved that growth limiting nutritional problems exist in forests. In Sweden 250-year-old spruce stands showed increased diameter growth for 10 to 12 years after heavy applications of nitrogen (179). Stands of 40- to 60-year-old beech, pine, and spruce also showed marked growth response to nitrogen fertilization. Fifty to seventy-year-old spruce stands in Germany showed significant and profitable volume responses to Ca, N, and P fertilizer mixtures (90, p. 291). In similar spruce stands in another section of Germany, Mitscherlich and Wittich (136, p. 187-188) noted marked diameter growth responses to nitrogen applications. Bruning (32, p. 202-204) reported that growth of 20- to 25-year-old Scots pine on sandy soils in Germany was stimulated by K_2O and Mg applications. One hundred-year-old Scots pine in Norway was fertilized with $Ca(NO_3)_2$ or NPK at rates of 100, 200, 300 and 400 kilograms per hecatre per year for two to three years (23). Diameter growth following fertilizer application increased with increasing levels of fertilizer. Leyton (113) related that plantation establishment in

Britain is aided by phosphorus and later growth is stimulated by nitrogen.

Dramatic responses in both height and diameter growth have been obtained in pine plantations of western Australia with applications of superphosphate (170, p. 25-26). Nitrogenous fertilizers, on the other hand, did not effectively increase growth rates in initial studies. Recent experience with pines in both Australia (196) and New Zealand (171, p. 1-17) indicates that nitrogen may become a limiting factor as cropping continues.

Fertilization of southern pine forests has resulted in growth responses primarily to the nitrogenous fertilizers. Zahner (215) found a ten percent increase in diameter growth of young loblolly pine plantation trees in southern Arkansas over a five year period after application of 100 pounds of N per acre. Walker and Youngberg (194) reported a significant 35 percent average diameter growth increase of young slash pine over a three year period after a treatment of 100 and 44 pounds per acre of N and P respectively. Nitrogen alone significantly stimulated the diameter growth of the 400 largest trees per acre. A mixture of NPK (220, 180, and 120 pounds per acre respectively) almost doubled diameter growth over an 11 year period after fertilization of 35 - year -old shortleaf pine in South Carolina (153). Maki (122, p. 363-375) found nitrogen increased diameter growth in both old and young plantations of loblolly pine in North Carolina. Pole-sized slash pine (97) responded with increasing diameter growth to increasing rates of nitrogen at a seed production area in Florida. Over a four year period, basal area growth of shortleaf pine in Tennessee was increased with application of nitrogen (300 pounds per acre) by as much as 40 percent when the stands had been thinned (44). Unthinned stands gave only modest responses to nitrogen and responses to phosphorus were erratic.

Substantial and long-term responses in both height and diameter growth of northeastern conifers have been noted from applications of potash fertilizers to sandy glacial outwash soils in northern New York (91; 92, p. 142-153; 93; 94). Diameter growth of a 20-year-old shortleaf pine plantation in Illinois was significantly increased over a two year period by applications of 100 pounds per acre N alone or in combination with 100 pounds per acre P_2O_5 (19, 73). The subsequent three years, however, revealed no further growth advantage for the fertilized trees (74).

Forest-fertilization-research activities in the Pacific Northwest have recently revealed that forest trees growing over a broad range of soil and climatic situations in this region will show a growth response to applications of nitrogen fertilizers. A fertilized 30-year-old Douglas-fir plot on the University of Washington's Pack Forest had twice as much diameter growth for the five years after initial fertilization on an average tree basis than did the unfertilized plot (71). The initial application consisted of NPK and lime at modest levels and urea nitrogen was added each year bringing the total N to 350 pounds per acre by the end of the third year. Near Molalla, Oregon, diameter growth of 20-year-old Douglas-fir was increased by increasing nitrogen levels and decreased by increasing phosphorus levels (124, p. 27-29). The highest rate tested was 1200 pounds per acre applied over a three year period on a single tree basis. In a similar age Douglas-fir stand on the Yacolt burn in Washington but on a higher site (Site II as compared to Site IV), diameter growth increased with increasing levels of nitrogen fertilization to a maximum of 400 pounds N per acre (168). Phosphorus at the same rates did not increase growth though no depression was noted as was the case at Molalla where the same 400 pound per acre rate of P_2O_5 was repeated annually over a three year period.

The fact that nutritional factors of the forest site can limit growth of forest trees throughout the forested regions of the world has certainly been well established by the results of these studies. Nitrogen seems to be the element most often in limiting supply. This situation appears to be particularly prevalent in the Douglas-fir Region.

Soil Fertility and Site Productivity

The assessment of site productivity in terms of soil fertility has for the most part been approached by soil-site correlation studies (36; 76; 112; 121; 183, p. 1-89; 208, p. 123-137). The objective of this approach is to obtain a basis of predicting site quality using one or more soil characteristics. Soil description and analyses have been the basic tools of the evaluator. Foliar analysis has recently been suggested as a more meaningful approach (114, p. 323-345; 203). Both Viro (190) and Wilde (205) have carefully examined the merits of this suggestion and recommended continuing to improve soil analyses as the basic tool. In Wilde's opinion foliar analysis because of its expense and the difficulty involved in its interpretation would only be suitable for elaborate research projects. Both techniques seem to have limitations and each is useful for understanding nutritional aspects of tree growth. In situations where it is practical to use both types of analyses a better insight should be gained for interpretation of either soil or foliar analysis with respect to growth of trees.

Another supplementary method which can be applied to soil fertility status problems is a bioassay of productivity, the pot fertility test. Test seedlings are grown in pots of the soil to be assessed under a favorable moisture regime. A number of different fertilizer treatments are assigned systematically to reveal growth effects on test plants of single elements at one or more levels as well as the different combinations of elements at the selected levels. California soils have been broadly assayed for fertility status with romaine lettuce (Lactuca sativa longifolia) as an indicator plant (101). Assays of forest soils have been made with this technique also (72, 192). Conifer test plants have likewise been used for this purpose (57, p. 181-193; 110, p. 1-172; 134, p. 1-138; 172; 191; 195; 197, p. 42-43, 50-59; 206, p. 1-53). Waring's (197, p. 52-53) pot tests with redwood [Sequoia sempervirens (D. Don) Endl.] and Douglas-fir did not show a consistent relationship between productivity or site index of soil-sample source and the pot yields. However, with Douglas-fir seedlings, Lavender (110, p. 59-79) was able to demonstrate growth magnitudes in the same relative sequence as the productivity of the sites sampled.

Some authorities question the validity of pot experimentation especially in the greenhouse environment (39). McComb (150, p. 444) commented on the lack of agreement between field and greenhouse results of fertilization of hardwood seedlings. Cook and Millar (41) recommended techniques to obtain better agreement which resulted in good correlation when the soils involved came from the same location. Terman, Bouldin, and Webb (181, p. 306-307) thought that greenhouse experiments were useful for soil fertility assay. No doubt there are hazards involved in extrapolation or generalization of greenhouse pot experimentation. The risks should be minimized, however, when its limitations are well recognized and it is coupled with adequate field information and experimentation.

AREA DESCRIPTION

Clackamas Tree Farm - General

Physiography

The Clackamas Tree Farm lies five to fifteen miles east of Molalla (Figure 1) in the foothills of the Oregon Cascade Mountains. It ranges in elevation from 600 feet at the Molalla River on the west to 4500 feet at the crest on the eastern extremity. A series of parallel east-west drainages dissect a gradual slope uplifted to the east. Figure 2 illustrates this pattern as well as shows the location of the tree study areas, ML 1, ML 2, and HESPA (ML - Molalla; HESPA - High Elevation Seed Production Area). Mud flows and extrusive flow breccia give ample evidence of the violent volcanic history of the area. Cascade andesite is the principal soil parent material east of the South Fork of the Molalla River. West of this line, basalt bedrock appears to predominate. Alpine glaciation has shaped the valleys and provided a series of cirque lakes near the eastern tree farm boundary. Glacial till soils are evident below the cirque lakes and along the walls of the present valleys.

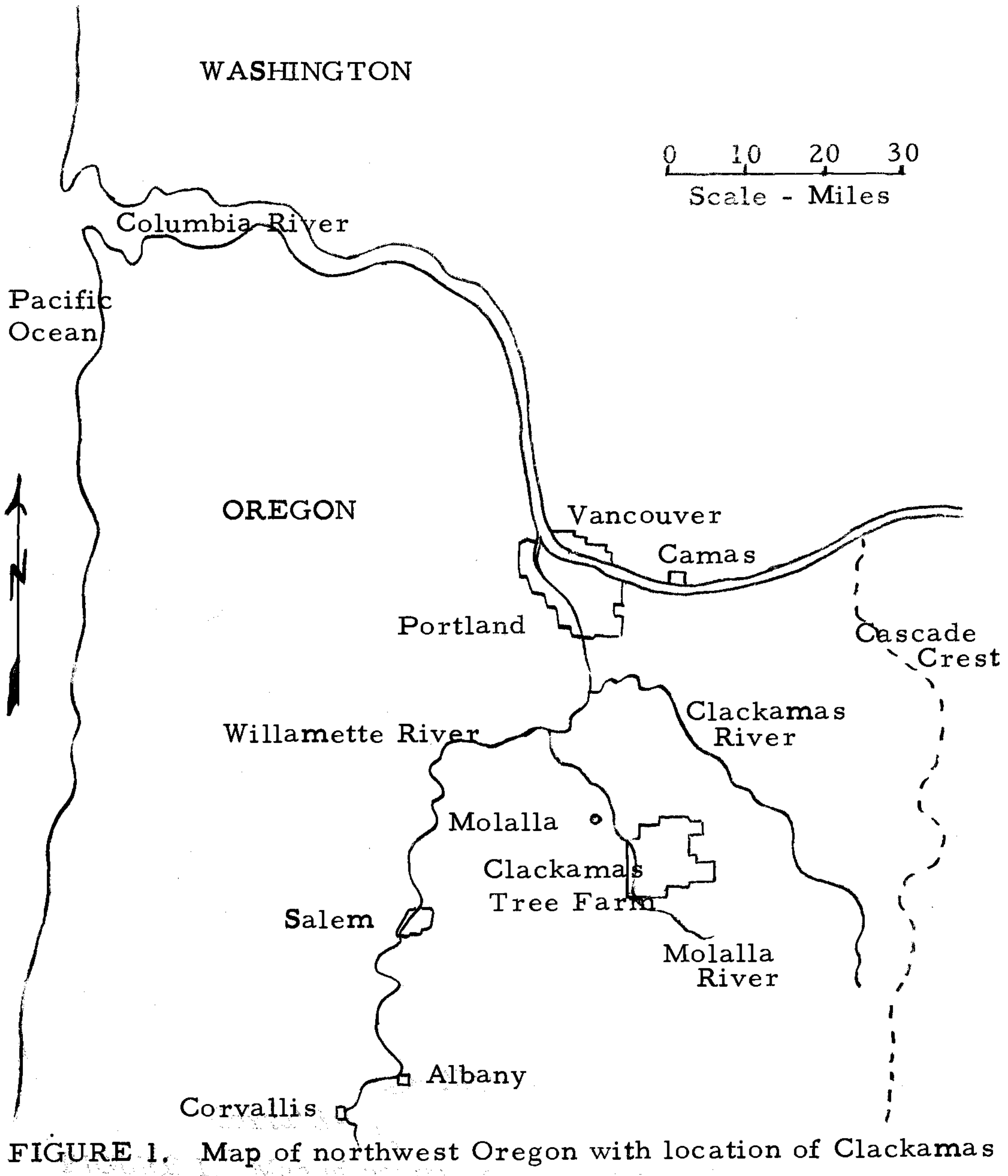

FIGURE 1. Map of northwest Oregon with location of Clackamas Tree Farm.

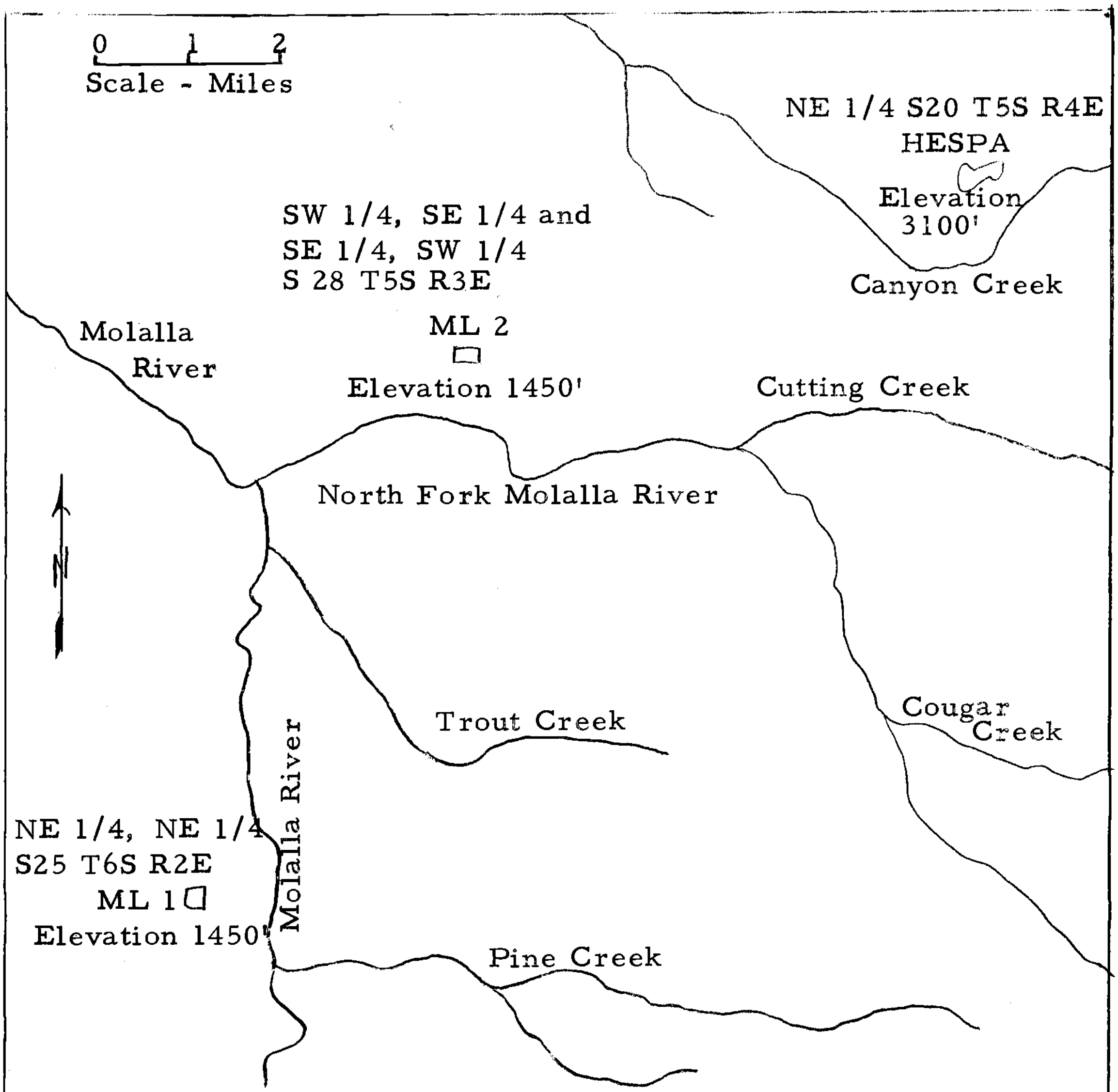

FIGURE 2. Location of research areas on Clackamas Tree Farm in relation to major drainages: ML 1 - 45-year-old Douglas-fir, ML 2 - 30-year-old Douglas-fir, and HESPA - 20-year-old Douglas-fir.

Vegetation

Douglas-fir is the principal conifer type at Clackamas Tree Farm with western hemlock [Tsuga heterophylla (Raf.) Sarg.], western red-cedar (Thuja plicata Donn), and grand fir [Abies grandis (Dougl.) Lindl.] mingling on moist sites at lower elevations. At higher elevations noble fir (Abies procera Rehd.) and Pacific silver fir [Abies amabalis (Dougl.) Forbes] form pure stands as well as mixtures with Douglas-fir and western hemlock. Hardwoods commonly found along drainages and mixed in young conifer stands include red alder (Alnus rubra Bong.), northern black cottonwood (Populus trichocarpa Torr. and Gray), willow (Salix spp.), vine maple (Acer circinatum Pursh), big leaf maple (Acer macrophyllum Pursh), and bitter cherry (Prunus emarginata Dougl.). An extensive stand of 120-year-old Douglas-fir resulting from a major fire sweeping up from the Willamette Valley occupies the western tree farm fringe. To the east most of the old-growth Douglas-fir has been removed 20 to 30 years previously. As a result of natural and artificial (planting) regeneration a major portion of this area has been restocked with Douglas-fir, noble fir, and western hemlock. Further east, mixed stands of old-growth of the previously mentioned composition are intermingled in a mosaic pattern with recent cut-overs. Site quality of the Douglas-fir stands ranges from Site II on lower coves or benches to Site V - on rocky ridge tops.

Research Area Selection

Selection of areas for forest production research was guided in general by requirements of full and uniform stocking of a single species with a minimum age variation; good accessibility and topography; minimum size of 10 to 15 acres; and uniformity of slope, site quality, topography, and soil conditions. Oldest age class desired was 40 years with emphasis on 20- to 30-year-age classes. Because of Clackamas Tree Farm's recent logging history there was a very limited number of suitable candidate stands. The initial selection was a 40-year-old stand (ML 1) in 1954 followed by one in the 25-year-old range (ML 2) in 1955.

ML 1 - 45-year-old Douglas-fir Stand

ML 1 is located on a spur ridge top at 1450 feet elevation above and to the west of the South Fork of the Molalla River (Figure 2). The soil is residual on basalt and is described in the Appendix (App. A, p. 143). Results of soil chemical and physical analyses are also shown in Table 16 (App. A, p. 140). Annual precipitation is probably similar to the 55 inch average of the Clackamas Marion Forest Protective Association's North Fork Station, four miles to the north at the same elevation (Figure 2). There was very little subordinate vegetation under the dense Douglas-fir stand before thinning. Small patches of bracken fern (Pteridium aquilinium pubescens), sword fern (Polystichum munitum), and assorted grasses were scattered in the small openings throughout the stand. The old-growth Douglas-fir stand originally present was clearcut in 1890 and the area was pastured for several years. Later it was cropped and then returned to pasture. Douglas-fir seedlings began to appear profusely after 1910.

ML 1 was established in 1954 under the direction of the Resident Forester, Mr. Kenneth Clark and Research Forester, Mr. Donald Baisinger (11, p. 1-16). Its total of 12 acres was split into three subareas; ML 1A, commercial crown thinning; ML 1B, light crown thinning; and ML 1C, unthinned (Figure 26, App. A, p. 136). Site index varied somewhat across the subareas (ML 1A - Site Index 162, ML 1B - Site Index 160, and ML 1C - Site Index 155). Thinning cuts were made in 1955, 1957, 1959, and 1961. Unfortunately the Columbus Day Storm (October 12, 1962) destroyed the study as such, because of the widespread blowdown in the stand. Treatment specifications and stand statistics are given in the Appendix (App. A, p. 145 and Table 17, p. 142). Figures 27 through 31 (App. A, p. 137-139) show the various subareas before and after thinning.

ML 2 - 30-year-old Douglas-fir Stand

ML 2 is located on a ridge top one half mile northeast of the North Fork Guard Station (Figure 2) above and north of the North Fork of the Molalla River at 1450 feet elevation. The soil is residual on andesite and is described in the Appendix, (App. B, p. 153). Results of soil chemical and physical analyses are also shown in Table 18 (App. B, p. 150). The average annual precipitation at North Fork Station is 55 inches as previously stated. There are abundant clumps of vine maple which have been overtopped and suppressed by the Douglas-fir stands. Other subordinate vegetation include bracken fern, sword fern, salal (*Gaultheria shallon*), Oregon grape (*Mahonia aquifolium*), and ocean spray (*Holodiscus discolor*). The old-growth stand of Douglas-fir at ML 2 was cut in 1921, burned in 1925, and pastured for about six years. Around 1930 the Douglas-fir seedlings began to appear among the vine maple and bracken fern cover on the area.

ML 2 was established in 1955 under the direction of Clark and Baisinger (11, p. 1-16). The 20 acre area was divided into three subareas (App. B, Figure 32, p. 146). Subarea A has been lightly thinned in 1956, 1958, 1960, and 1962. Subarea B was reduced from approximately 1500 trees per acre to 400 by one cutting in 1956. Subarea C was designated as a control. As was the case at ML 1 site quality was somewhat lower in the control subarea C (Site Index 125) than in A (Site Index 130) or B (Site Index 135). Treatment specifications and stand statistics are given in the Appendix (App. B, p. 155 and Table 19, p. 152). Figures 33 through 37 (App. B, p. 147-149) show the various subareas before and after thinning.

HESPA - 20-year-old Douglas-fir Stand

HESPA is located on a sloping bench facing southwest at 3100 feet elevation above and north of Canyon Creek six miles southeast of Colton, Oregon (Figure 2). The soil is an uncorrelated Sol Brun Acide developed on andesite residium and colluvium (App. C, p. 159). Results of chemical and physical analyses are given in Table 20 (App. C, p. 158). The annual precipitation is probably between 60 and 75 inches. Site quality is Site IV (Site Index 120). Subordinate vegetation includes dense stands of fireweed (Epilobium angustifolium) and thimbleberry (Rubus pariflolius) as well as occasional patches of wild trailing blackberry (Rubus spectabilis) and salal. Bitter cherry is very prevalent both as understory and as a stand associate of Douglas-fir. Western hemlock and noble fir also occur in both the understory and overstory at HESPA. The old-growth stand was cutover in 1937 and natural regeneration of Douglas-fir and noble fir as well as some western hemlock commenced shortly thereafter.

This site was selected in 1957 as a seed production area for high elevation seed since it was the oldest second-growth stand available and because of the network of roads and catroads along with the moderate slope that made future mechanization of treatment and harvest possible (175, p. 1-11). The layout of the fertilization and irrigation studies is shown in Figure 38 (App. C, p. 156). Figure 39 (App. C, p. 157) gives a view of the thinned seed production trees at HESPA.

METHODS

Soil, Forest Floor and Litter Analyses

Sample sites for soil and forest floor collections were located by random selection of coordinates of a 50-foot by 50-foot grid parallel to the local section lines (Figure 26, App. A, p. 136 and Figure 32, App. B, p. 146). All 16 sample sites in the subarea, sampled the top two levels of the soil profile; A11 and A12 (ML 1, 0 to 4 inches and 4 to 8 inches - ML 2, 0 to 4 inches and 4 to 10 inches); eight sampled the B1 and upper B2 horizon levels (ML 1, 10 to 14 inches and 22 to 26 inches - ML 2, 12 to 16 inches and 22 to 26 inches); while only four sampled the lowest level, the lower B2 horizon (30 to 36 inches for both ML 1 and ML 2). This procedure was designed to take the most samples at the depth where there was the most variation and the least difficulty in sampling. Chemical and physical analyses were performed on composited soil samples composed of four samples per composite. Methods of sample preparation and analysis were carried out according to regional forest soil procedures (61, p. 1-38) with the following exceptions:

(1) Available phosphorus by bicarbonate extraction (157, p. 4-7).

(2) Moisture tension curves by pressure membrane apparatus (149, p. 101-109).

(3) Dispersion for mechanical analysis by prolonged shaking (212).

(4) Exchangeable cations by procedures used at Oregon State University Soil Testing Laboratory (4).

A square foot of forest floor material was collected at each sample site and prepared for analysis with a Wiley mill using a 20-mesh screen. Total nitrogen was determined by Kjeldahl analysis of the ground material. For the remaining determinations a nitric acid-perchlorate digestion was used with evaporation to dryness followed by addition of concentrated hydrochloric acid. The following methods were used for the various determinations from these basic solutions:

Phosphorus - Ammonium molybdate (7, p. 162; 143, p. 290-293).

Calcium - Permanganate method (7, p. 112-115; 104, p. 345-351).

Magnesium - EDTA method (104, p. 345-351).

Potassium and Sodium - Flame photometer from calcium determination extract (104, p. 345-351).

Forest litter and seed traps (Figure 3) 1/4-milacre in size (32 by 49 inches) were constructed as a modification suggested by Dimock[1] of one described by Shaw (162). These were installed ten

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[1] Personal communication. March 14, 1958.

feet north of even number growth plot centers at ML 1 and ML 2 in October 1958. Collections were made five times in 1959 and four times in 1960 at dates roughly corresponding to ones used in a similar study by Dimock (55) at the United States Forest Service Voight Creek Experimental Forest near Puyallup, Washington. Sample preparation and chemical analysis were identical to the methods described previously for forest floor analysis.

Soil Moisture and Temperature Measurements

Four stacks of Colman fiberglas soil-moisture units (39, p. 1-20) were installed at three depths, 5 inches (midpoint 0 to 10 inches), 15 inches (midpoint 10 to 20 inches), and 28 inches (midpoint 20 to 36 inches) in each subarea of ML 1 and ML 2 (Figure 26, App. A, p. 136 and Figure 32, App. B, p. 146) during the winter of 1956 and 1957. Later, in 1960, four stacks with similar depth placements were located at HESPA as well as two additional ones at ML 2B in the midst of groups of four or five unfertilized trees of the irrigation-fertilization studies. Another four stacks were installed in the unthinned fertilization-irrigation study at HESPA in 1961. Moisture units were not used in conjunction with fertilizers because the increased salt concentrations in the soil solution would affect the readings of the resistance meter. Location of the subarea stacks of ML 1 and ML 2 was made within a 1/5 acre plot in each subarea (indicated in Figure 26, App. A, p. 136 and Figure 32, App. B, p. 147). The stacks of moisture units were concentrated at one location in the subarea in this manner to facilitate calibration of the units by gravimetric field sampling. An elaborate random selection procedure (174, p. 3-4) was used for stack site location. These locations were stratified at three, four, and five feet from the reference tree for ML 1 and at two, three, and four feet for ML 2. An attempt to calibrate the fiberglas moisture unit in the laboratory (40, p. 1-20; 96) failed due to shifting of the calibration curve with each drying cycle. Numerous workers have experienced similar difficulties (34, 35, 147, 199). Field samplings for calibration of the moisture units were made during 1958 and 1959 on ML 1 and ML 2. Similar samples were taken at HESPA and the ML 2B irrigation study during 1960, 1961, and 1962. A three-inch soil auger was used to collect samples no closer than four feet and no further than ten feet from the stack location. An alinement chart was used to correct Colman unit readings for soil temperature (99). The corrected dial reading was used with the sampled soil-moisture content to calculate a simple linear regression for prediction of soil-moisture content. Correlation coefficients for 60 of the 72 units in the initial study at ML 1 and ML 2 exceeded 0.8 and 70 had an "F" value significant at the 0.05 level. The range of moisture content of the soil samples gave especially strong representation at the dry end of the depletion curve.

For the thinning comparison at ML 1 and ML 2, soil-moisture content in percent was converted to inches of available soil moisture. Bulk density values necessary for this computation were obtained by averaging bulk density samples (166) taken in each subarea for the entire area. Further sampling at ML 2 turned up density differences in the 1/5 acre plots representing each subarea. This necessitated resampling on a local basis near the 1/5 acre soil-moisture-measurement plot in each subarea to obtain more valid estimates of bulk density and soil-moisture constants for available moisture calculations. Two undisturbed cores (5.1 cm. in diameter and 3.9 cm. in length) samples (28) were taken at each of three depths on each ML 2 subarea. Considerations of time and money did not permit resampling of localized plots at ML 1. In this case generalized bulk density values and determinations of soil-moisture tension on disturbed samples were used. Soil-moisture-tension values of 1/3 and 15 atmospheres were used as an upper and lower limit for available moisture. For the irrigation and fertilization studies at HESPA and ML 2, soil-moisture content in percent was converted to atmospheres of moisture tension instead of to inches of available water.

Dendrometer Measurements

Dendrometer stations were located at dbh. on three to seven trees surrounding each moisture stack. These stations faced toward the soil-moisture stack and consisted of three (No. 8, 2-3/4 inch stainless steel or blued iron) wood screws and a brass bearing plate (1/2 inch by 1/2 inch by 1/16 inch). A dial gauge dendrometer, shown in Figure 4, [identical to Holsoe's (98, p. 8-10)] measured the outward progress of the bearing plate in relation to the fixed position of the screws. The bearing plate was glued to the bole outside the active phloem with an epoxy resin. The screws were placed in such a way as to support the base of the dendrometer in the same position each time the tree was measured. Readings of radial growth were taken periodically during the growing season. The dial gauge was read to the nearest 10^{-4} inch.

Irrigation

HESPA - 20-year-old Douglas-fir Stand

Comparisons of irrigation as well as fertilization were set up at HESPA in 1959 during the latter part of the growing season. A total of 32 trees was selected and released from competition (with the exception of low understory plants and occasional adjacent study trees) and fitted with dendrometer stations. Half of these

FIGURE 3. Litter and seed traps. Twelve-inch ruler in foreground.

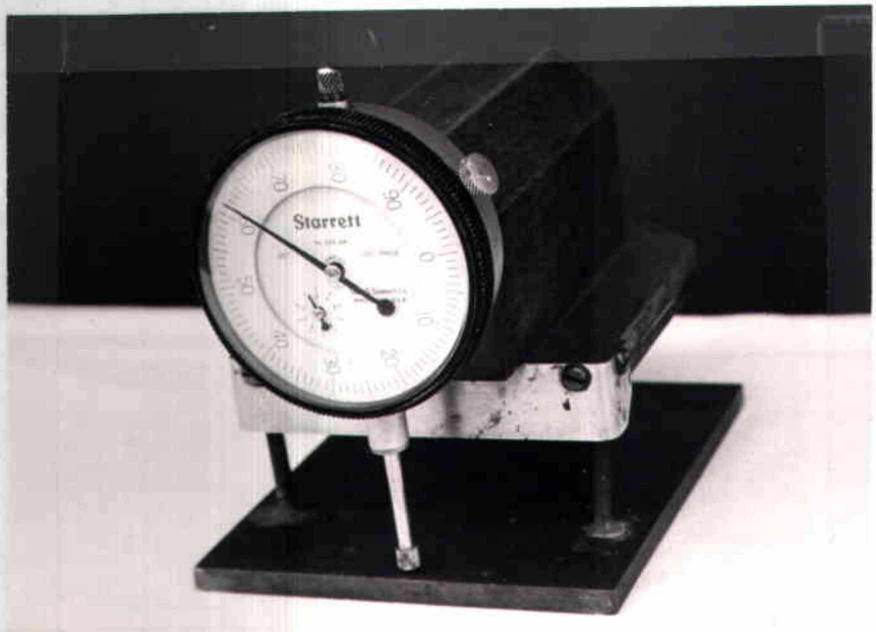

FIGURE 4. Dial gauge dendrometer.

trees were selected for irrigation using a gravity system with nine sprinklers arranged to cover four tree groups of four trees each (Figure 38, App. C, p. 156). Rainjet sprinkler heads 66C (square pattern 25 feet by 25 feet) were mounted on half-inch standpipes of convenient heights. Total amount of water added was calculated on a precipitation equivalent basis from the water pressure, the manufacturer's specifications on the sprinkler and the total lapsed time of irrigation. Scheduling of irrigation was on a trial and error basis. Relative trends of soil-moisture readings (attempting to hold them up to June levels) and past weather conditions helped guide decisions. Starting in 1961 radial dendrometer-growth records were kept current and these also were helpful in this respect. In 1961 some 32 additional trees were added that were not released from competition (unthinned - see Figure 38, App. C, p. 156). Six additional sprinklers were added to cover the four new tree groups for irrigation.

ML 2B - 30-year-old Douglas-fir Stand, Thinned

In 1960 dendrometer stations were installed on nine trees suitably situated for irrigation in ML 2B (Figure 32, App. B, p. 146). These trees were matched by dbh. with nine trees around two of the four soil-moisture stacks which were part of the existing dendrometer growth study on that subarea. Two Rainjet sprinklers were placed so that each serviced a surrounding group of four or five trees.

Water for irrigation was transferred from pumper trucks to a 3000 gallon tank truck and pumped by a Universal pump, Model WXE 4-1, 200 feet through 1-1/2 inch plastic pipe to the sprinkler heads. In 1961 nine additional trees were added which combined irrigation and fertilizer treatments. Calculation of irrigation water applied was on the same basis as HESPA as was also the scheduling of irrigation.

Fertilization

HESPA - 20-year-old Douglas-fir Stand

Half of the tree groups selected for the irrigation comparison at HESPA were fertilized by broadcast applications of nitrogen and phosphorus. Previous experience at HESPA indicated the greatest growth response of Douglas-fir was at the highest rate of fertilizer application [400 pounds per acre of N and P_2O_5 each year for three years (124, p. 27-34)] . This is calculated on a single tree area of 1/200th of an acre (8. 32 foot radius) and thus amounts to about six pounds of ammonium nitrate and four and one half pounds of treble superphosphate per tree per year. Fertilization of the 16 trees in the thinned comparison was made in June 1959, April 1960, and April 1961. Trees in the unthinned area were fertilized in April 1961, and April 1962. Since Mason's analysis (124, p. 27-34) showed phosphorus to be of doubtful value for growth improvement it was omitted from the 1962 refertilization.

ML 2B - 30-year-old Douglas-fir Stand, Thinned

Fertilizations at ML 2B were made on the same basis and at the same rates as HESPA but close tree spacing (average 11 by 11 feet) made extension of the outside perimeter around the tree group necessary. Applications were made in April 1961, and April 1962, to 18 trees in four groups of four or five trees each. Phosphorus was omitted in the 1962 refertilization.

Root Distribution

A comparison of root distribution between the heavily thinned subarea (ML 2B) and the control subarea (ML 2C) proved desirable to help interpret soil-moisture patterns. Studies of tree root distribution have been made principally by soil trenches or wells with scale sketches of root patterns (2, p. 16-17; 30, p. 5-6; 42; 117, p. 11; 182; 210, p. 8-11). Small volume or core sampling by depth through the profile are also helpful in making numerical comparisons (102, p. 5-8; 103, p. 18-19; 111; 133, p. 3; 158). Both methods were used at ML 2 but the soil well wall was photographed instead of sketched.

In May and June of 1963 two sets of core samples each (three holes per sample) were taken in the thinned and unthinned subareas (ML 2B and ML 2C). These sets or pairs were taken in locations adjacent to one another but on either side of the boundary between the control and heavily thinned subareas. The site of the sample hole was the center of the unoccupied polygon formed by surrounding trees. The three holes making up a single sample were located in adjacent polygons. The soil cores were seven inches in diameter and were taken every eight inches in depth to a lower limit of 32 inches. The core cutter used was developed by Mr. Michael Newton, Instructor, Oregon State University, School of Forestry, for taking undisturbed core samples. It consisted of a hardened steel pipe seven inches in diameter by 12 inches long and 1/8-inch thickness with a tooth cutting edge prepared on one end. The other end had a 1/4-inch steel plate welded across the top with a one-inch, augerlike, pipe handle attached. A plunger consisting of an iron rod slightly smaller in diameter and greater in length than the handle was attached to a round 1/2-inch iron plate slightly smaller than the cutting cylinder diameter. This was designed to help clear stubborn soil cores; but in actual practice tapping with a heavy hand hammer on the top plate was more effective and avoided compaction of the core and its attendant root damage.

Core samples were washed with a fine spray of water on a 20-mesh screen. Live roots were picked off the screen and separated into the following six diameter classes:

1. < 1 mm.
2. 1-3 mm.
3. 3-5 mm.
4. 5-10 mm.
5. 10-25 mm.
6. >25 mm.

The roots were oven dried and weighed by diameter class as a total by depth of the three cores comprising the sample.

Two additional sets of core samples were taken at the 24- to 32-inch depth during December 1963. The same procedure was applied as previously described for core sampling.

A soil well was dug both in the thinned (ML 2B) and unthinned (ML 2C) subareas. These were 15 to 20 feet long and two feet wide. They were dug parallel to a line between two trees (dominants and/or codominants) about four feet from the base of each tree. The trench was excavated to a depth at which no more roots were encountered in the rotted andesite layer which ranged from three to four feet in depth. The roots on the side facing the reference trees were cut off flush and then the soil picked away from the roots six inches back toward the trees. The roots thus exposed were sprayed with white enamel paint and the soil surface picked off to provide a dark background (160). The rear edge of the trench was trimmed off to facilitate photographing the profile.

Pot Fertility Studies

ML 1 - ML 2 - 30- and 45-year-old Douglas-fir Stands

In August 1962, a total of six soil samples, three each from ML 1 and ML 2 (three horizons - A1, B1, and B2) were collected in quantity for pot fertility testing. These were screened moist through a 1/2-inch mesh screen and transported in polyethylene bags to Corvallis. Details of the procedure for the pot assay are set forth in the Appendix (App. G, p. 186). An incomplete factorial design (82, 137) was utilized which consisted of three fertilizer elements (N, P, and S) at five levels with 23 of the 125 possible combinations selected for treatment (57, p. 182). Since facilities for chill treatments to break dormancy of Douglas-fir (207, p. 164) were not available, Monterey pine, a species used previously in pot studies by Wollum (206, p. 1-53), was selected instead as the test plant. This trial was harvested in March 1963, and evaluated for top growth and N, P, and S uptake. Another trial was started in April 1963, to compare the growth behavior of two test plants: Douglas-fir and Monterey pine. Soil from the B1 horizon at ML 1 was utilized and nine fertilizer treatments, selected from the original 23 used in the previous pot study, were applied. Harvest and top weight evaluations were made in October 1963.

HESPA - 20-year-old Douglas-fir Stand

Topsoil (Al - zero to six inches) from HESPA was collected in March 1962, and transported to the greenhouse and workshed facilities of Crown Zellerbach's Central Research Laboratory at Camas, Washington. The soil was screened through a 1/2-inch mesh hardware cloth and thoroughly blended. Fertilizer materials were mixed into the soil by a cement mixer. Douglas-fir seedlings (five per pot) were transplanted in May 1962, into five-gallon plastic pots. The pots were placed in outside beds for two growing seasons. Two fertilizers (N and P) were used at five levels with 13 of the possible 25 treatment combinations selected for testing (incomplete factorial design). Further details of the procedure used in this study may be found in the Appendix (App. G, p. 188). The study was harvested and evaluated for size in September 1963.

RESULTS

Thinning Comparisons

Litter Fall and Forest Floor

Dry weight of forest litter per acre is averaged for area (ML 1 and ML 2) and subarea in Table 1.

TABLE 1. Average weight of annual litter fall[1] and forest floor material for different thinned subareas at ML 1 and ML 2. (45- and 30-year-old Douglas-fir stands)

	ML 1			ML 2		
	A light crown thin.	B med. crown thin.	C control unthinned	A light thin.	B heavy thin.	C control unthinned
	pounds per acre					
Litter fall	2,425	2,280	3,632	1,767	1,642	2,134
Forest floor	14,820	12,440	17,700	17,230	26,200	12,100

[1] Includes twigs, branches and needles.

Table 2 gives the percent and pounds per acre of the mineral element composition of the litter fall averaged annually for ML 1 and ML 2 as well as seasonally for both areas. Table 21 (App. D, p. 161) and Table 22 (App. D, p. 163) give a complete compilation of dry weight per acre, of litter and its mineral elemental components. Litter fall was heaviest for the control subareas. This may be due

TABLE 2. Average amount and percent of mineral element constituents of litter fall (averaged on an annual basis) and forest floor material for ML 1 and ML 2 as well as the seasonal content of litter fall averaging the combined values from ML 1 and ML 2 (45- and 30-year-old Douglas-fir stands).

	N	P	K	Na	Ca	Mg[1]
ML 1						
Annual litter fall[2]						
percent	0.68	0.12	0.18	0.10	0.85	0.14
lbs. /A	12.9	2.3	3.4	1.8	16.4	2.6
Forest floor						
percent	0.93	0.15	0.09	0.11	0.99	0.14
lbs. /A	139.9	21.8	13.3	16.6	148.6	21.4
ML 2						
Annual litter fall						
percent	0.62	0.11	0.15	0.10	0.83	0.16
lbs. /A	9.9	1.8	2.4	1.6	13.3	2.6
Forest floor						
percent	0.90	0.12	0.09	0.11	0.86	0.19
lbs. /A	167.2	22.0	15.8	20.2	158.4	34.8
ML 1-ML 2						
Seasonal litter fall						
Jan. -April						
percent	0.94	0.14	0.22	0.11	0.71	0.15
lbs. /A	2.9	0.4	0.7	0.3	2.1	0.4
May-Aug.						
percent	0.62	0.12	0.18	0.10	0.62	0.18
lbs. /A	2.4	0.5	0.7	0.4	2.5	0.8
Sept. -Dec.						
percent	0.59	0.11	0.15	0.10	0.96	0.15
lbs. /A	6.2	1.1	1.6	1.0	10.2	1.4

[1] Magnesium determinations had appreciable variation. Therefore, differences between ML 1 and ML 2 as well as dates of collection should probably be discounted.

[2] Litter fall includes only needles and leaf material-no twigs or branches.

in part to the greater needle shading in the denser stand. Felled tree crowns in thinned subareas are not accounted for in a litter trap analysis, however. Dimock (55) found that litter fall for Douglas-fir reached its peak in October which was generally the case for ML 1 and ML 2. The fact that fall litter in contrast to spring litter had somewhat lower levels in percentage of mobile elements, N, P, and K as well as slightly higher amounts of immobile Ca (Table 2) is obviously due to the heavy fall drop of old needles. Spring collections consist to a greater extent of young foliage from winter blowdown. ML 1 had a greater overall amount of litter fall and proportion of minerals. In the case of N and P this might be attributable to its higher level in the soil profile (Table 3), but this would not apply for the basic mineral constituents. It is possible that in some way the age differences of the two stands are involved.

TABLE 3. Average levels of soil nutrient elements for the top three feet of soil profile at ML 1 and ML 2 (45- and 30-year-old Douglas-fir stands).

				Exch. cap.	Exchangeable cations			
		Avail.		m. e. per 100 gm. OD soil				
	Percent N	P_2O_5 ppm	pH	Total	K	Na	Ca	Mg
ML 1	0.19	14.4	5.1	33.6	0.63	0.07	5.63	3.17
ML 2	0.12	9.2	5.5	28.2	0.98	0.07	6.77	3.15

A summary of the total weight in pounds per acre of dried forest floor material for ML 1, ML 2 and their various subareas is given in Table 1. Table 2 gives the average mineral composition of forest floor material at ML 1 and ML 2. Forest floor data are summarized in Table 23 (App. D, p. 164). The thinned subareas at ML 2 had greater amounts of forest floor material than the control and greater also than the thinned areas at ML 1. The control subarea ML 1C, however, had more material than the control of the younger stand ML 2C. Since forest floor sampling was done two years after the initial thinning, the dense slash at ML 2B was especially effective in building and maintaining the amount of forest floor cover. The removal of logs and scattering of slash at ML 1 with its resultant mixing of forest floor into mineral soil compared to the relatively undisturbed state of the slash at ML 2 probably accounts for the difference in forest floor patterns observed. The level of nutrient content seemed to vary inversely with the amount of woody material. Samples which had suspiciously low nutrient percentages were found upon re-examination to contain abnormally large amounts of twigs, limbs, and half rotted wood in relation to needle and leaf derived material. Much of the variation between subareas in nutrient content was consistent with the amount of forest floor material. This would lead one to suspect that difference in wood content was an important contributing factor. It is not possible to make statistical comparisons of these data since all replicate samples were composited for chemical analyses.

Available Soil Moisture

Figure 5 shows the available moisture trends for ML 1 and ML 2 for the 1957 through 1960 growing season. Available soil moisture apparently remained in the profile of these areas and their subareas throughout the four-year period (Figures 6 and 7).

A convenient measure of relative soil-moisture depletion is the minimum level of available moisture during the growing season. Table 4 gives a summary of available moisture and/or soil-moisture tension at the date of minimum content or maximum depletion for ML 1, ML 2 and HESPA averaged by subarea (thinning treatment) over comparable years of measurement. Table 24 (App. E, p. 165) gives the available soil-moisture information for ML 1 and ML 2 for each individual year. An analysis of variance of these available soil-moisture values (Table 25, App. E, p. 166) showed for the 1957 to 1960 period that only depth had a significant effect. A similar analysis for HESPA and ML 2 for 1961 and 1962 (Table 26, App. E, p. 167) showed the maximum soil-moisture tension to be significantly different for the two areas but not for thinning nor depth of measurement. Though consistent differences are apparent in Figures 40 through 49 (App. F, p. 171-180) for subareas of ML 1 and ML 2

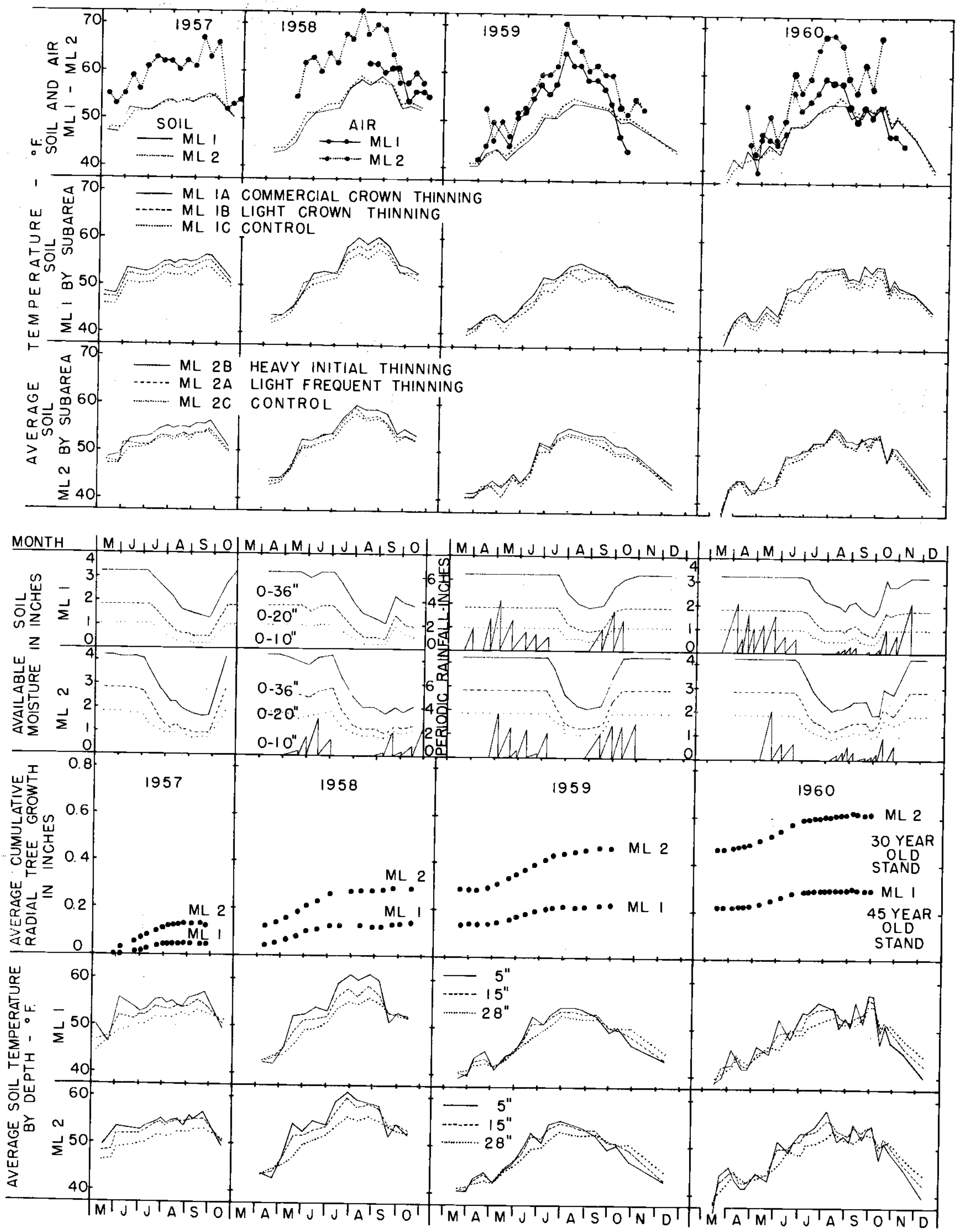

FIGURE 5. Average soil moisture and temperature - average air temperature and periodic rainfall in relation to average cumulative radial growth of 45- and 30-year-old Douglas-fir trees for different thinning intensities at ML 1 and ML 2 (1957-1960).

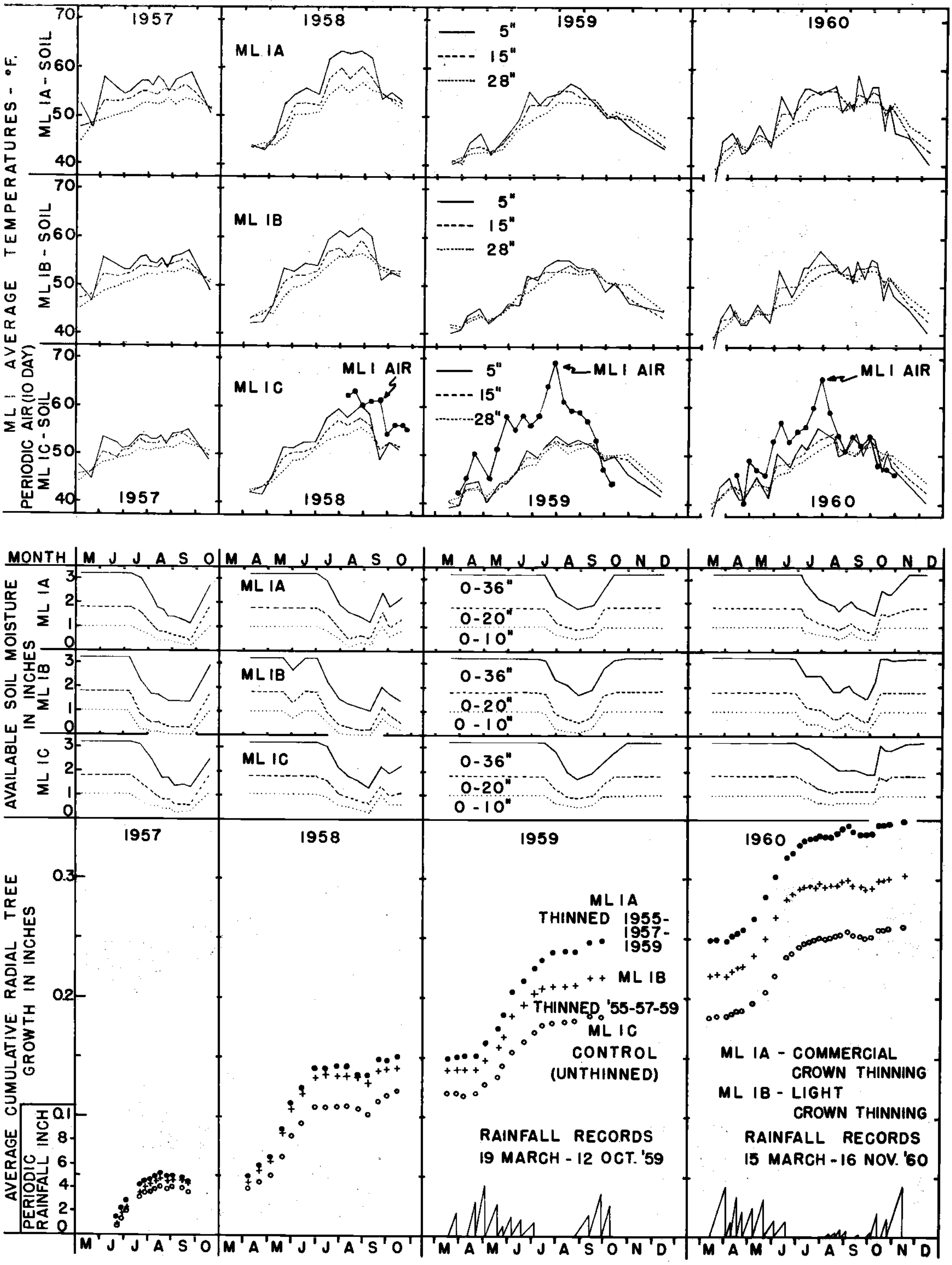

FIGURE 6. Average soil moisture and temperature - average air temperature and periodic rainfall in relation to average cumulative radial growth of 45-year-old Douglas-fir trees for different thinning intensities at ML 1 (1957-1960).

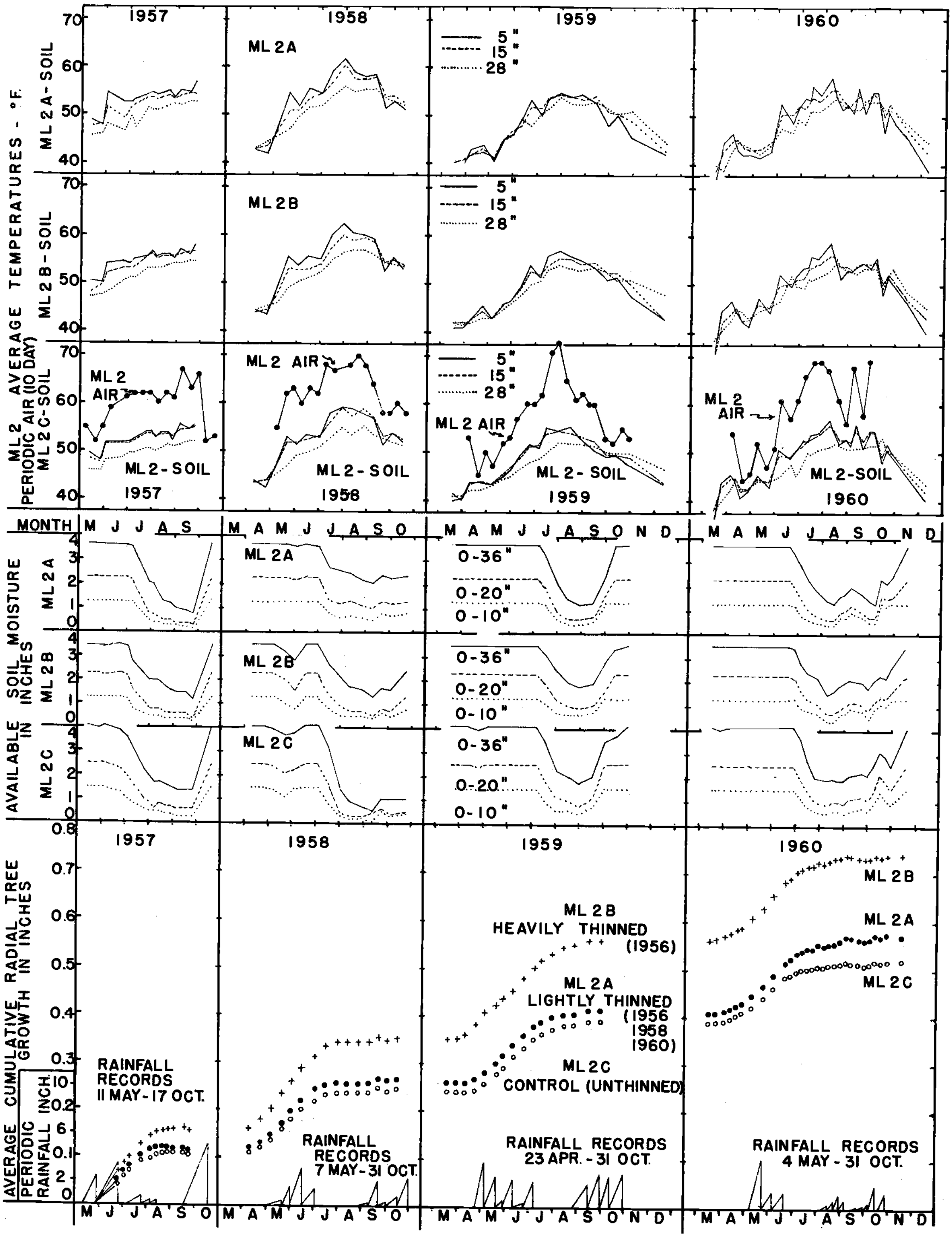

FIGURE 7. Average soil moisture and temperature - average air temperature and periodic rainfall in relation to average cumulative radial growth of 30-year-old Douglas-fir trees for different thinning intensities at ML 2 (1957-1962).

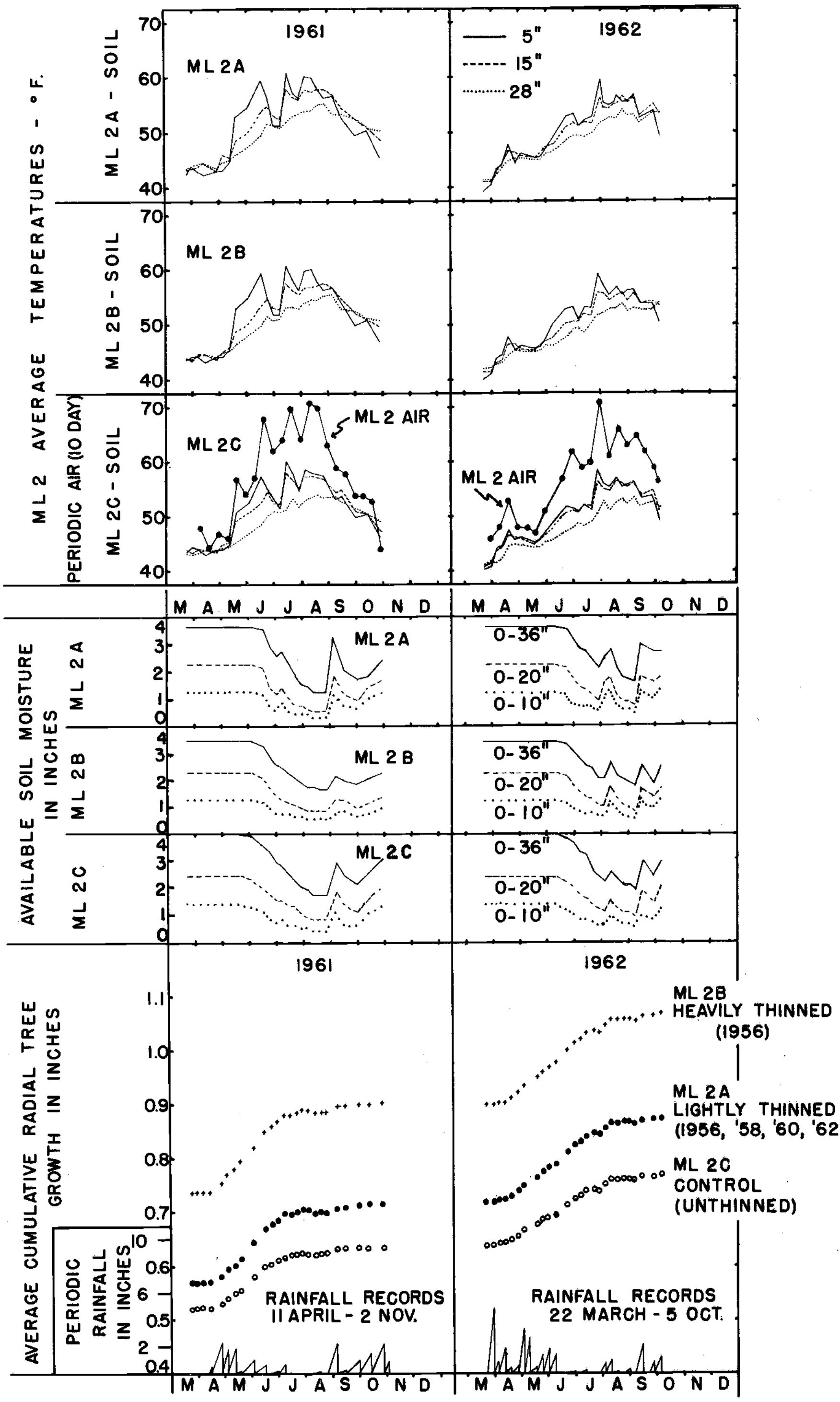

FIGURE 7. Continued.

TABLE 4. Average available soil moisture and/or soil moisture tension at date of greatest depletion each year and average growing season soil temperature[1] for the various thinning and irrigation treatments at ML 1, ML 2 and HESPA (45-, 30- and 20-year-old Douglas-fir stands).

	Inches available moisture				Soil temperature °F		
	Depth in inches				Depth in inches		
	0-10	10-20	20-36	0-36	5"	15"	28"
1957-1960							
ML 1A-Light Crown thinning	0. 39	0. 29	0. 81	1. 49	53. 3	52. 1	50. 1
ML 1B-Medium Crown thinning	0. 07	0. 35	1.07	1.49	52.0	50. 8	49.9
ML 1C-Control	0. 44	0. 38	0. 80	1. 62	50. 4	49. 8	49.0
1957-1960							
ML 2A-Light thinning	0. 31	0. 24	0. 72	1. 27	51.6	51. 4	49,9
ML 2B-Heavy thinning	0. 38	0. 23	0. 88	1. 49	53. 0	52. 4	50. 8
ML 2C-Control	0. 33	0. 29	0. 83	1. 45	51. 4	51. 4	49. 3
1961-1962							
ML 2A-Light thinning	0. 36	0. 24	0. 72	1. 32	52. 2	52. 2	50. 6
ML 2B-Heavy thinning	0. 50	0. 28	0. 87	1. 65	52. 8	52. 0	50. 4
ML 2C-Control or unthinned	0. 45	0. 40	0. 94	1. 79	52. 0	52. 0	49. 4
1961-1962		Soil moisture tension-atm.					
HESPA	5"	15"		28"	- Depth in inches		
Unthinned					50. 2	49. 9	47. 9
Irrig.	2. 2	0. 4		0. 4			
Non-irrig.	3. 0	3. 6		3. 6			
HESPA Thinned					47. 3	46. 4	45. 4
Irrig.	0. 6	0. 3		0. 4			
Non-irrig.	1. 6	1. 5		0. 5			
ML 2B							
Irrig.	0. 8	3. 7		0. 8			
Non-irrig.	5. 7	6. 4		2. 4			
ML 2C Unthinned	5. 6	3. 7		3. 0			

[1] Based on 13 measurements spaced between April and early to mid-October.

the overall variation in soil-moisture measurements was too great to permit very serious consideration of these trends.

Originally estimates of bulk density and soil-moisture constants were taken from the overall soil sampling of ML 1 and ML 2. On this basis the heavily thinned subarea, ML 2B, had appreciably greater moisture depletion each year than the control, ML 2C. Subsequent sampling and analyses showed that this apparent difference was due to soil bulk density and soil-moisture constant, differences between the two 1/5-acre plots on which the soil-moisture measurements had been made and could not be attributed to thinning.

The effect of temperature and precipitation on soil moisture is clearly shown graphically by individual years in the Appendix (App. F, p. 171-180; Figures 40 through 49). When spring rainfall declines in intensity and frequency, and as daily air temperatures rise, soil-moisture depletion begins. In the fall the profile is completely rewetted again after four to six inches precipitation accompanied by lower daily air temperatures. Midsummer rain is generally ineffective for rewetting the profile or stimulating growth. No doubt this is due to high interception losses induced by high air temperature and low humidity conditions prevalent during this period. However, during 1962 both available soil moisture and tree growth were affected by a July rainstorm (Figure 49, App. F, p. 180).

Soil and Air Temperatures

The pattern of temperature over the growing season at three levels in the soil profile (5, 15, and 28 inches) as well as for the air at ML 1, and ML 2 (1957-1962) is graphically portrayed in Figures 6 and 7 as well as Figures 40 through 49 (App. F, p. 171-180). Similar patterns for HESPA are given in Figure 12. The soil and air temperatures presented in this fashion are principally intended to provide a rough index of temperature aspects of transpirational stresses. A casual examination of moisture depletion and dendrometer growth patterns will confirm their value in this respect. The relative difference in air temperatures (as measured within a standard instrument shelter in a nearby field) between ML 1 and ML 2 (Figure 5) averaged five to seven degrees Fahrenheit warmer for ML 2 over the growing season. Soil temperature at the five-inch level was only one degree Fahrenheit warmer for ML 2 (Table 4). A substantial part of the apparent difference in air temperature is probably an artifact resulting from either constant instrument calibration error or the location of the measurement station in relation to the research stands.

In addition measured soil temperatures provide a useful basis to compare the effect of thinning treatments on temperature regimes. An estimate of the average soil temperatures on these subareas with different stand management treatments over the growing season was made by averaging 13 measurements taken periodically from late

April to early or mid-October. Table 4 present the results of this compilation averaged over a comparable span of years for ML 1, ML 2, and HESPA. Table 27 (App. E, p. 168) provides the same information for each individual year. Analyses of variance were made (Tables 28 and 29, App. E, p. 169, 170) on the temperature averages comparing ML 1 and ML 2 (1957-1960) and ML 2 (B and C) and HESPA (1961-1962). For all three areas there was a very highly significant effect of depth of soil-temperature measurement. The effect of thinning treatment was likewise very highly significant in both analyses, ML 1-ML 2 and ML 2-HESPA. The magnitude of these differences are no more than four or five degrees Fahrenheit. The small variance of temperature measured in soil leads to statistical significance of rather small temperature differences induced by thinning treatments.

The seasonal soil temperature patterns in the previously mentioned figures show the expected lag of the deepest measuring units. They are the last to warm up in the spring and summer and last to cool in the fall. A difference of eight to ten degrees Fahrenheit between the upper and lower units was experienced at ML 1 on occasion while at ML 2 and HESPA five to seven degrees Fahrenheit was the largest difference observed.

Dendrometer Growth Patterns

The average cumulative radial growth patterns for four growing seasons (1957-1960) are shown for ML 1 in Figure 6. The same type of patterns are shown in Figure 7 for six growing seasons (1957-1962) at ML 2. Both areas are compared over the four year growing season in Figure 5. Obviously the radial growth differences between ML 1 and ML 2 do not reflect total growth difference since the radial growth at ML 1 is laid down over a larger circumference and through a greater height. Radial growth became active on these areas in early April or late March, and built up to a maximum rate in May which was sustained until late June or early July.

The week of bud bursting of lateral buds is shown in Table 5. This stage of bud activity is attained three to six weeks after appreciable radial growth is detected at dbh. This is in accord with earlier work on Douglas-fir (37, p. 13). Growth starts in the upper bole of the crown and proceeds down the stem before externally visible bud changes.

TABLE 5. Week of bud bursting for 45- and 30-year-old Douglas-fir trees[1] on ML 1 and ML 2 respectively.

Year	ML 1	ML 2
1957	20 - 27 May	6 - 13 May
1958	Not available	
1959	1 - 8 June	25 May - 1 June
1960	23 - 31 May	16 - 23 May

[1] Based on 75% of the buds open (green showing) on 75% of the trees.

Figures 40 through 49 (App. F, p. 171-180) allow a much more detailed look at seasonal growth patterns in relation to available soil moisture and temperatures. It is apparent by casual examination of these figures that the pattern of tree growth in the latter part of the season is strongly influenced by factors affecting the tree's internal moisture stress; available soil moisture, precipitation, and temperature. Late season upsurges are associated with increasing available soil moisture and precipitation, and lower temperatures. Decreasing or irregular growth is associated with decreasing or low soil moisture, lack of precipitation, and higher temperatures. Actual shrinkage by dehydration is evident in growth patterns for ML 1 trees during August and September of 1957 (Figure 6). The effect of thinning on growth pattern is apparent but difficult to ascribe to soil-moisture differences.

Tree growth patterns during 1958 through 1960 for ML 1 and ML 2 were compiled by various crown classes[1] (Figures 50 and 51, App. F, p. 181, 182). The striking differences in radial growth of the trees of different crown classes is not unexpected. The shape of the growth curve suggests a somewhat longer growing season with increasing crown position (intermediate to dominant). Kozlowski and Peterson (109) likewise found that dominant trees (34-year-old red pine) had a generally longer growing season than intermediates.

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[1] Crown classification was made with reference to the tree crown position prior to thinning.

In the present study it must be borne in mind that to a limited extent stand treatment enters the picture because the trees are averaged by crown class regardless of thinning treatment; and there is a disproportionate or skewed distribution with more intermediate class trees in the control subareas and more dominant and codominant trees on the thinned areas. Suppressed trees were not included because of an inadequate sample of this category, especially at ML 2.

An attempt was made to assess the relative distribution of growth at dbh. over the growing season for the various tree crown classes as well as the different thinning intensities at ML 1 and ML 2. The amount and proportion of late season growth was examined to see if there were important and consistent differences related to the stand treatment or tree crown position. Late season growth was defined as that occurring after the date when radial growth rate fell from its previously steady maximum or departed from the linear phase of the cumulative growth curve (see p. 100 for further discussion). The results of this compilation and analysis are shown in Table 6.

None of the differences due to thinning are significant though at ML 2 there is a trend of increasing amount and proportion of late season growth with increasing thinning intensity. The differences in amount of late season growth at ML 1 and ML 2 for the various crown classes of these two Douglas-fir stands were quite marked and each

TABLE 6. Average amount and proportion of late season radial growth for 45- and 30-year-old Douglas-fir at ML 1 and ML 2 for three thinning treatments and crown classes (averaged annually for 1958-1960).

	Subareas Thinning Treatments			Crown Classification		
	A	B	C			
ML 1 -	Lt.	Med.	Cont.		Co-dom.	Inter-med.
ML 2 -	Lt.	Hvy.	Cont.	Dom.		
ML 1						
Amount inches	0. 031	0. 022	0. 020[1]	0. 047	0. 025	0. 013
Percent	28. 7	22. 0	26. 9	30. 6	25. 8	22. 3
ML 2						
Amount inches	0. 036	0. 044	0. 034	0. 056	0. 037	0. 024
Percent	22. 1	22. 6	20. 6	23. 6	21. 1	20. 2

[1] Values not underlined by the same line are significantly different at the 0. 05 level ("t" test).

was significantly different from the other. The percentage of late season growth was consistently increased with increasing crown position of the tree but only one significant difference was obtained (ML 1, dominant - intermediate). Late season growth appears to be more markedly influenced by the initial tree crown position in the stand than by release effects.

Root Distribution at ML 2B and ML 2C - 30-year-old Douglas-fir Stand

The heavy initial thinning of ML 2B in 1956 and its marked growth response focused interest on the relative root development of this stand as compared to the control subarea ML 2C. Results of the two sets of root samples taken early in the 1963 growing season are shown in Table 7. The principal difference would seem to be

TABLE 7. Root distribution by depth for ML 2B and ML 2C (30-year-old Douglas-fir stand).

		Dry wt. of roots - gm. /l. of soil						
		root diameter						
Depth in.	Treat-ment	< 1 mm.	1-3 mm.	3-5 mm.	5-10 mm.	10-25 mm.	>25 mm.	Totals
0-8"	Control	1. 21	0. 51	0. 15	0. 21	0. 16		2. 24
	Thinned	1. 05	0. 45	0. 12	0. 30	0. 30		2. 22
8-16"	Control	0. 29	0. 43	0. 10	0. 10	0. 96	0. 02	1. 90
	Thinned	0. 44	0. 32	0. 22	0. 34	0. 54		1. 86
16-24"	Control	0. 22	0. 36	0. 08				0. 65
	Thinned	0. 13	0. 26	0. 02	0. 19	0. 24		0. 84
24-32"	Control	0. 19	0. 40	0. 25	0. 16	0. 07		1. 07
	Thinned	0. 12	0. 09					0. 21

that ML 2C has five times more roots than ML 2B at the 24 to 32 inch depth. The pattern observed in the soil trenches (Figure 8) further supported this conclusion. It is apparent that the thinned trees have not completely occupied the site in the eight years subsequent to the heavy thinning. Bulk density determinations at three depths, however, indicated that the soil was appreciably denser in the vicinity of the trench on the heavily thinned subarea. Table 8 gives values representing an average of six determinations as well as the total

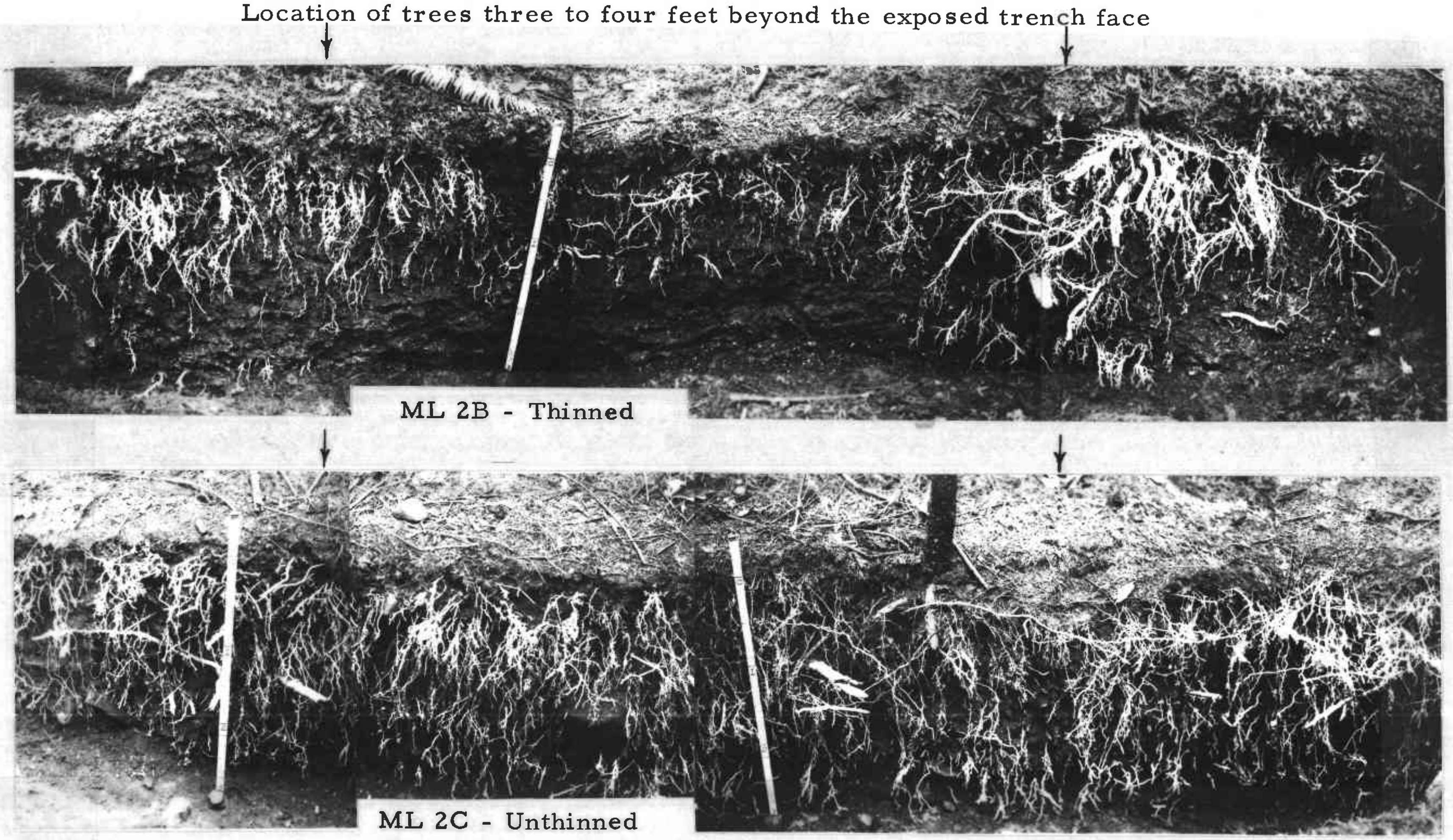

FIGURE 8. View of soil well or root trench face of thinned (ML 2B) and unthinned (ML 2C) 30-year-old Douglas-fir stands eight years after thinning.

TABLE 8. Average values and total range of soil bulk density for three depths at ML 2B and ML 2C (30-year-old Douglas-fir stand).

	Depth					
	5"		15"		28"	
	gm. /cc.					
	Avg.	Range	Avg.	Range	Avg.	Range
ML 2B		0. 98		1. 11		1. 40
Heavily	0. 84		1. 05		1. 28	
thinned		0. 74		0. 95		1. 07
ML 2C		0. 86		1. 01		1. 29
Control	0. 80		0. 89		1. 10	
		0. 73		0. 81		0. 96

range obtained from these measurements.

Comparison of the root content of ML 2B and ML 2C at the 24- to 32-inch depth (Table 9) showed that the control, ML 2C, contained almost three times as much weight of roots $<$ 5 mm. in diameter as did the soil at the same depth in the heavily thinned sub-area at ML 2B. The difference is not only striking but also

TABLE 9. Dry weight of roots $<$ 5 mm. for ML 2B and ML 2C (30-year-old Douglas-fir stand) at the 24 to 32 inch depth.

	Dry weight gm. /l. of soil	
Replication no.	Thinned ML 2B	Control ML 2C
1	0. 28	0. 75
2	0. 18	0. 94
3	0. 36	0. 95
4	0. 51	1. 03
Ave.	0. 32	0. 92
"t" value	7. 8	
Significance	***(at the 0. 001 level)	

consistent and thus should be representative of the entire subarea and not just the densely packed soil at the trenched profile. Drastic reduction in number of stems per acre at age 25, therefore, appears to have caused an unequal distribution of roots throughout the profile which is still evident at age 33.

Irrigation - Fertilization

HESPA - 20-year-old Douglas-fir Stand

In 1959 it was possible to record dendrometer growth on the irrigation-fertilization study trees only from late July into mid-September (Figure 9) but the results were quite interesting. Radial growth was increased by either fertilization or irrigation. Fertilized trees showed more growth than irrigated trees and the growth effects of the two together were approximately additive. As the study progressed through 1960 and 1961 it became apparent that irrigation as applied during 1960 was far in excess of what was necessary. In 1960 irrigation water equivalent to nine inches precipitation was applied at HESPA before the non-irrigated trees showed any evidence of growth retardation (Figure 10). In 1961 growth of the irrigated trees fell below that of comparable non-irrigated trees (Figure 11). The reason that this was not obvious during 1960 is that the soil-moisture units were not yet calibrated and the growth record was not

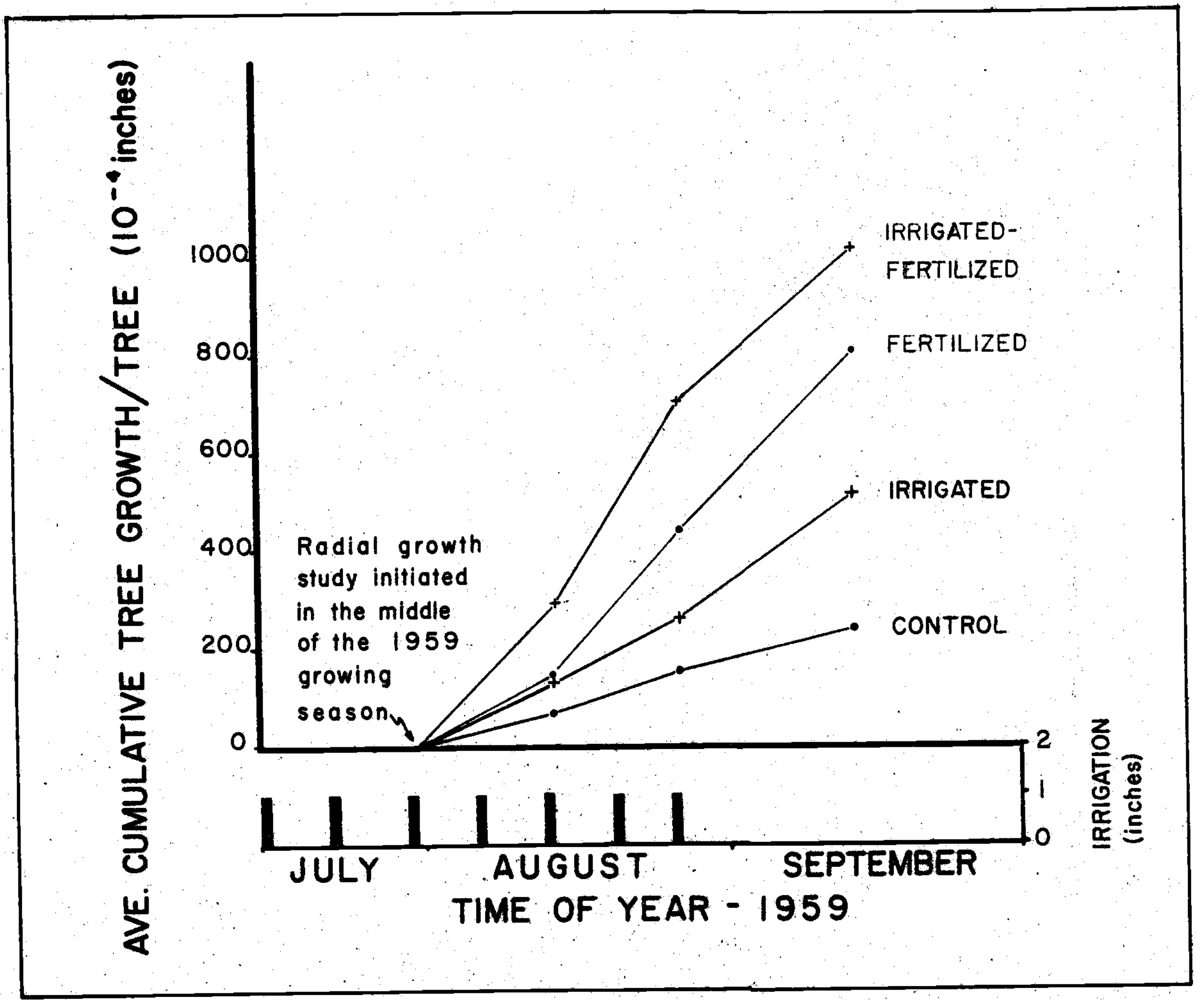

FIGURE 9. Effect of irrigation and fertilization on cumulative radial growth of 20-year-old Douglas-fir at HESPA (1959).

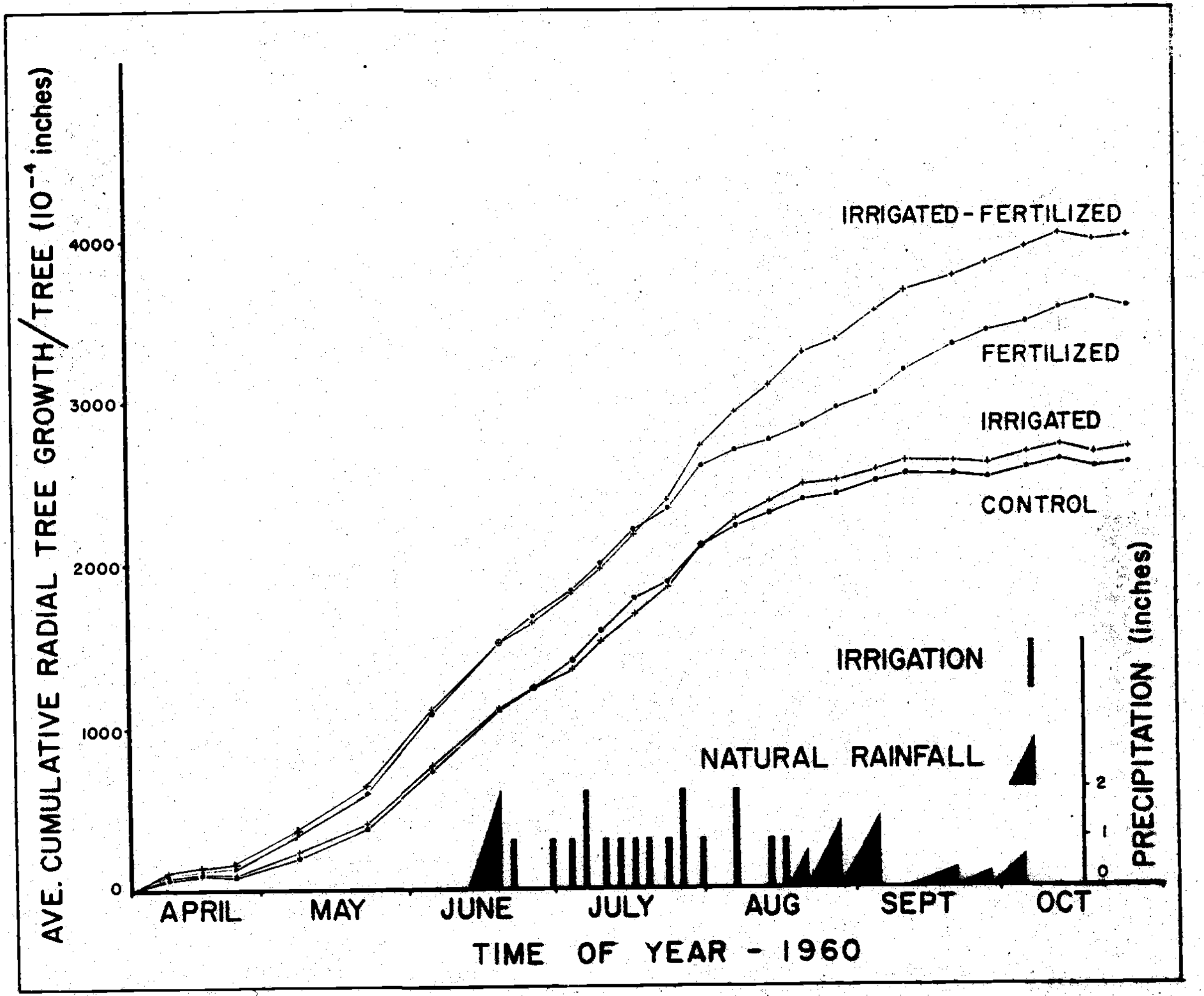

FIGURE 10. Effect of irrigation and fertilization on cumulative radial growth of 20-year-old Douglas-fir at HESPA (1960).

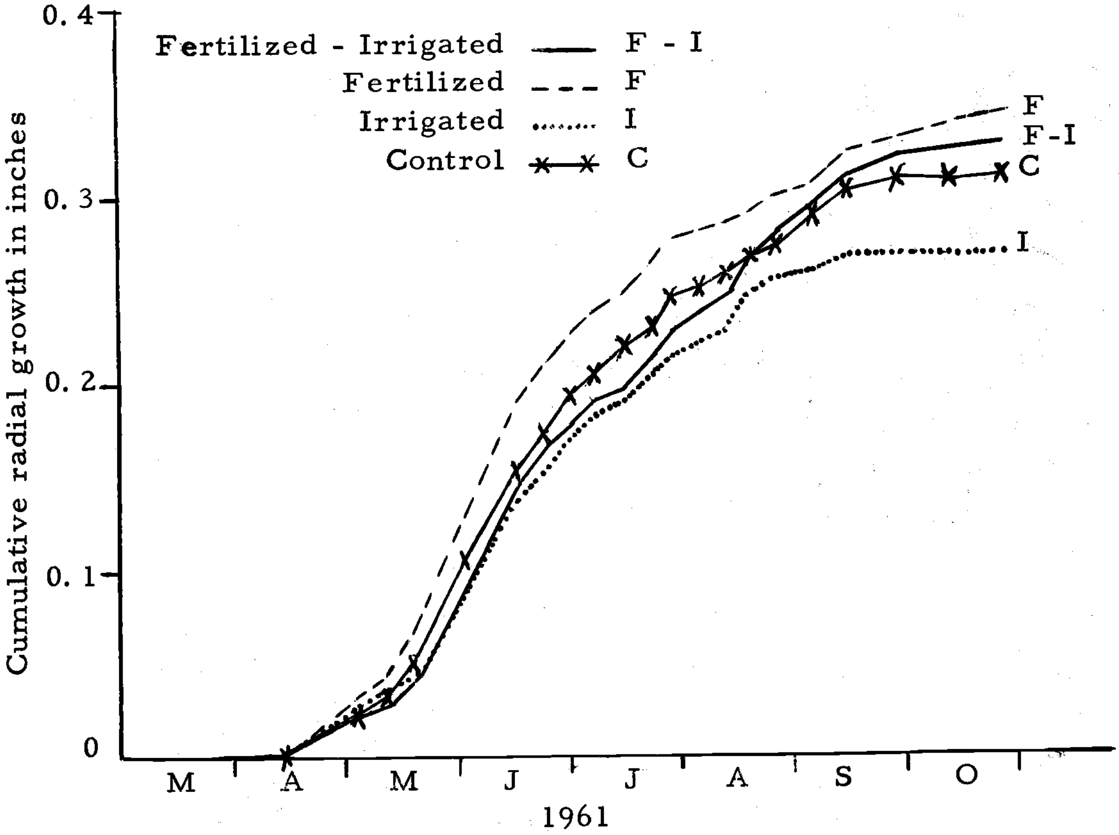

FIGURE 11. The effect of irrigation and fertilization on cumulative radial growth of 20-year-old Douglas-fir at HESPA (1961).

compiled until the following winter. The amount and frequency of irrigation were reduced in subsequent years after the 1960 results were compiled and examined. Thereafter a current plot of radial growth patterns was maintained to help guide irrigation decisions.

A comparison of the growth effects of irrigation on thinned and unthinned trees (Figures 12 and 13) would seem to indicate that moisture deficits are more serious where there is no volume of unrooted soil available for root extension. Average soil-moisture-tension values measured at the date of greatest soil-moisture depletion (Table 4) likewise show that soils supporting unthinned stands had substantially higher levels of moisture tension. The significant "F" value for the thinning treatment mean square (Table 26, App. E, p. 167) confirms the fact that there were valid differences in soil moisture status between thinned and unthinned stands. The near significant interaction of this treatment with area suggests that the greater difference observed at HESPA in contrast to that at ML 2 is likewise a valid trend.

Figure 14 gives an overall look at the effect of fertilization with the irrigation treatments included. It is apparent from the contrast with Figure 13 that nutritional deficiencies are more growth limiting at HESPA than moisture deficits. It is noteworthy that a substantial portion of the response to fertilization occurs late in the growing season.

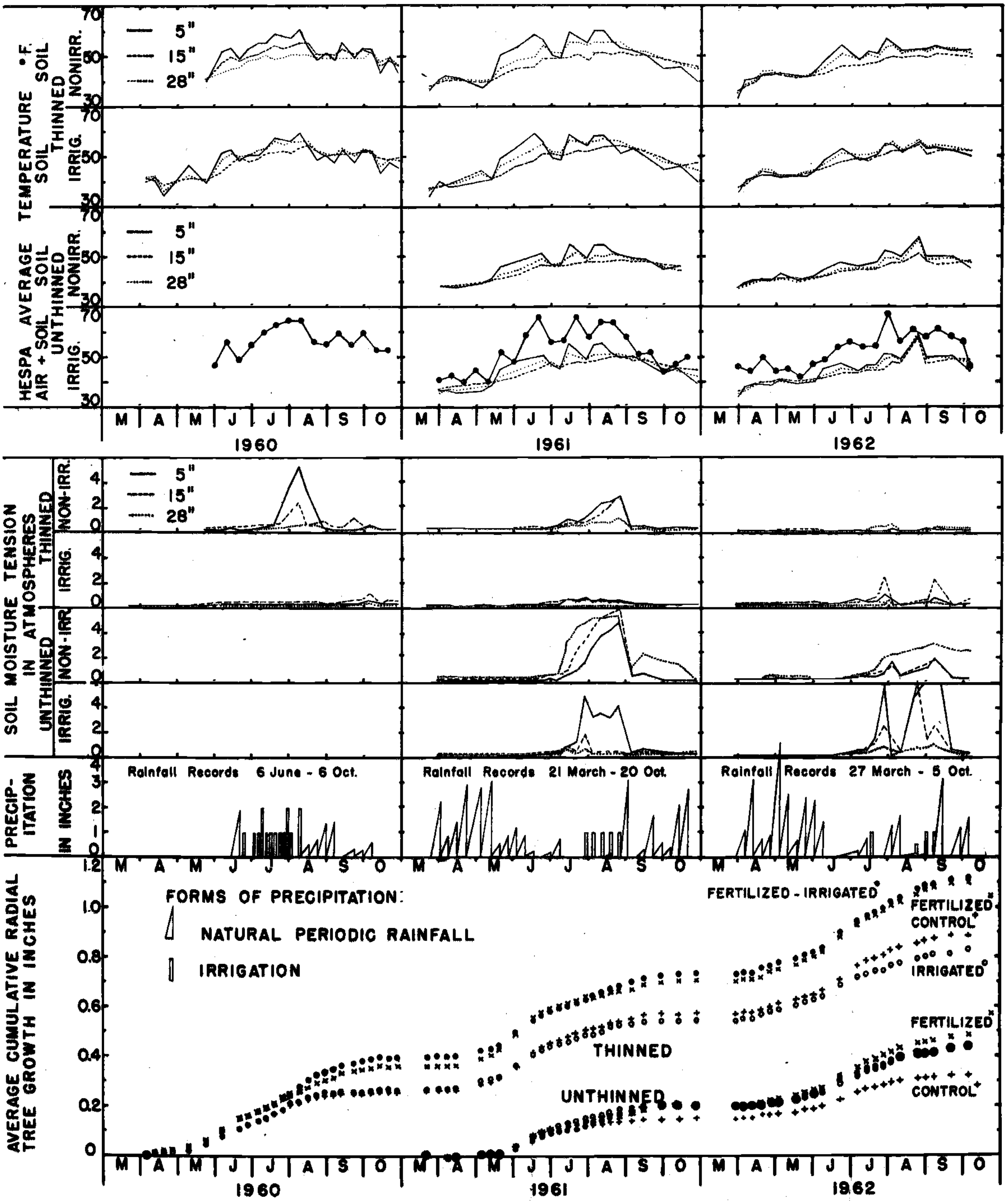

FIGURE 12. Average soil moisture tension, temperature - average air temperature, irrigation and periodic rainfall in relation to average cumulative radial growth for irrigated and fertilized Douglas-fir (thinned and unthinned 20-year-old stands) at HESPA (1960-1962).

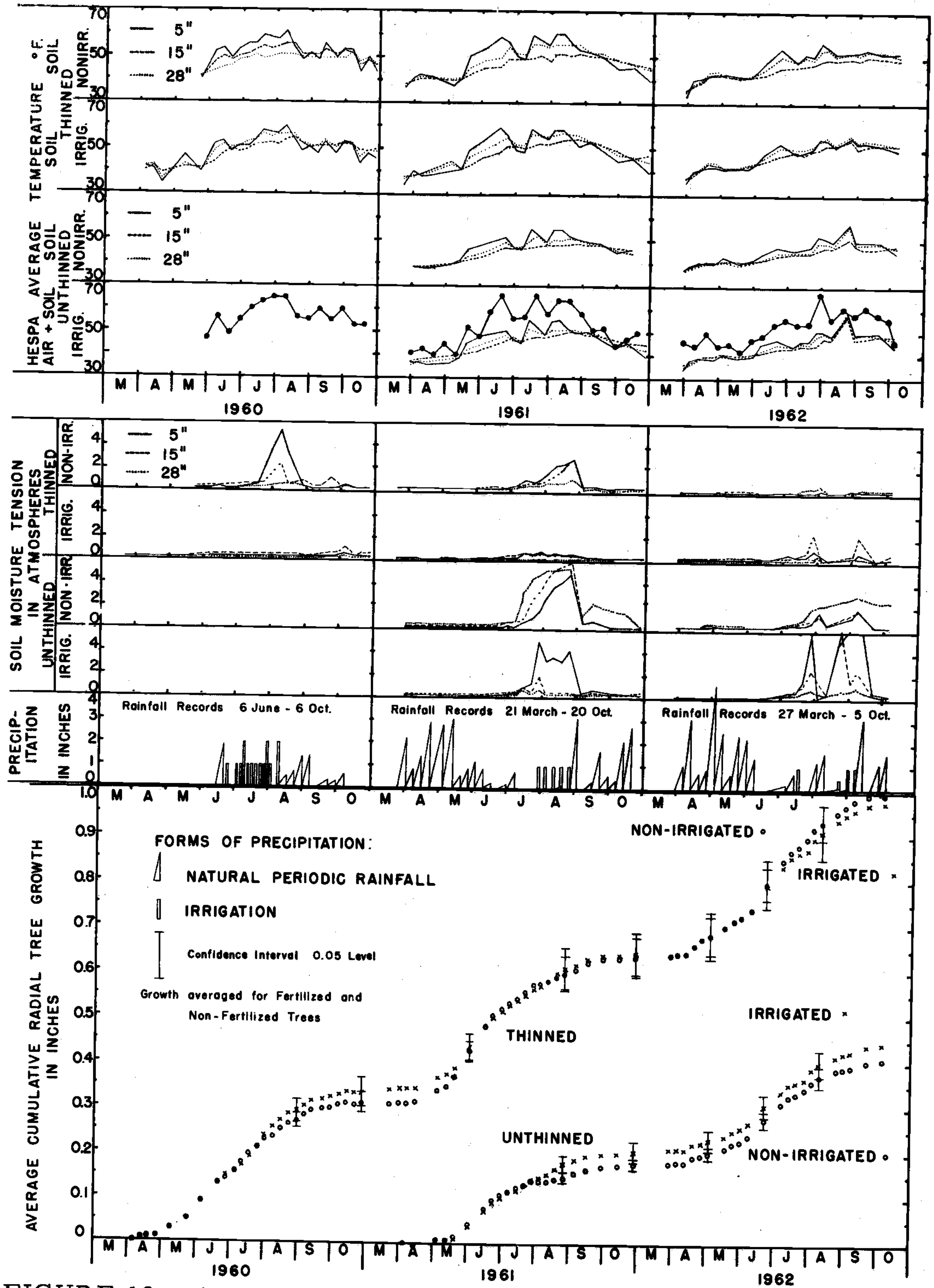

FIGURE 13. Average soil moisture tension, temperature - average air temperature, irrigation and periodic rainfall in relation to average cumulative radial growth for irrigated and non-irrigated Douglas-fir (thinned and unthinned 20-year-old stands) at HESPA (1960-1962).

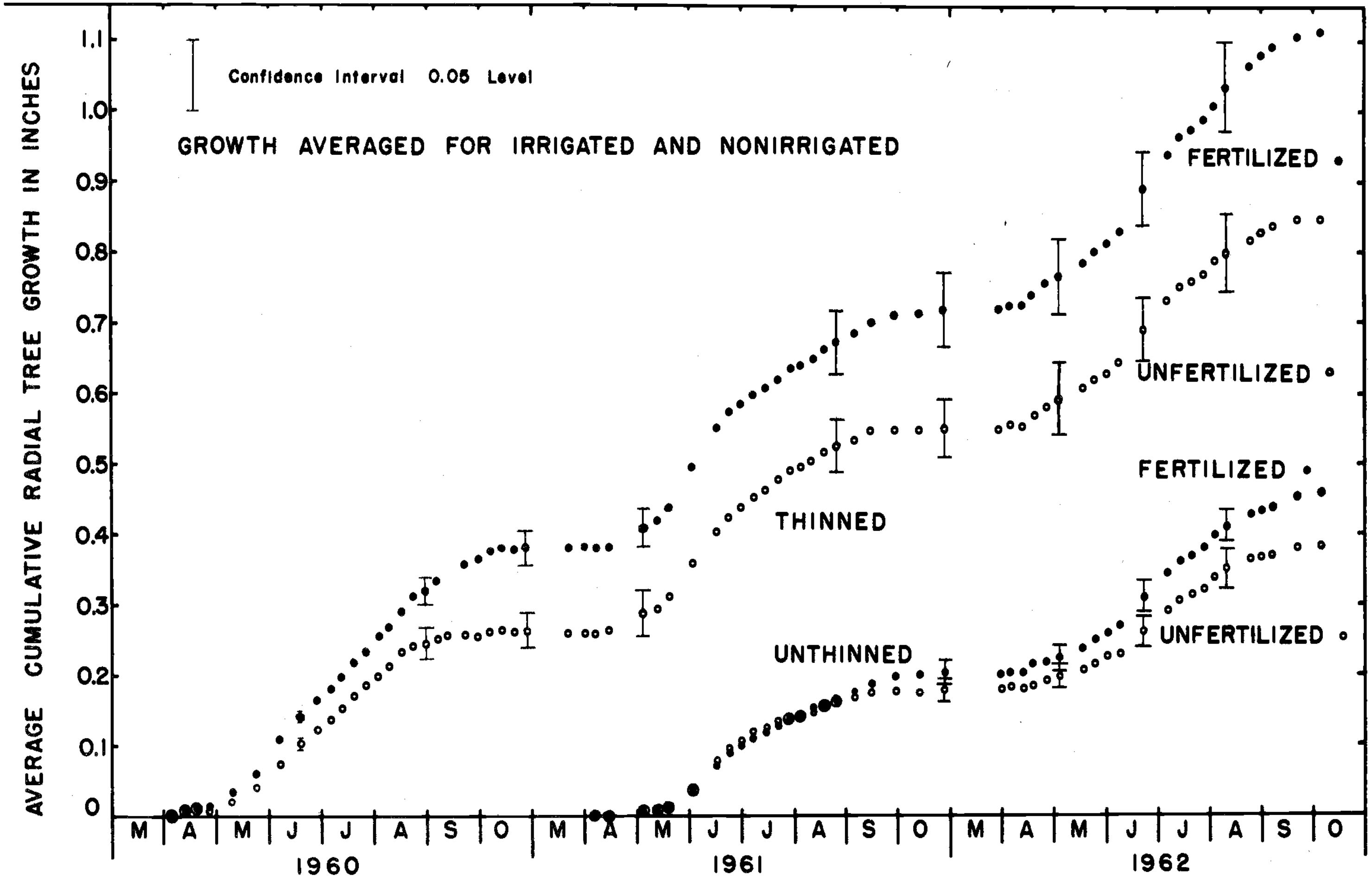

FIGURE 14. Effect of fertilization on cumulative radial growth of 20-year-old Douglas-fir at HESPA (1960-1962).

ML 2B - 30-year-old Douglas-fir Stand, Thinned

For the first two weeks after installation on June 6, 1960, the dendrometer trees added for the irrigated study grew at a rate identical to the nine matching dendrometer trees selected from the thinning soil-moisture study plot on ML 2B. The assumption, therefore, has been made for purposes of graphical representation (Figure 15) that the growth pattern of the irrigated trees in the 1960 growing season prior to June 6 was also identical to the control trees. Irrigated trees continued the initial rapid growth rate into the latter part of August while the non-irrigated trees declined in growth rate with an irregular pattern commencing late June and early July. In 1961 two additional matched sets of nine dendrometer trees each were included in the study. Both sets were to be fertilized and one was also to be irrigated. Figure 16 shows an early growth advantage taken by the irrigated trees which can be interpreted as prior conditioning since no irrigation was made until June. It is interesting to note the strong late season effect of fertilization both with irrigated and non-irrigated trees. In examining the three year graphical record of growth (Figure 17) it is apparent that this was also the case in 1962.

Figures 18 and 19 show the effects of fertilizers (averaging irrigated and non-irrigated treatments) and irrigation (averaging fertilized and unfertilized treatments) on cumulative radial growth

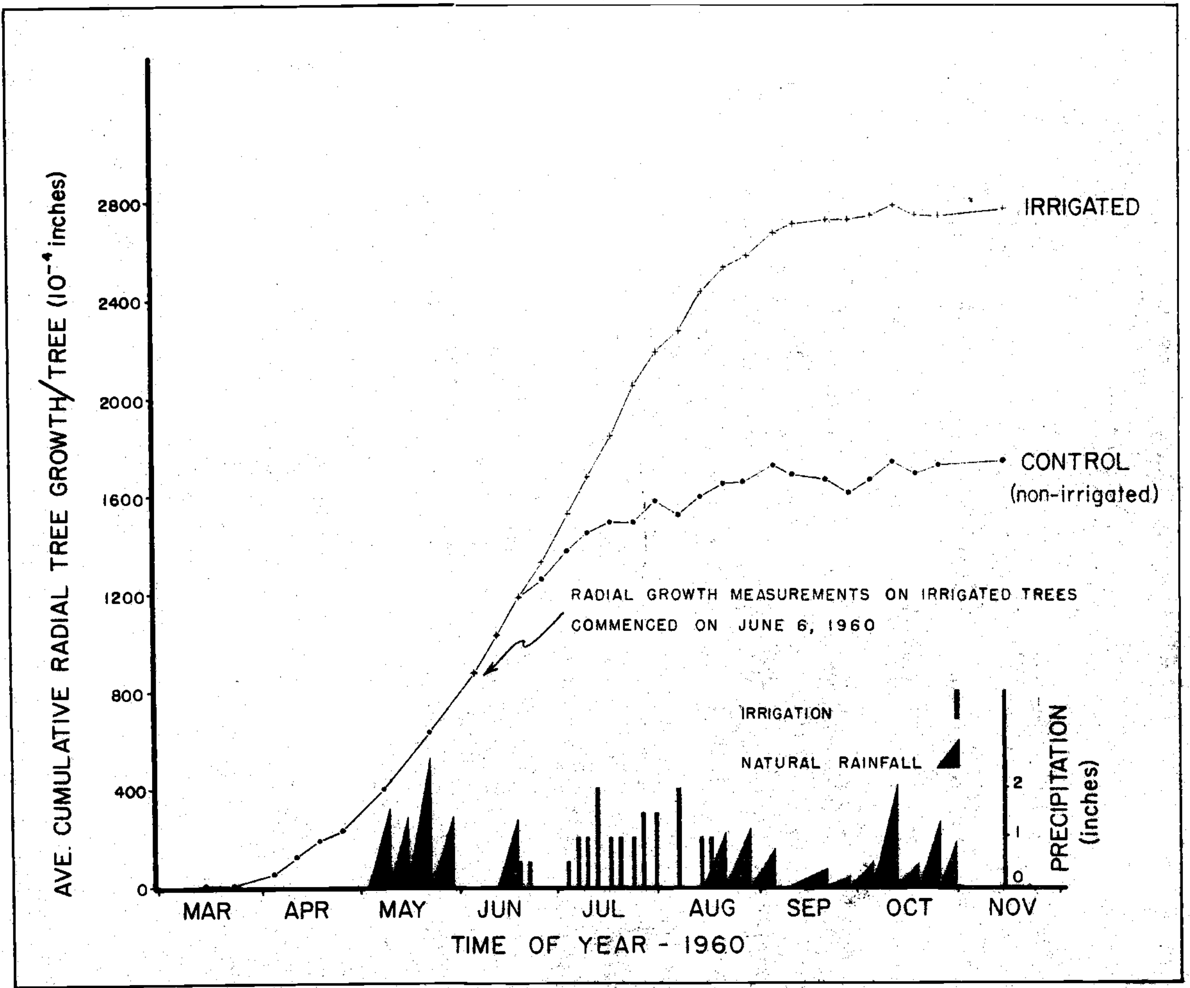

FIGURE 15. Effect of irrigation on cumulative radial growth of unthinned 30-year-old Douglas-fir at ML 2B. (1960)

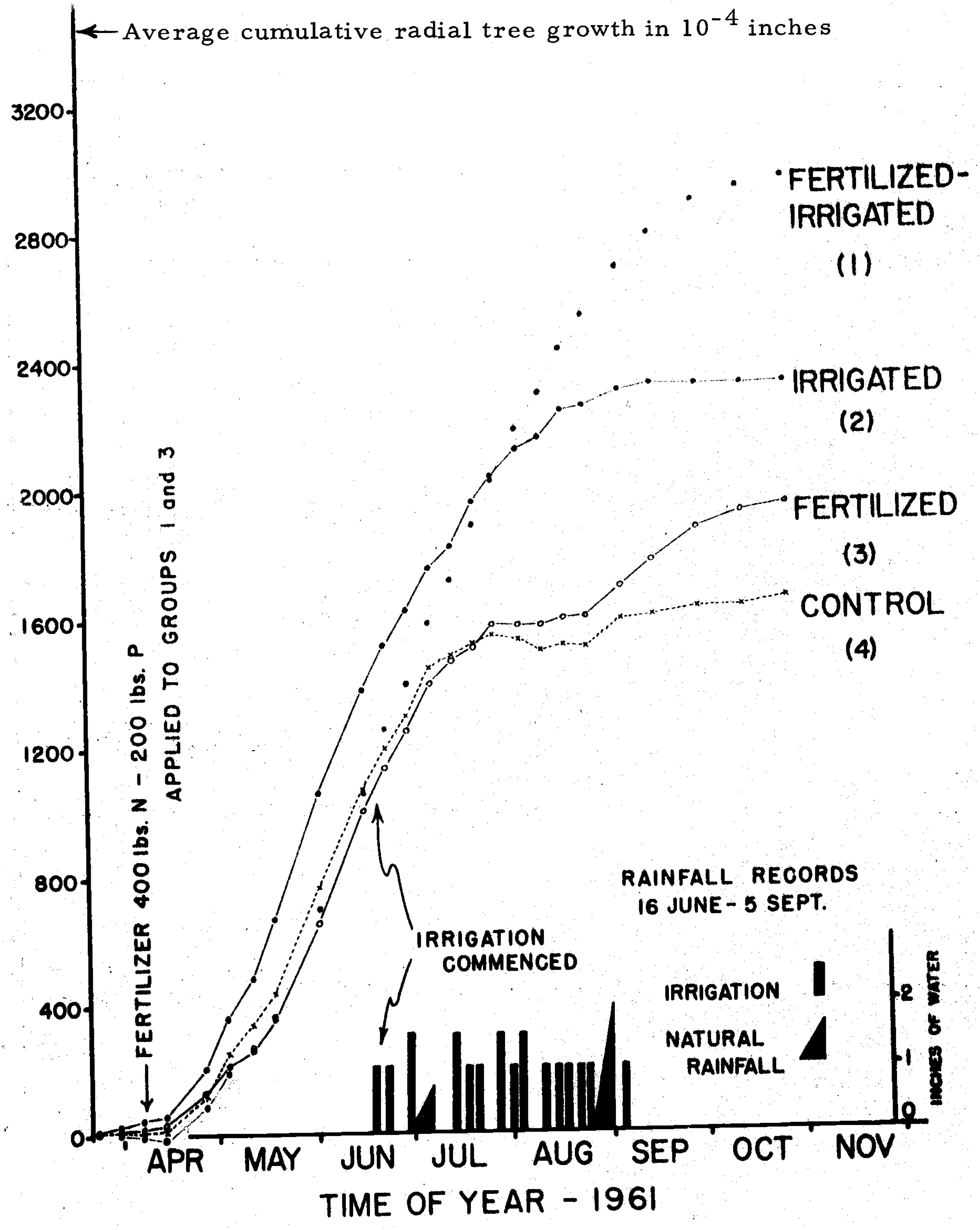

FIGURE 16. Effect of irrigation and fertilization on cumulative radial growth of thinned, 30-year-old Douglas-fir at ML 2B (1961).

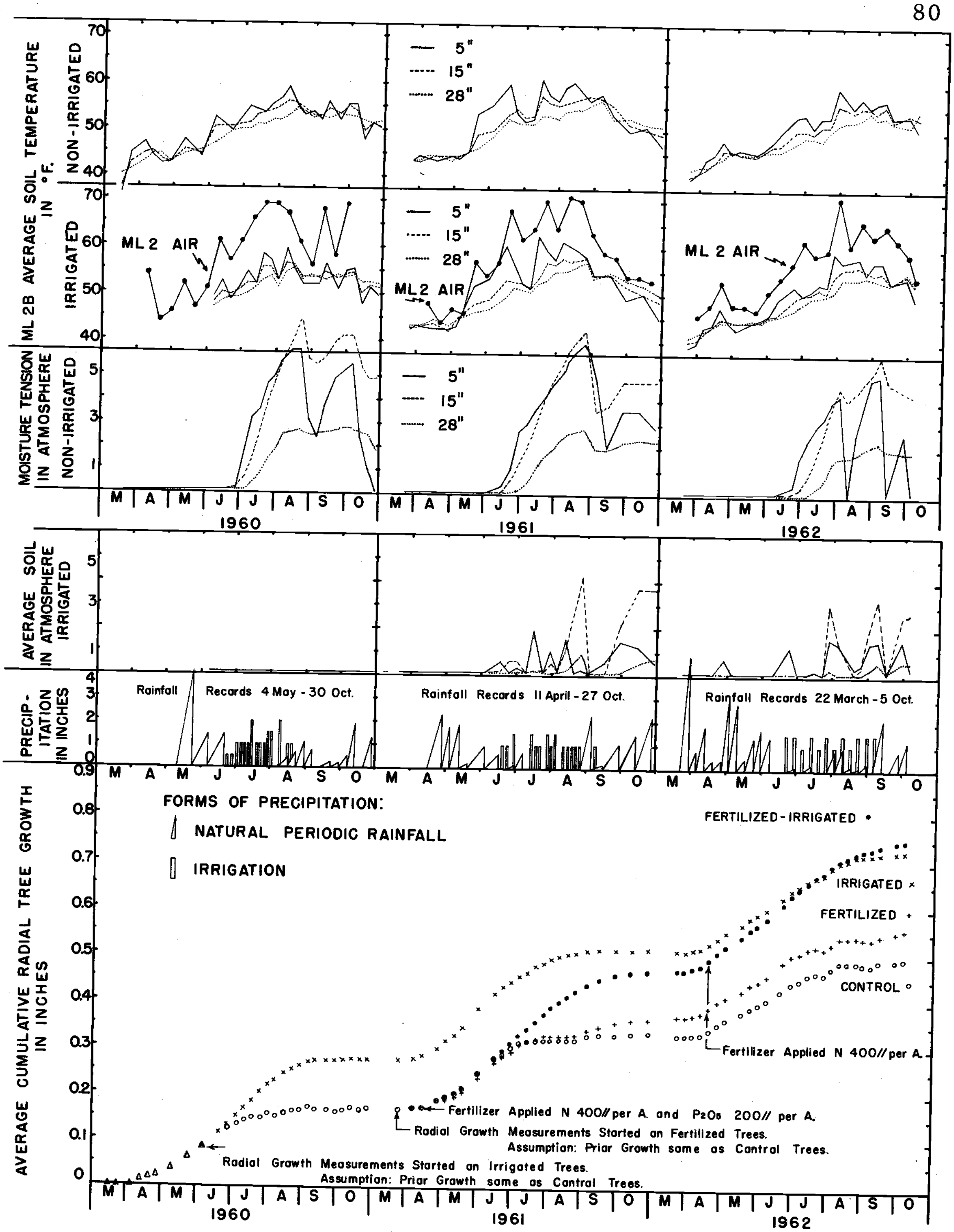

FIGURE 17. Average soil moisture tension, temperature - average air temperature, irrigation and periodic rainfall in relation to average cumulative radial growth for irrigated and fertilized Douglas-fir (thinned and unthinned 30-year-old stands) at ML 2 (1960-1962).

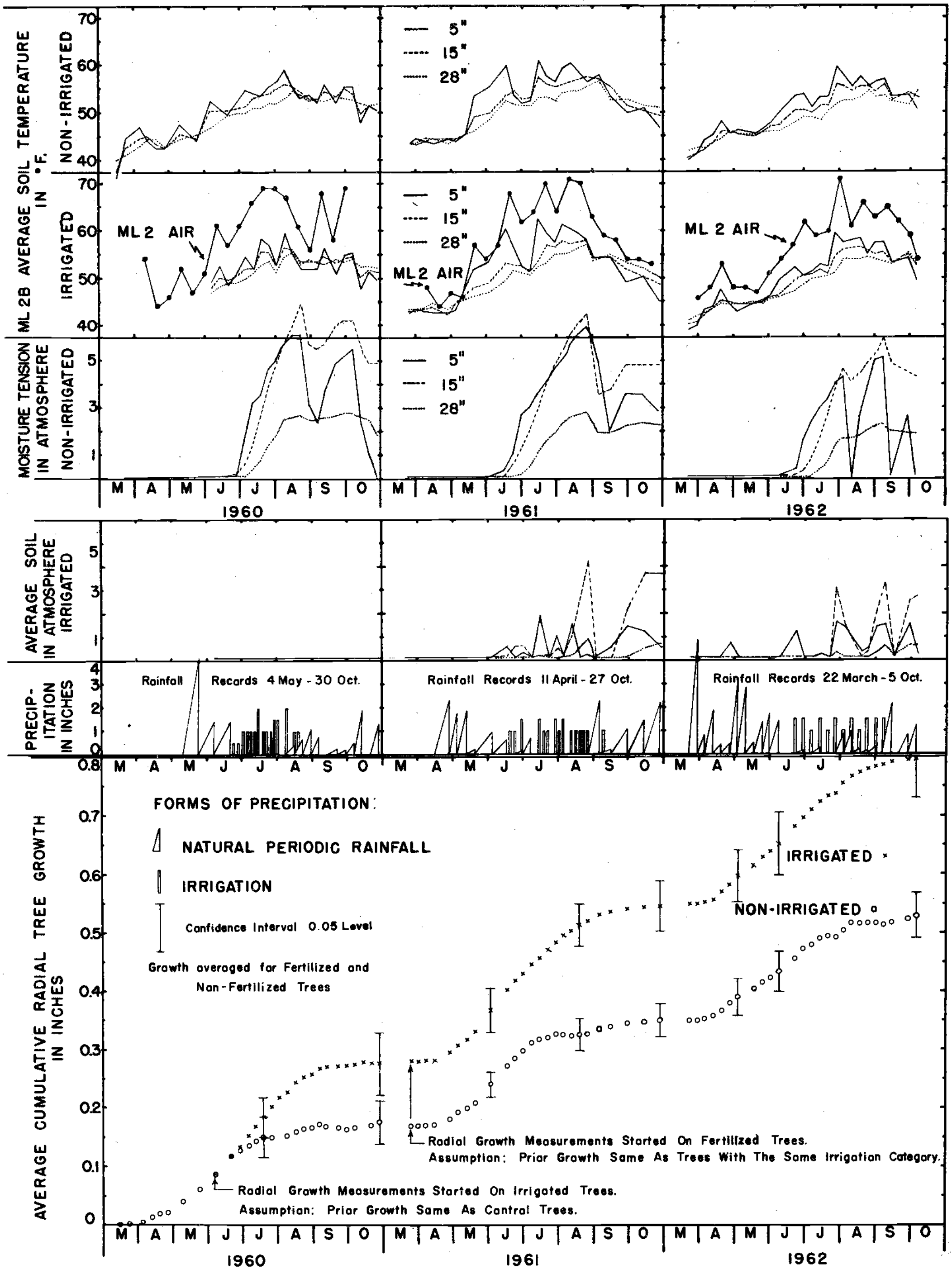

FIGURE 18. Average soil moisture tension, temperature - average air temperature, irrigation and periodic rainfall in relation to average cumulative radial growth for irrigated and non-irrigated Douglas-fir (thinned 30-year-old stands) at ML 2 (1960-1962).

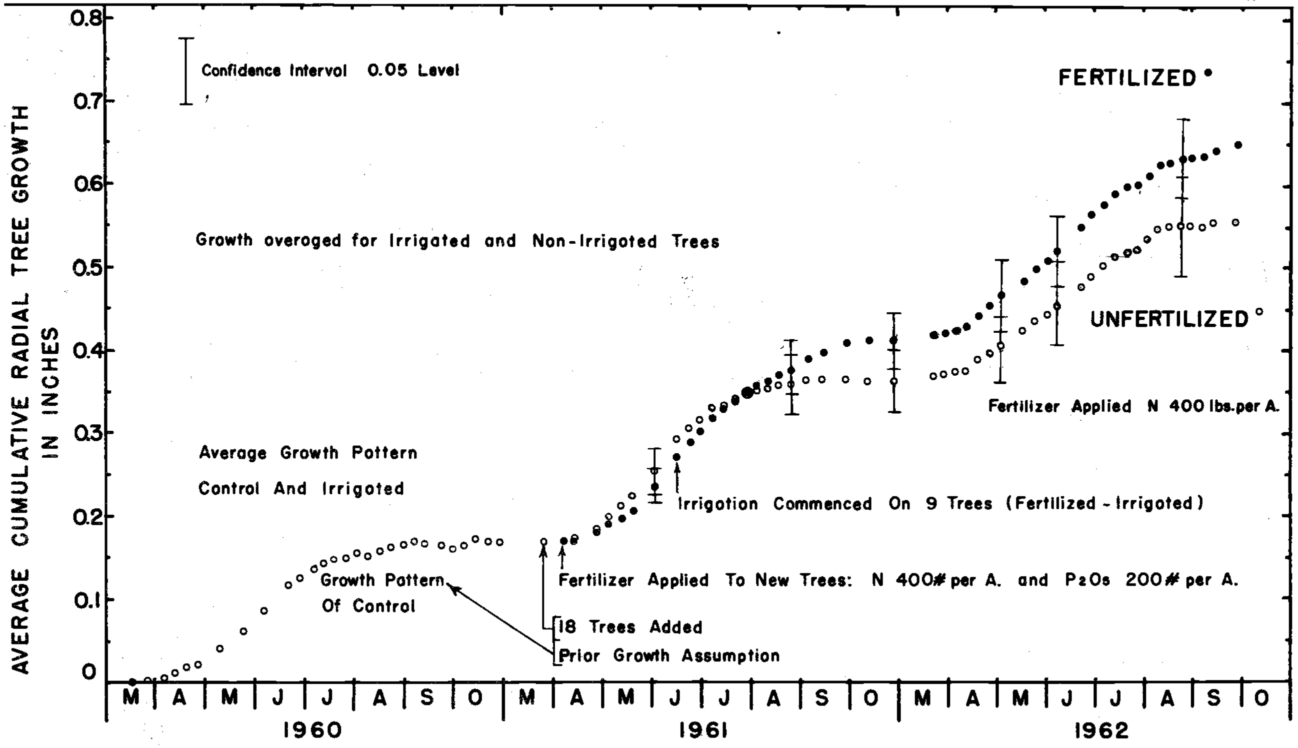

FIGURE 19. Effect of fertilization on cumulative radial growth of 30-year-old Douglas-fir at ML 2 (1960-1962).

of 30-year-old Douglas-fir at ML 2B over a three year period. Figure 20 shows graphically for 1960 through 1962 the relative importance of nutrition and moisture at ML 2B and at HESPA as growth limiting factors. At HESPA fertilizers increased radial growth about 30 percent while irrigation resulted in five percent less growth (ten percent more growth in 1960) for thinned trees. Unthinned trees at HESPA on the other hand increased in radial growth roughly 50 percent by fertilization and 40 percent by irrigation. At ML 2, on the other hand, fertilizer applications produced about a 20 percent advantage in growth over that of unfertilized trees while irrigation resulted in an approximate 45 percent increase in diameter growth. Irrigation

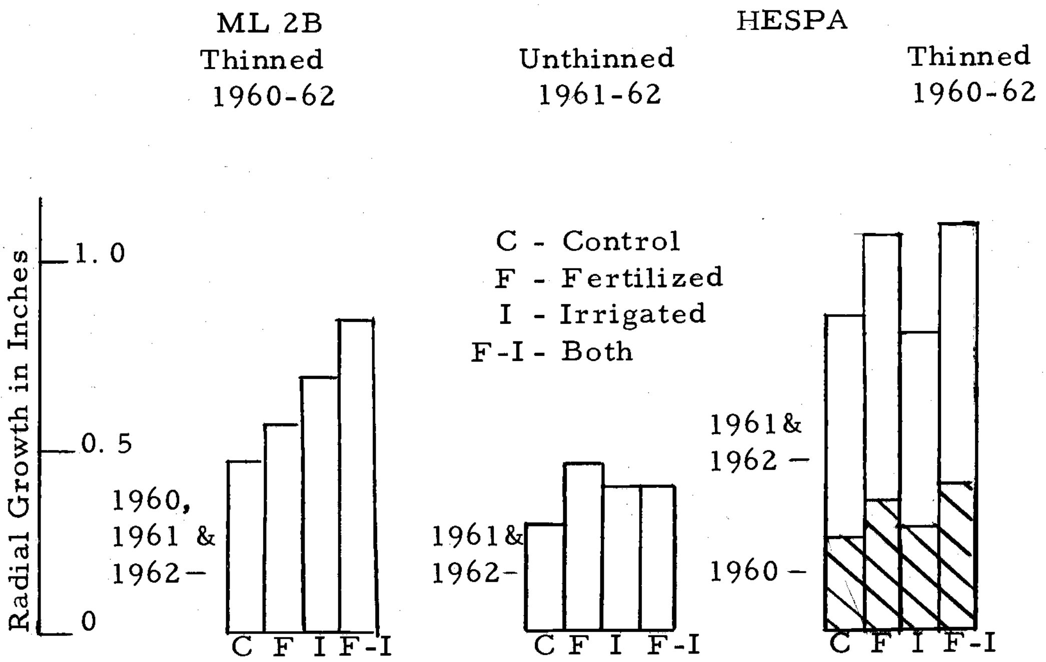

FIGURE 20. The effect of irrigation and fertilization on cumulative radial growth of thinned and unthinned Douglas-fir at ML 2B (30-year-old stand) and HESPA (20-year-old stand). 1960-1962.

and fertilization combined were nearly additive in their effect on growth rate (ML 2B - 60 percent and HESPA, thinned - 35 percent) except for HESPA-unthinned where the irrigated-fertilized treatment (approximately 40 percent radial growth increase) appears to have given anomolous results in this respect.

The ridgetop situation at ML 2B in contrast to the midslope bench of HESPA probably accounts for the greater importance of soil moisture as a growth limiting factor at the former site. If downslope moisture movement at HESPA is used as an explanation of its apparent lack of drought the subsoil should be quite moist in contrast to the subsoil at ML 2B and to the topsoil at HESPA. Maximum soil-moisture-tension values in Table 4 for top and subsoils show the opposite is the case. The fact that numerous springs and high water table are observed in the late spring at HESPA, however, suggests that the tension values are misleading in this case.

Soil Fertility

A comparison of soil analyses for ML 1 and ML 2 (Table 10) reveals two soils very similar in texture and texturally derived properties, but differing somewhat in organic matter and thus in characteristics derived from organic matter content. The higher values of cation exchange capacity, soil moisture constants, and total nitrogen for ML 1 is undoubtedly due to its higher level of organic matter

TABLE 10. Average values for soil horizons at ML 1 and ML 2 of texture (clay) and organic matter as well as other soil physical and chemical characteristics directly influenced by each or both.

	Clay 2 micron %	Moisture Equivalent %	Moisture Tension 15 atm.	Organic Matter %	Total N %	Available P_2O_5 ppm	Exch. cap. me/100 gm. OD soil
ML 1							
A11	46. 1	38. 4	27. 3	10. 6	0. 35	24. 0	37. 6
A12	49. 7	35. 3	24. 7	7. 7	0. 26	14. 7	34. 3
B1	52. 6	34. 0	25. 1	5. 3	0. 15	11. 2	32. 8
B2	54. 2	33. 4	26. 0	2. 8	0. 08	11. 0	29. 6
ML 2							
A11	40. 6	36. 5	22. 0	8. 7	0. 24	23. 1	31. 8
A12	43. 6	33. 0	21. 2	4. 0	0. 16	8. 5	28. 1
B1	46. 2	31. 2	20. 8	2. 9	0. 11	6. 2	25. 8
B2	49. 4	32. 7	23. 8	1. 4	0. 06	4. 2	27. 9
ML 1	51. 4	35. 0	25. 8	5. 7	0. 19	11. 9	32. 8
ML 2	45. 8	33. 2	22. 3	3. 7	0. 12	9. 2	28. 3

through the profile. The difference in pattern of available phosphorus with depth is an interesting one and probably indicates a difference in phosphorus fixing abilities of the clay minerals formed from basalt compared with those formed from andesite. On the basis of soil analyses ML 1, the most productive site (Site Index 160) would appear to have more fertile soil than ML 2 (Site Index 130).

The results of pot fertility tests, likewise, are consistent with productivity differences between the two areas. Figures 21,

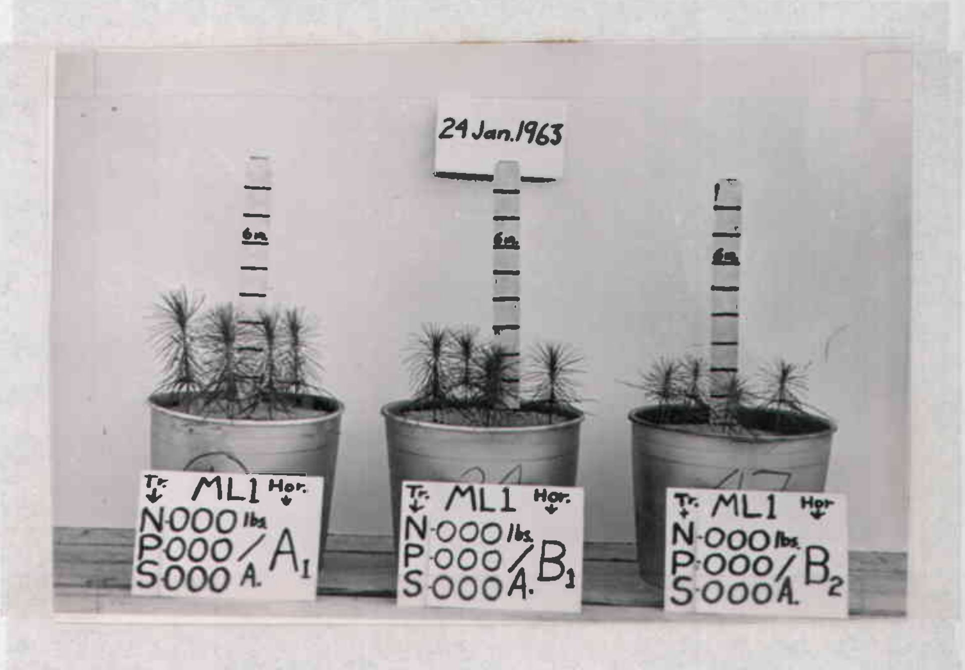

FIGURE 21. Monterey pine seedlings growing on different soil horizons of ML 1 (45-year-old Douglas-fir stand) three months after germination.

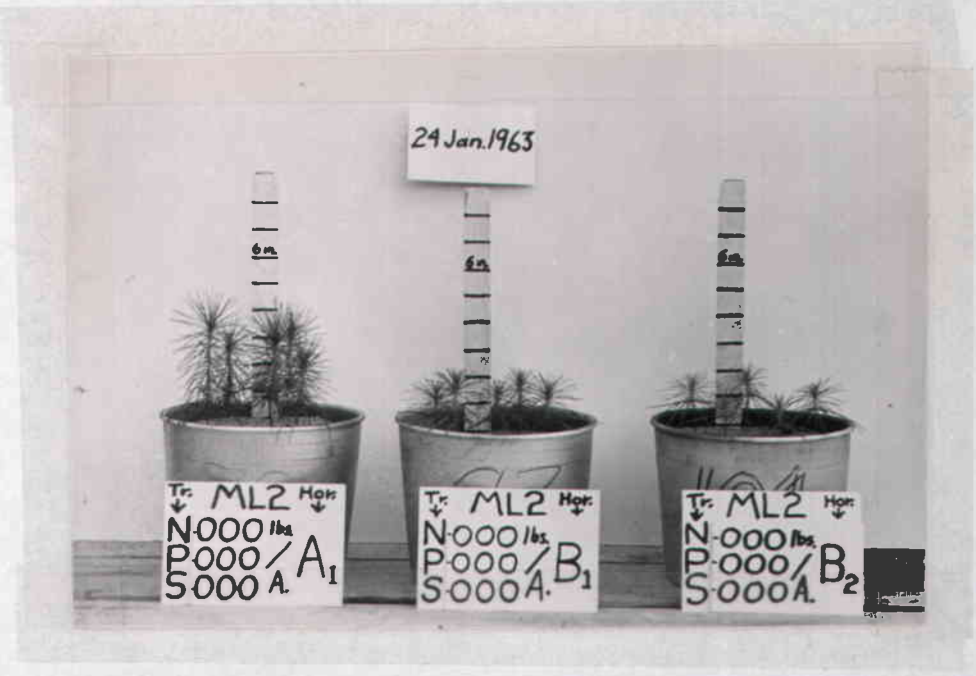

FIGURE 22. Monterey pine seedlings growing on different soil horizons of ML 2 (30-year-old Douglas-fir stand) three months after germination.

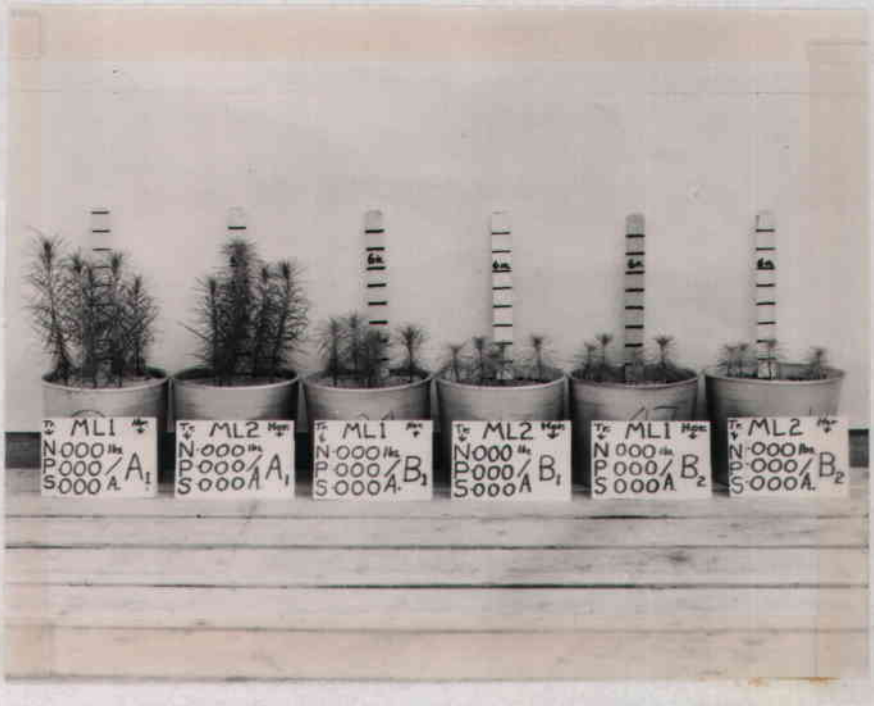

FIGURE 23. Monterey pine seedlings growing on three different soil horizons on both ML 1 and ML 2 (45- and 30-year-old Douglas-fir stands) at harvest time (five months after germination).

22, and 23 contrast the growth of Monterey pine seedlings by horizon on the two soils. Table 11 provides dry weight of seedling tops data which show quantitatively that in comparable soil horizons ML 1 produces the larger seedlings. Table 12 has a seedling weight predictive equation for each horizon of the two soils based on applied N, P, and S levels while Table 30 (App. G, p. 183) gives the actual average top weight of seedlings. It may be noted that seedlings grown on ML 1 topsoil (A1) have a negative N coefficient in contrast to a positive N coefficient for ML 2. In general nitrogen was more effective for stimulation of seedling growth in application to subsoils (B1 and B2) than to surface horizons. Sulphur was more successful for seedling growth improvement in topsoils especially at ML 2. Its effect on growth of

TABLE 11. Average dry weight of Monterey pine seedling tops per pot in fertility study of three soil horizons at ML 1 and ML 2 (45- and 30-year-old Douglas-fir stands).

	Dry wt. in gms.		
Area/Horizon	A1	B1	B2
ML 1	4.88	2.10	1.12
ML 2	4.77	1.33	0.95
Difference	0.11	0.77	0.17
"t" test	<1	15.6	2.65
Significance	NS	***[1]	*[2]

[1] *** significantly different at the 0.001 level.
[2] * significantly different at the 0.05 level.

TABLE 12. Regression equations derived from top weight data of Monterey pine and Douglas-fir seedlings in a pot fertility assay of ML 1, ML 2 and HESPA soil horizons using an incomplete factorial design with five levels of three added elements (N, P, and S) (1962-1963).

Coefficient	ML 1 Monterey pine A1	 B1	 B2	ML 2 Monterey pine A1	 B1	 B2	HESPA Douglas-fir A1
Ave.	522.94	159.93	91.45	418.88	158.65	62.21	1076.36
N	-8.60	16.89	19.01	23.97	36.67	29.56	145.15
N^2	-0.11	-0.59	-0.62	-0.89	-1.21	-0.89	-19.06
P	17.88	21.00	17.89	31.59	30.66	34.26	90.44
P^2	-0.27	-0.40	-0.38	-0.49	-0.74	-0.80	-9.83
S	56.39	67.69	32.23	57.57	18.73	6.09	---
S^2	-4.60	-6.96	-3.09	-4.95	-1.34	0.591	---
NP	0.01	0.01	0.01	0.20	0.22	0.07	5.33
NS	0.12	0.51	0.56	0.73	1.03	0.86	---
PS	-0.25	-0.42	-0.52	-0.95	-0.87	-1.15	---
Correlation r^2	0.689	0.575	0.571	0.772	0.631	0.615	0.522

seedlings was improved by N and retarded by P. Phosphorus was more effective at ML 2 while the nitrogen-phosphorus interaction was negligible for soils from both areas. On the other hand, the fertilizer response pattern at HESPA (Table 12) has a strong positive nitrogen-phosphorus interaction. The prediction equation for top weight of Douglas-fir given in this table is based on levels of N and P applied to HESPA topsoil (A1, 0-6 inches). The relationships are graphically illustrated in response surface form for ML 1 and ML 2 topsoil and subsoil at intermediate levels of S, and for HESPA topsoil in Figures 52, 53, 54, 55, and 56 (App. G, p. 189-193).

A comparison of Monterey pine and Douglas-fir as pot fertility test plants was made on the B1 horizon soil from ML 1. The results shown in Figure 24 (also Tables 31 and 32, App. G, p. 184, 185) indicate that relative response patterns are quite similar but Douglas-fir is more sensitive to high nitrogen levels and more responsive to high levels of P_2O_5. Therefore, soil fertility assays by Monterey pine should give valid trends though the seedling of the conifer occupying the site, Douglas-fir, undoubtedly would be more appropriate for this purpose.

Soils at HESPA were sampled in 1962 at the zero to one-half inch, one-half to one inch, one to three inch, and three to six inch levels to check the vertical distribution of fertilizer phosphate through the profile. Available soil phosphorus (139, p. 1-18) was

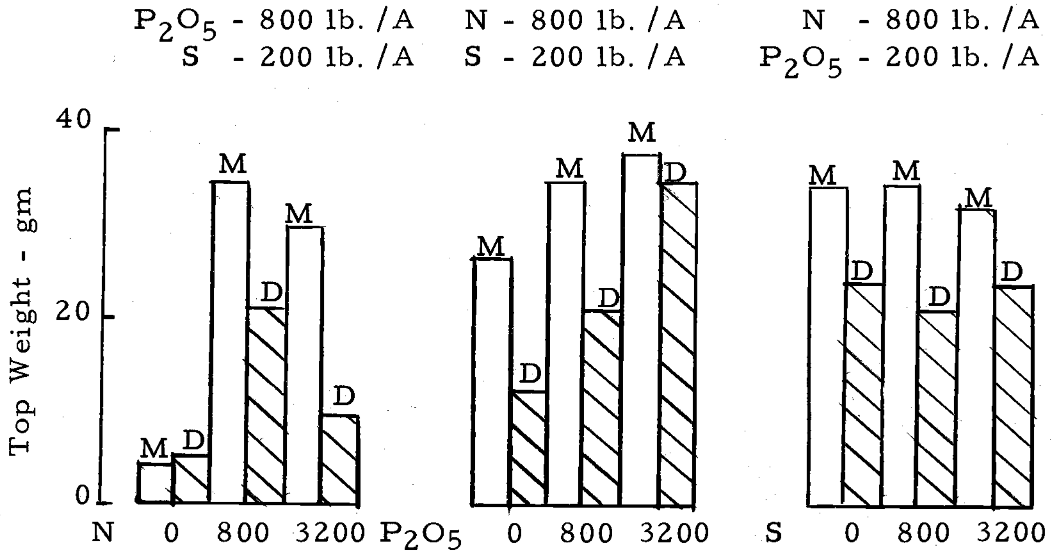

FIGURE 24. The effect of selected combinations of nitrogen, phosphorus and sulphur fertilizers on the top weight yields of Douglas-fir and Monterey pine seedlings in a greenhouse pot fertility trial with B1 horizon soil at ML 1. 1963.

determined for these depths under six control trees and six trees with applications of 400 pounds per acre of P_2O_5 in 1957, 1958, and 1959. It may be seen from Table 13 that 35 percent of the added phosphorus is accounted for in the top six inches of soil. Thirty percent of this added P_2O_5 appears to be spread rather evenly through the top three inches of soil. The lower half of the sampled profile (three to six inch level) had only five percent of the added P_2O_5. Considering only the relative vertical distribution pattern of P_2O_5 one might conclude that fertilizer phosphate moved downward only about four to five inches since it was applied. The fact that 65 percent of the original fertilizer material is not accounted for might be attributed to leaching loss. Movement of phosphorus

TABLE 13. Average vertical distribution of phosphorus through the top six inches of HESPA soil profile for fertilized and unfertilized trees three years after last fertilization.[1]

	Soil profile depth in inches				
	0-1/2	1/2-1	1-3	3-6	0-6
	Available phosphorus in ppm[2]				
Control	6.5	3.8	1.9	1.6	2.3
Fertilized	62.3	70.4	61.7	12.1	37.8
Added P_2O_5 accounted for in percent[3]	4.6	5.6	20.0	5.3	35.5

[1] Fertilized 400 lbs./A N and P_2O_5 in 1957, 1958, and 1959 (six trees)

[2] Available phosphorus by bicarbonate extraction (139, p. 4-7)

[3] Assuming soil bulk density 0.88 gm./cc.

in soil, however, is known to be extremely slow (155, p. 446-447). A more likely possibility would be phosphorus fixation, a very active process in acid forest soils, since available phosphorus determinations used for this check would not account for the fixed form of phosphate.

DISCUSSION

Seasonal Growth Patterns- Soil Moisture Relationships

Equal Availability of Soil Moisture - Growth

It is obvious from the contrast of irrigated and non-irrigated growth at ML 2 that moisture deficits are affecting growth rate despite the fact that the supply of available moisture is not exhausted. This is further proof to add to the mounting evidence that soil water held between field capacity and wilting point is not equally available for plant growth. The soil-moisture tension at which growth retardation was first evident for ML 2B was quite comparable to the 0.5 atmospheres reported by Bassett for loblolly pine (13, p. 137). Virtual growth cessation at ML 2B occurred when soil-moisture tensions for the top 20 inches of soil first reached roughly the 3.0 atmosphere value noted for growth cessation in loblolly pine (217).

Excess Soil Moisture - Growth

Comparisons of cumulative radial growth patterns at HESPA (Figure 11) have definitely established the fact that irrigation under certain conditions can cause slower growth rates than those attained by non-irrigated Douglas-fir. These conditions appear to include a substantial release from root competition and frequent applications of irrigation water. The demonstration of this growth sensitivity to high soil-moisture levels by Douglas-fir is concrete evidence that its growth can be adversely affected by high soil-moisture levels on poorly drained sites. This would help to explain its presence on well drained soils.

It is not obvious from Figure 12 nor from Tables 4 and 24 (App. E, p. 165) that the soil-moisture levels are particularly high as a result of irrigation. One should consider, however, the values shown are from measurements taken three to seven days after the last irrigation and just prior to the next application. In 1960, for example, Figure 12 shows soil-moisture tensions as high as 0. 5 atmospheres during July. Irrigation applications were so frequent and heavy in relation to actual needs (as inferred from the growth pattern of non-irrigated trees) that soil-moisture levels were probably at saturation after each irrigation. Allowing two days for drainage to field capacity the soil would be above the field-capacity-moisture content for 18 days in July. It's not too surprising that this treatment would affect subsequent growth rate. The fact that there was no abrupt decline in subsequent growth rate during 1960 could be used to support the hypothesis that this was an inhibition of root expansion and not root injury which led to reduced radial growth rates in 1961 and 1962. Without detailed examination of the root systems, however, one could not say for sure whether or not root injury was involved. Whichever the case, the prime cause seems to be a lack of adequate or optimum aeration for growth; a condition induced by frequent periods of high soil-moisture levels.

Soil-Moisture Depletion - Root Growth

The fact that there was no measured difference in soil-moisture depletion for various intensities of thinning at ML 1 and ML 2 does not mean that such differences did not occur. It is quite probable that thinning in fact decreased overall soil-moisture depletion in this study. As previously discussed (page 6) thinning results in unequal distribution of roots throughout the soil volume and thus unequal soil-moisture distribution. A single stratified stack location such as used in this study can not give a true relative picture of soil-moisture depletion. It would take numerous random samples or a series of stratified locations (i. e. , two, four, six, and eight feet from the reference tree) to accomplish this task. If tree spacing is regular, however, a very useful single stratified location is the center of the unoccupied polygon made by the surrounding trees. As Barrett and Youngberg (12, p. 10) point out this method may not give a completely realistic picture of total water use but one could infer from measurements at this point when roots have completely occupied the site.

Zahner and Whitmore (217) measured soil moisture gravimetrically four feet from crop trees after a drastic thinning in a young loblolly pine plantation. Moisture depletion in this case was slower and less complete than in the unthinned stand. With a very similar experimental setup for the 30-year-old Douglas-fir stand at ML 2 there appeared to be about the same rate of moisture depletion for all stand densities. This raises an interesting question. Why should the two stands behave so differently in this situation? In exploring this question it is desirable to examine carefully what takes place in soil as a result of thinning operations. When trees are cut, unless their root systems are attached to other trees or unless root systems are overlapping, a volume of soil is left unrooted. Stands as young as the ones in question would not as yet have much opportunity for overlapping root systems. Root grafting was observed, however, for about 15 percent of the remaining trees at ML 2B. Schultz (161, p. 33) observed that 25 percent of the stumps were grafted in a thinned 45- to 50-year-old Site III Douglas-fir stand in western Oregon. Usually the grafted stumps at ML 2B were quite close to the remaining trees and did not occupy too much additional soil volume. Figure 8 affords a good opportunity to see the effect of an adjacent grafted and ungrafted stump on the root development of the remaining Douglas-fir trees. On the right a grafted stump has obviously enhanced the tree's root development while for the tree on the left (stump has been removed) there is a general lack of root development. Schultz (161, p. 49-53) found that the occurrence of root grafting for Douglas-fir increased with increasing number of trees per acre. The chances for appreciable root grafting in the nine-year-old loblolly pine plantation with an initial six by six foot spacing (217) seem rather small.

Moisture depletion of unrooted soil is a slow process since movement of moisture in unsaturated soils is quite slow (14, p. 247-261; 123, p. 30-32). Richards and Wadleigh (150, p. 85) state: "The effective distance through which water in the available range moves toward the root is certainly in the order of inches not feet". Thus steep gradients of soil moisture can develop and be maintained. As moisture depletion progresses to higher soil-moisture stresses in surrounding soil the gradient steepens and for short distances on the fringe appreciable moisture may be moved along it (180). Concurrently, however, this gradient encourages root growth and development into the more moist soil volume. Hagan and fellow workers (83; 84, p. 88-91; 85) contend that access to moist soil from fringe roots allows growth and transpiration to continue at a maximum rate to a higher apparent soil-moisture tension than would be the case if there was a uniform stress over the whole root system. If root growth proceeds very rapidly, however, one would expect lower soil-moisture stresses for the overall root system than if the rate of root extension was relatively slow.

It is quite probable that the remarkably rapid early growth rate of loblolly pine on its better sites makes possible very rapid root extension after thinning cuts in young stands. Table 14 contrasts some of the principal features of the two experimental stands, loblolly pine (217) and Douglas-fir at ML 2. It is apparent from the relative space for root expansion and the rate at which it was occupied that loblolly root growth was considerably more rapid than the Douglas-fir at ML 2B. It should be noted that the basis for site occupation in the loblolly pine study (217) was moisture depletion of the top 24 inches of soil while at ML 2 it was the small root concentration at the 24- to 32-inch level (Table 9) which is not exactly comparable.

If rapid root expansion permits thinned loblolly stands to deplete less soil moisture within the established root system, one would expect diameter growth rates to be little affected by moisture deficits. Examination of the diameter-growth pattern for the heavily thinned loblolly pine (217) reveals a very rapid growth throughout the summer somewhat like that obtained with irrigation at ML 2. On the other hand, growth for the control loblolly stand virtually ceased in June. The contrast in growth rates between the heavily thinned ML 2B and the control ML 2C was not nearly as marked (Figure 7). Thus it would appear that the rate of root

TABLE 14. Comparison of thinning - soil-moisture studies of loblolly pine (217) and Douglas-fir (ML 2B)

Species	loblolly pine	Douglas-fir
Stand origin	plantation	natural stand
Age of study start	9	25
Initial density (stems/acre)	1, 020	1, 514
Thinned density (stems/acre)	100	368
Area per tree	436 ft. ^{2}	117 ft. ^{2}
Years to occupy soil mass	5	8
Initial ave. dbh. (thinned)	4. 2 in.	5. 7 in.
Dbh. after 5 years	8. 5 in.	7. 5 in.
Ht. at 9 years	22 ft.	5 ft. [1]
Soil depth	4 ft.	3-1/2 - 4 ft.
Soil texture	silt loam	silty clay loam
Climate	south Arkansas	western foothills Oregon Cascades

[1] Taken from yield table curves (127, p. 61).

growth in the loblolly pine study (217) is sufficient to avoid moisture-stress effects on diameter-growth rate for heavily thinned trees whereas root growth of Douglas-fir at ML 2B seemed much less successful in this respect.

Model Growth Pattern

Foresters and ecologists frequently speak in general about length of growing season or time of growth cessation as though tree growth had a clearcut and self-evident termination date. Even a casual inspection of seasonal growth curves, Figures 40 through 49 (App. F, p. 171-180), is enough to acquire an appreciation for the specific problem of selecting ends of growing seasons for comparison. Fowells (62) arbitrarily assigned the date at which the growth was 95 percent complete at the end of the season. Gasser (70) hypothesized that cessation of cambial activity occurred when cumulative radial measurement values first reach a maximum and decline. This would exclude the possibilities of a late season growth surge.

In the present study the pertinent question is not when did it stop growing but to what extent growth is affected by additional soil moisture made available through thinning. If trees grew at a constant rate until water for growth was exhausted and growth at this point ceased, defining the end of the growing season would make an adequate comparison for thinning treatments. Since this is obviously not the case it would seem more appropriate to compare growth made after the date when moisture begins to affect growth rate of the unthinned stand. Radial growth patterns of irrigated trees at ML 2B in contrast to non-irrigated trees have provided some valuable insight into the problem of selecting this date. Figures 15 and 16 suggest that departures from linear growth rate result from moisture deficits. Harms (17, p. 8) noted a nearly linear growth rate for six-year-old slash pine which seemed associated with high levels of soil moisture from summer rainfall. Fraser's (66, p. 192-194) data for diameter growth of forest trees on sites with various soil moisture regimes strongly suggest extension of linear growth rates late into the growing season on moist sites. Daubenmire (47) also showed this effect for coniferous species at high elevations (low moisture stress) in contrast to the same species at low elevation (high moisture stress). Eggler (58) describing radial growth curves of southern tree species refers to a time of most rapid uniform growth which he calls the period of maximum growth. On cumulative growth curves he notes, "it is represented by a steep, nearly straight slope". Figure 25 schematically illustrates the four phases of radial growth apparent from the seasonal growth measurements at ML 2. This would assume that except for soil moisture other environmental factors such as light, temperature, and nutrition are at adequate levels. It may be noted in Figure 16 that this assumption is probably not met for the irrigated treatment growth in 1961. Its rate declined markedly in August in

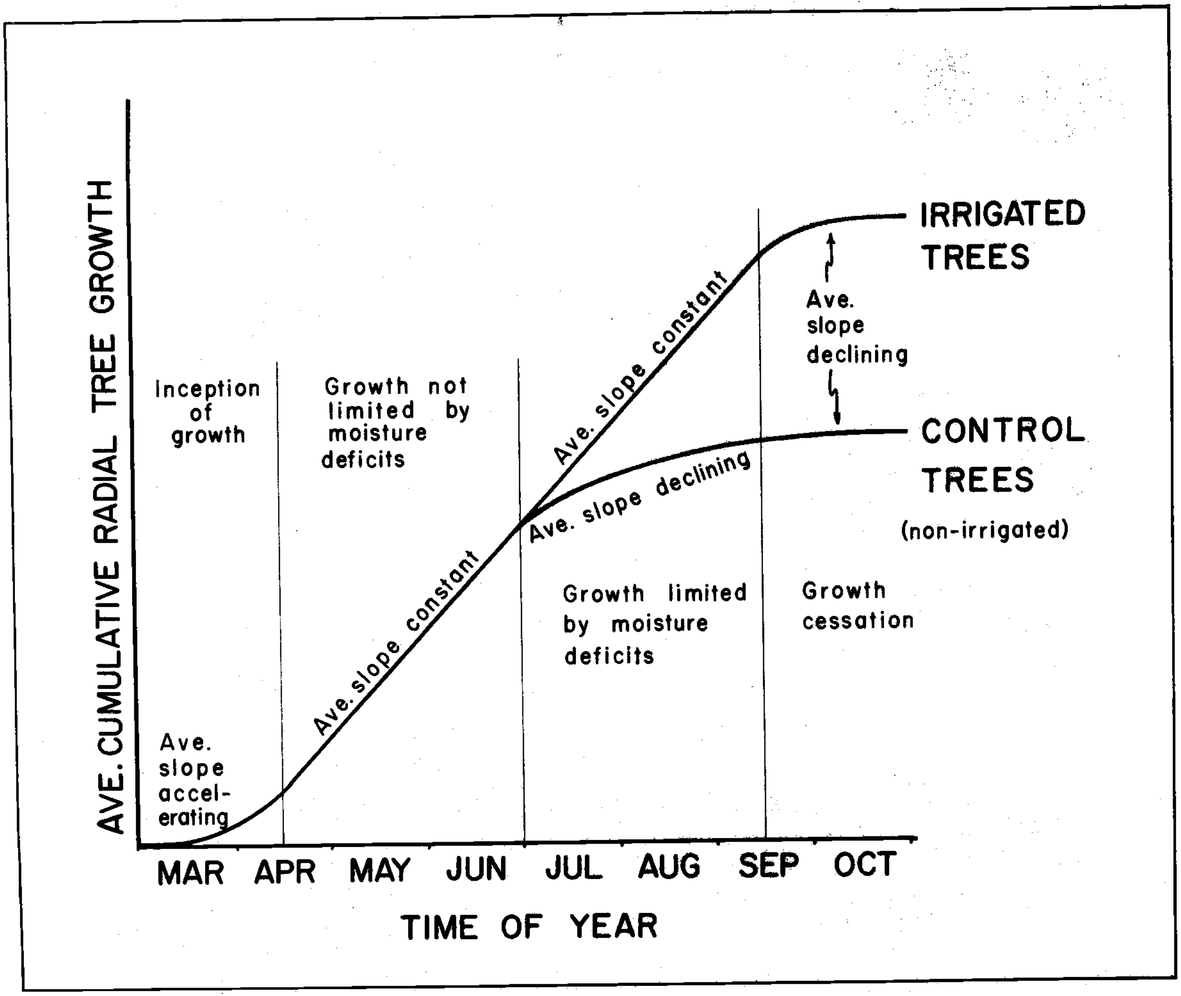

Figure 25. Model Cumulative Radial Growth Pattern.

comparison to that of the fertilized - irrigated treatment group. Apparently the rapid growth promoted the previous year as well as the early growth surge in 1961 has led to inadequate N or P supply in the latter part of the growing season. Another circumstance which would modify the relationship depicted in Figure 25 would be fluctuations in marginally low summer temperatures. This could cause fluctuations in growth patterns throughout the growing season not necessarily related to moisture supply. Daubenmire and Deters (49, p. 10-11) noted a radial growth interruption of conifers and hardwoods associated with a June frost. Other examples of this nature are probably growth curves at northern latitudes (65, p. 783-785; 75). The linear phase should be a practical maximum for the crown's carbohydrate producing elements. Decline from the maximum would represent some disturbance or "bottleneck" in carbohydrate production for growth. Early and late growth phases are temperature conditioned though internal control is also involved which is triggered by photoperiod stimuli (48, p. 464-475).

The recognition of this linear growth phase as representing inherent growth capacity of the tree with adequate or optimum supply of moisture, temperature, or mineral nutrients should provide a useful basis to compare growth capacities of different tree crown classifications, species, stand treatments, and sites. It might be expressed as a slope of the growth curve or as the maximum growth rate. Difference in size could be compensated by conversion of radial growth to a basal area or a volume basis. The use of initial tree size as an independent variable (covariance analysis) would be another useful technique to apply to comparisons involving a range of tree sizes.

Seasonal Growth Pattern - Fertilization

Responses to fertilization were most striking late in the growing season both at HESPA and ML 2 (Figures 10, 11, 14, 16, and 19). Increased early season-growth rates noted for fertilized trees in the second or third season after initial fertilization are probably attributable to prior conditioning effects as noted for irrigated trees (page 77). The late season response was evident for non-irrigated trees but was especially pronounced for treatments including irrigation. Veits (189, p. 261) concluded that fertilizers may increase root development within soil and permit soil water use to higher soil-moisture tensions. There was no opportunity in the present study to check this possibility because no soil-moisture measurements were made under fertilized trees. This explanation may have some value in considering the results from the non-irrigated treatments but it would not, of course, be appropriate for irrigated comparisons. The explanation for late season growth response to fertilizer by irrigated trees is more logically a diminished nutrient supply brought about by growth and/or leaching. Whether this shortage of nitrogen or phosphorus is also the case where irrigation is not involved remains a moot question.

Although both nitrogen and phosphorus were included in the fertilization phase of this study, all experiences to date on these soils (124, p. 27-34) indicate that nitrogen is primarily responsible for positive growth effects. The cycling of nitrogen within the forest ecosystem has been intensively studied (95, p. 386-402; 200, p. 1-28). Cole and Gessel (38, p. 3-7) found very little leaching loss of nitrogen (0. 62 pounds per acre) over a ten month period after a 200 pounds N per acre application of urea fertilizer. In these studies loss from the same profile without fertilization was about 0. 48 pounds per acre for the same period. Thus leaching losses from the heavier forest soils at ML 2B and HESPA with or without fertilization and/or irrigation should not be very appreciable. André (8, p. 49) sampling under a Douglas-fir stand, quite similar in soil, vegetation, and climate to ML 1 and ML 2, noted that available nitrogen of the top three inches of soil was at its lowest level in the late summer. This would tend to support the theory that late season growth advantages of fertilization are brought about by a diminishing and limiting supply of nitrogen available for uptake and growth near the end of the growing season.

Site Productivity - Soil Fertility

The relative productivity of ML 1 (Site Index 160) and ML 2 (Site Index 130) is reflected in both soil analysis and pot fertility assay results. The similarity of climate, vegetation, and physical soil factors suggest that in this case soil fertility has a direct link with productivity. Diameter growth responses to nitrogen at ML 2 confirm that this element is growth limiting. Response surfaces from ML 1 and ML 2 in Figures 52 through 55 (App. G, p. 189-192) show that Monterey pine seedlings grown in Al horizon soil of ML 2 respond to nitrogen in contrast to results from the same horizon at ML 1 where seedling yield is depressed by added nitrogen. Seedlings grown on subsoil horizons (B1 and B2) for both ML 1 and ML 2 however, showed responses to nitrogen. Unfortunately field applications of fertilizers were not carried out at ML 1. Presumably diameter growth responses would have been less than those obtained at ML 2.

At HESPA height growth was increased by increasing rates of nitrogen fertilization (124, p. 27-30). Measurement of possible height growth response as well as form changes of the bole would be useful at ML 2 to assess the site quality change. Furthermore, the nature of the wood produced by these treatments should be determined. Fertilization has been found to decrease wood densities of Douglas-fir (59), loblolly pine (218), and slash pine (213). Irrigation was observed to increase percentage of summerwood of mature longleaf pine and thus presumably wood density (142). Irrigation of two-year-old loblolly pine, however, reduced percentage of summerwood and specific gravity of wood over a three year period (216). Future work to be done at ML 2 and HESPA includes stem analysis and wood property determination of treatment trees to accurately assess the added volume and quality of wood promoted by fertilization and/or irrigation.

The results of fertilization at ML 2 and HESPA showed Douglas-fir on the latter site to be much more responsive to nitrogen fertilization than those on the former site (Figure 20). This difference is not reflected, however, in the results of total nitrogen analysis on both soils. Table 15 shows that total percent N is quite similar for HESPA and ML 2 through the profile but organic matter

TABLE 15. Organic matter and total nitrogen for comparable soil horizons at ML 2 and HESPA.

		Total N percent		Organic matter percent	
ML 2	HESPA	ML 2	HESPA	ML 2	HESPA
A11 0-4"	A1 0-5"	0. 24	0. 23	8. 7	15. 8
A12&B1 4-22"	A3 5-20"	0. 13	0. 13	3. 4	6. 5
B2 22-36"	B1&B2 20-38"	0. 06	0. 02	1. 4	0. 8

is almost twice as great which indicates that the organic fraction of the soil at HESPA has only half the nitrogen content of that at ML 2B. This indicates that nitrogen mobilization is entirely different at the two areas despite the similarity in total content.

The behavior of phosphorus in soil fertility is rather difficult to interpret. The failure of P fertilizers to improve diameter growth in the HESPA field study (124, p. 27-34) is hard to reconcile with the marked response of the same species to high phosphorus levels (associated with moderate to high levels of nitrogen) in the pot fertility study (Table 12 and Figure 56, App. G, p. 193). Recently Meagher and Armson (131) demonstrated the importance of placement of phosphorus on the growth of white spruce seedlings in pots. Phosphorus was mixed with the soil for the HESPA pot study while field applications were broadcast on the surface. The depression of growth at HESPA caused by high broadcast application rates of P_2O_5 (124, p. 27-34) might have been created by a high ionic environment inhibiting nitrogen mineralization in this microbiologically active zone. Another possible explanation for the lack of response to phosphorus is that the bulk of it was fixed at the soil surface layer and was not available for uptake. However, the analyses in Table 13 show clearly movement of ample P_2O_5 down into the top three to five inches of soil at HESPA. It should be noted that the sampling and analysis were done several years after the fertilizer applications and the subsequent growth analyses. It is difficult to believe, however, that these trends of P2O5 distribution developed only in the last few years.

Another possible explanation for phosphorus growth responses is a lack of mycorrhizal development thought to be so beneficial for tree roots in uptake of P_2O_5 (106, p. 264-268). The Douglas-fir in the HESPA pot trial, however, did show some evidence of mycorrhizal infection such as short root development and visible fungal hyphae. A more probable reason for the response of seedling growth to phosphorus in fertility trials is the confinement of the root system to a small volume of soil. This might tend to stress the seedling's capacity to obtain soil phosphate while an unconfined root system in the same soil would not be limited in this respect. The tendency of lateral roots to concentrate on the pot inner surface with only partial contact with the soil may further contribute to the seedling's response to phosphate.

Monterey pine grown on soils from ML 1 and ML 2 show substantial growth responses to phosphorus in pot fertility tests (Figures 53 through 55, App. G, p. 190-192 and Table 24, App. E, p. 165). Unpublished results of pot fertility tests for Crown Zellerbach Corporation Tree Farms (31, p. 3-9) give similar results with Douglas-fir and western hemlock seedlings for Astoria and Hembre topsoils (A1) while field applications of 1, 000 pounds per acre P_2O_5 failed to promote growth responses in 40-year-old hemlock stands. Marked growth responses of western hemlock to nitrogen in both pot and field studies were evident for these soils. Recent pot studies on other Clackamas Tree Farm soils (31, p. 3-9) showed nitrogen responses for Douglas-fir seedlings but no response to applications of phosphorus (results also unpublished).

The possibility of tree growth responses to sulphur applications on Clackamas Tree Farm especially at ML 1 is suggested by the positive S coefficients derived from the pot fertility test with Monterey pine (Table 12). Agricultural crops on many Oregon soils respond to sulphur fertilization (209, p. 42-43). To date, however, there has been no sulphur fertilization of field plots at Clackamas Tree Farm.

SUMMARY AND CONCLUSIONS

The productivity differences between Douglas-fir at ML 1 (45-year-old stand, Site Index 160) and ML 2 (30-year-old stand, Site Index 130) are probably due to soil fertility differences revealed by soil analyses and pot fertility assay. Other factors of climate, soil physical characteristics, physiography, and elevation are much the same for both areas. Thinning in these two stands as well as at HESPA significantly increased soil temperatures from one to five degrees Fahrenheit. This effect decreased with depth and increased with increased thinning intensity. At ML 2 trees that had been heavily thinned tended to have a greater amount and percentage of late season growth. Trees with increasing order of crown classification (intermediates to dominants) at ML 1 and ML 2 had increased amounts and percentages of late season growth regardless of thinning treatments. Soil-moisture depletion as measured in this study for ML 1 and ML 2 was not significantly affected by thinning treatments. Root pattern comparisons at the heavily thinned ML 2B and the control ML 2C revealed unequal root distribution throughout the soil mass for ML 2B which would indicate less overall soil-moisture depletion for this heavily thinned subarea. Soil-moisture levels under thinned 15- to 20-year-old Douglas-fir at HESPA were significantly higher than those under unthinned stands.

Irrigation treatments at ML 2B extended the spring maximum growth rate throughout most of the summer. Using this growth rate as a basis of comparison, retardation of radial growth was detectable at quite low soil-moisture-tension values of one-half to one atmosphere. Growth cessation for all subareas of ML 1 and ML 2 occurred at much lower tensions than the conventional, 15 atmosphere, lower limit of soil-moisture availability. Excessive irrigation at HESPA depressed the subsequent years' radial growth rate for thinned trees. This may explain the absence of Douglas-fir on poorly drained sites. The effect of high soil-moisture levels was probably to restrict expansion of the root system into unrooted areas though actual root injury might have been involved.

The radial growth responses to fertilization occurred to a large extent in the latter part of the growing season. A plausible explanation is that the supply of mineralized nitrogen becomes growth limiting near the end of the summer. Phosphorus had a beneficial effect on growth of conifers in pot fertility tests but was ineffective for this purpose in field experiments. Problems of fertilizer placement may be involved in this apparent anomolous behavior of Douglas-fir in respect to phosphorus. Sulfur produced growth responses in Monterey pine on ML 1 and ML 2 soils but it was not tested by applications in the field.

It is hypothesized that potential radial tree growth rate is virtually linear over most of the growing season except for an accelerated and decelerated slope phase at the beginning and end of the growing season. Departures from this linear slope would result principally from shortages in moisture, mineral nutrients, or heat. The maximum growth rate is proposed as an important characteristic, reflecting the potential productive capacity of the tree's "carbohydrate factory", the crown, when "bottlenecks" in the supply of raw materials have been eliminated.

The use of irrigation and fertilization to uncover growth limiting site factors on these research areas has been quite revealing. Although soil moisture and soil nutrients were of a different order of importance for ML 2 and HESPA, neither factor was entirely controlling tree growth. The limitations imposed were not absolute, but the effects were appreciable. For thinned 20-year-old Douglas-fir at HESPA fertilization increased radial growth about 30 percent and irrigation only about ten percent (discounting 1961 and 1962 growth depressions) and for unthinned trees growth increases were about 50 percent and 40 percent respectively. For 30-year-old Douglas-fir at ML 2B, fertilization increased radial growth roughly 20 percent and irrigation 45 percent. Combination of irrigation and fertilization gave approximately additive growth responses (HESPA - thinned, 35 percent and ML 2B 60 percent) except for HESPA - unthinned (40 percent).

The possible commercial use of irrigation and/or fertilization to increase growth and yield of Douglas-fir on similar Cascade foothill sites is suggested by these striking growth responses at dbh. The quality of the added wood as well as its distribution over the bole are two major questions to be resolved if economic feasibility is to be explored.

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FIGURE 27. ML 1A, 40-year-old Douglas-fir stand before thinning (May 1955).

FIGURE 28. ML 1A, 40-year-old Douglas-fir stand after light commercial crown thinning (March 1956).

FIGURE 29. ML 1B, 40-year-old Douglas-fir stand before thinning (May 1955).

FIGURE 30. ML 1B, 40-year-old Douglas-fir stand after medium crown thinning. (March 1956).

FIGURE 31. ML 1C, 40-year-old Douglas-fir stand, unthinned (May 1955).

TABLE 16. Soil Analysis of Samples from Various Depths in the Profile at ML 1 (45 Year Old Douglas-Fir Stand) Clackamas Tree Farm - Molalla, Oregon.

	Soil Physical Characteristics							Soil Chemical Characteristics								
	Soil Texture			Moist. Equiv.	MC % for Tension Values- Pressure Membrane Determ.				Org. Mat	Tot. N	Avail. P_2O_5	Exchange Capacity	K	Na	Ca	Mg
	Sand	Silt	Clay	MC %	2 Atm.	5 Atm.	15 Atm.	pH	%	%	ppm	me/100 gm. OD Soil				
ML 1A																
0-4"	26.2	28.5	42.7	38.1	33.1	29.2	26.1	5.4	10.2	0.35	22.4	36.4	1.30	0.05	8.4	4.0
4-8"	24.1	27.1	48.8	35.1	30.6	27.7	24.5	5.3	7.4	0.26	11.0	33.3	0.78	0.05	6.8	3.4
10-14"	21.0	27.4	51.7	34.3	29.6	26.9	24.0	5.2	6.0	0.20	11.0	35.3	0.62	0.05	5.9	3.2
22-26"	21.8	27.2	51.0	33.5	28.9	27.2	24.0	5.1	3.4	0.12	10.3	30.1	0.32	0.05	4.0	2.6
30-36"	20.9	23.7	55.4	33.7	29.1	27.3	24.8	5.1	2.2	0.08	11.0	30.4	0.24	0.10	2.8	2.7
Ave.	22.8	27.8	49.9	35.0	30.3	27.6	24.7	5.2	5.8	0.20	13.1	33.1	0.65	0.06	5.6	3.2
ML 1B																
0-4"	28.7	24.3	46.7	38.4	26.4	32.4	29.2	5.4	10.0	0.36	24.0	39.5	1.36	0.05	8.6	4.5
4-8"	25.9	24.9	49.2	35.5	31.5	28.6	24.9	5.4	8.0	0.28	16.5	35.7	1.00	0.07	7.4	3.8
10-14"	21.1	27.7	51.3	34.3	32.3	30.0	27.6	5.2	5.0	0.19	11.5	31.8	0.60	0.10	5.9	3.1
20-26"	24.0	23.4	52.6	32.5	32.0	30.2	28.2	5.0	2.5	0.09	11.0	29.9	0.26	0.10	4.0	2.9
30-36"	18.5	24.3	57.2	35.5	34.0	31.4	29.8	4.9	1.5	0.06	11.9	29.2	0.10	0.12	1.8	2.0
Ave.	23.6	24.9	51.4	35.2	31.2	30.5	27.9	5.1	5.4	0.19	14.9	33.2	0.66	0.09	5.5	3.3
ML 1C																
0-4"	26.2	25.1	48.9	38.8	34.1	29.7	26.7	5.4	11.7	0.34	25.6	37.0	1.19	0.05	8.4	4.0
4-8"	21.0	27.9	51.0	35.3	32.2	27.7	24.8	5.4	7.7	0.25	16.5	34.0	0.82	0.07	6.4	3.3
10-14"	15.9	29.1	55.0	33.4	29.9	27.2	23.7	5.3	4.8	0.17	11.0	31.3	0.55	0.05	6.1	2.7
20-26"	20.3	23.8	55.8	34.0	30.1	25.1	25.0	5.1	2.7	0.10	9.2	29.0	0.23	0.10	4.4	3.1
30-36"	20.1	26.8	53.1	32.5	28.3	27.0	24.2	5.1	1.8	0.07	12.6	29.1	0.17	0.10	3.5	2.2
Ave.	20.7	26.6	52.8	34.8	30.9	27.4	24.9	5.2	5.8	0.18	14.9	32.1	0.59	0.05	5.8	3.1

TABLE 16. Continued.

	Soil Physical Characteristics							Soil Chemical Characteristics								
	Soil Texture			Moist. Equiv.	MC % for Tension Values - Pressure Membrane Determ.				Org.	Tot.	Avail.	Exchange				
	Sand	Silt	Clay	MC %	2 Atm.	5 Atm.	15 Atm.	pH	Mat %	N %	P_2O_5 ppm	Capacity	K	Na	Ca	Mg
												me/100 gm. OD Soil				
ML 1																
0-4"	27.0	26.0	46.1	38.4	30.3	30.4	27.3	5.4	10.6	0.35	24.0	37.6	1.28	0.05	8.5	4.2
4-8"	23.7	26.6	49.7	35.3	31.4	28.0	24.7	5.4	7.7	0.26	14.7	34.3	0.87	0.06	6.9	3.5
10-14"	19.3	28.0	52.6	34.0	30.6	28.0	25.1	5.2	5.3	0.15	11.2	32.8	0.56	0.07	6.0	3.0
20-26"	22.0	24.8	53.2	33.0	30.3	27.5	25.7	5.0	2.9	0.10	10.1	29.7	0.27	0.08	4.1	2.9
30-36"	19.8	24.9	55.2	33.9	30.5	28.5	26.3	5.0	2.6	0.07	11.7	29.6	0.16	0.11	2.7	2.3
Ave.	22.4	26.4	51.4	35.0	30.8	28.5	25.8	5.1	5.7	0.19	14.4	32.8	0.63	0.07	5.6	3.2

TABLE 17. ML 1 Stand Statistics Acre Basis Douglas Fir Site Index 160 Birth Date 1915.

Subarea	A	A	A	A	B	B	B	B	C	C	C	C
Age	41	43	45	47	40	42	44	46	41	43	45	47
						Spring						
Year of Measurement	1955	1957	1959	1961	1955	1957	1959	1961	1955	1957	1959	1961
Stand Statistics												
Before Thinning:												
No. of trees	380	310	288	222	364	316	284	230	522	498	454	428
Ave. DBH, inches	10.6	10.9	11.3	12.0	10.6	11.2	11.8	12.8	9.4	9.8	10.2	10.6
Height, feet	91	93	96	99	92	97	99	103	85	91	94	96
Total volume, cu. ft.	8206	8111	7959	7119	8498	8453	8631	8541	9175	9696	10153	10638
Basal area, sq. ft.	231	203	203	176	225	218	218	208	252	259	262	267
Removed in Thinning:												
No. of trees	66	18	54	40	42	32	54	30				
Ave. DBH, inches	10.5	11.2	10.6	9.4	8.7	8.3	8.3	10.6				
Height, feet	90	92	94	88	86	89	86	93				
Total volume, cu. ft.	1331	497	1296	746	649	446	755	725				
Basal area, sq. ft.	38	12	34	19	17	12	21	18				
Percent basal area	16	6	17	11	8	6	9	9				
After Thinning:												
No. of trees	314	292	234	182	322	284	230	200				
Ave. DBH, inches	10.6	11.0	11.5	12.5	10.8	11.5	12.5	13.1				
Height, feet	91	94	96	101	92	97	101	105				
Total volume, cu. ft.	6875	7614	6663	6373	7850	8007	7876	7816				
Basal area, sq. ft.	193	191	169	157	208	205	197	190				

Soil Profile Description

Nekia (tentative)

This profile was examined on May 28, 1957, by Ray C. Roberts, S. C. S. on leave to F. A. O., Ray Austin and Bob Strand, Crown Zellerbach Corporation and Chet Youngberg, Oregon State University. The sample site is located in the Crown Zellerbach Forest Production Research Area ML 1, NE 1/4 NE 1/4 Sec 25, T6S, R2E, Clackamas County, Oregon. The soil is a Reddish-Brown Latosol developed from basalt residuum in an area having 50 inches annual precipitation. The area is supporting second-growth Douglas-fir. The sample site is at an elevation of 1450 feet on a five percent slope on gently sloping upland. The solum is free of rocks, the soil is well drained with moderate permeability. The profile was moist when examined.

A_{00}	1-1/2 - 0"	Leaf litter
A_{11}	0 - 3"	Dark reddish brown (5 YR 3/2) moist, silty clay loam, strong very fine and fine granular, very friable, slightly sticky and slightly plastic, roots abundant, pH 5. 9.
A_{12}	3 - 9"	Dark reddish brown (5 YR 3/3) moist, silty clay loam, strong medium granular and fine subangular blocky, very friable, slightly sticky and slightly plastic, roots abundant, pH 5. 7. This horizon has high content of shot concretions.

B_1	9 - 21"	Dark reddish brown (5 YR 3/4) moist, silty clay loam, moderate fine subangular blocky, friable, slightly sticky and slightly plastic, roots common, pH 5. 4.
B_2	21 - 37"	Yellowish red (5 YR 4/8) moist, silty clay, weak fine subangular blocky with weak clay flows on ped surfaces, firm, sticky and plastic, roots few, pH 5. 3.
C DR	37+"	Yellowish red (5 YR 5/6) moist, silty clay, weak fine subangular blocky, firm, sticky and plastic, roots few, pH 5. 1. This horizon has abundant basalt fragments.

Stand Specifications

Treatment Objectives - ML 1

Subarea ML 1A - Commerical Crown Thinning

1. Crown thinning.
2. Commercially economical.
3. Stand improvement to the extent allowed by no. 2.
4. Rapid density reduction to an optimum level for this particular stand over the first two or three cuts to give the maximum initial economic returns while leaving the stand in a healthy growing condition.
5. Maintain best possible growth rate on fewest possible trees.

Subarea ML 1B - Light Crown Thinning

1. Crown thinning.
2. Maximum silvicultural stand improvement.
3. Commercially economical to the extent allowed by no. 2.
4. Careful density reduction by frequent light cuts to an "optimum" level for this stand to give maximum practical total growth rate per acre on high quality trees.
5. Minimum possible disturbance consistent with other objectives.

Subarea ML 1C - Control

1. No thinning or disturbance.

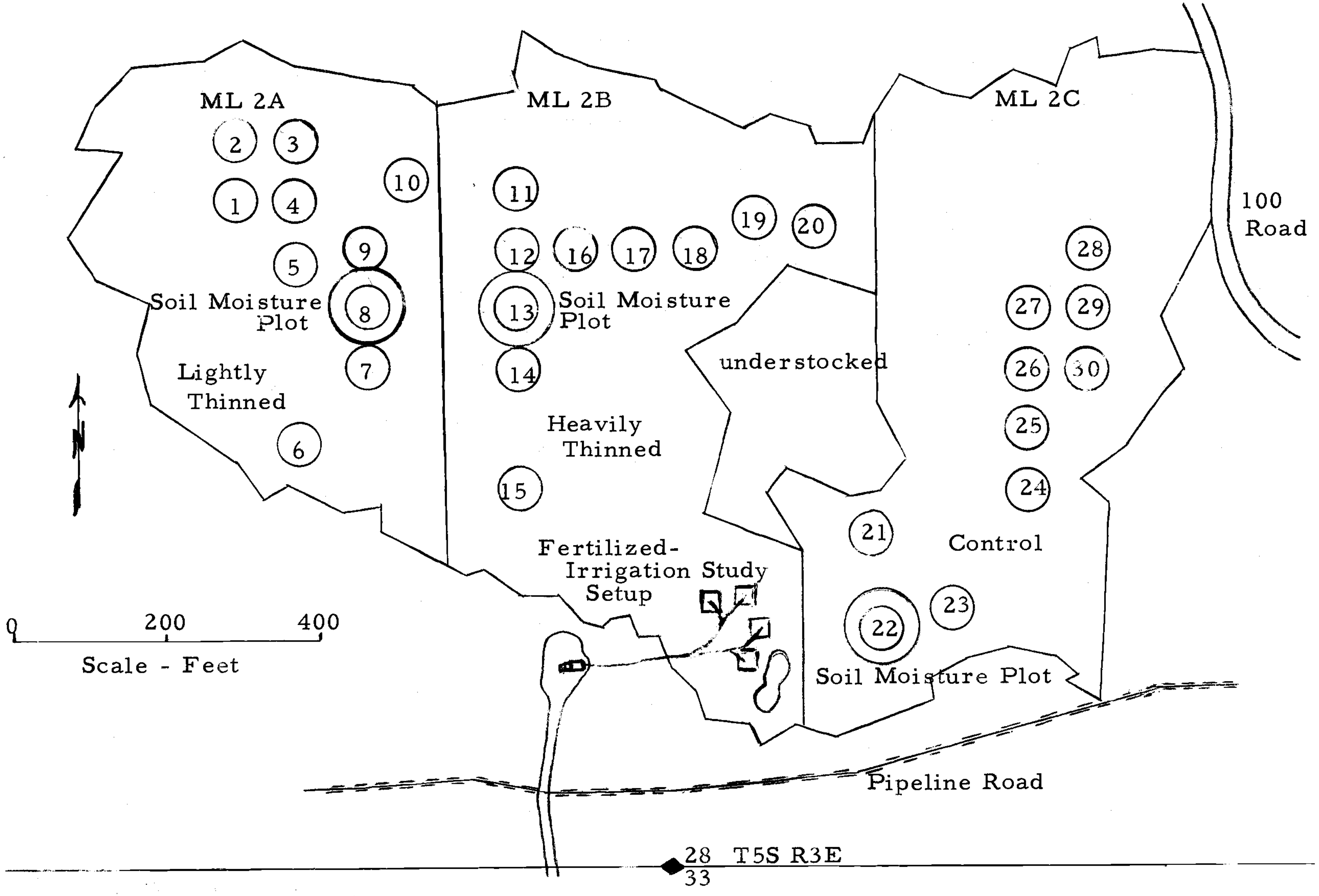

FIGURE 32. Layout of ML 2, 30-year-old Douglas-fir stand, Clackamas Tree Farm.

FIGURE 33. ML 2A, 25-year-old Douglas-fir stand, before thinning (March 1956).

FIGURE 34. ML 2A, 25-year-old Douglas-fir stand, after light initial crown thinning (April 1956).

FIGURE 35. ML 2B, 25-year-old Douglas-fir stand before thinning (March 1956).

FIGURE 36. ML 2B, 25-year-old Douglas-fir stand after heavy initial thinning (April 1956).

FIGURE 37. ML 2C, 25-year-old Douglas-fir stand, unthinned (March 1956).

TABLE 18. Soil Analysis of Samples from Various Depths in the Profile at ML 2 (30 Year Old Douglas Fir Stand) Clackamas Tree Farm - Molalla. Oregon.

	Soil Physical Characteristics							Soil Chemical Characteristics								
					MC % for Tension Values-Pressure Membrane Determ.											
	Soil Texture			Moist. Equiv.	2	5	15		Org. Mat	Tot. N	Avail. P_2O_5	Exchange Capacity	K	Na	Ca	Mg
	Sand	Silt	Clay	MC %	Atm.	Atm.	Atm.	pH	%	%	ppm	me/100 gm. OD Soil				
ML 2A																
0-4"	31.4	26.0	42.6	35.9	28.2	23.7	20.8	5.7	7.3	0.23	16.5	31.9	1.44	0.05	8.1	3.4
4-10"	25.8	27.1	47.1	31.9	27.9	23.7	20.2	5.6	3.6	0.16	8.0	28.6	1.14	0.05	6.8	2.9
12-16"	25.5	29.3	45.1	29.7	25.0	23.4	19.6	5.6	2.6	0.13	5.7	26.6	0.94	0.05	6.4	3.1
22-26"	23.6	26.6	49.8	30.2	25.8	22.8	21.6	5.2	1.1	0.07	4.1	26.8	0.66	0.07	5.2	3.4
30-36"	25.7	24.8	49.5	34.3	29.2	23.2	24.4	4.9	1.4	0.05	4.1	29.8	0.56	0.10	4.4	3.1
Ave.	26.4	26.8	46.6	32.5	27.2	23.3	21.3	5.4	3.1	0.12	7.8	28.7	0.95	0.06	6.2	3.2
ML 2B																
0-4"	29.6	28.9	41.6	36.0	30.8	26.5	22.7	6.0	9.0	0.23	25.2	31.0	1.68	0.05	10.4	3.8
4-10"	25.9	27.6	46.5	32.9	28.8	25.9	22.0	5.7	5.4	0.16	9.2	27.3	1.36	0.05	7.4	2.9
12-16"	22.6	28.8	48.4	31.3	27.4	24.7	20.8	5.7	3.8	0.11	8.0	24.7	0.82	0.07	6.2	3.1
22-26"	24.7	28.3	47.0	31.4	27.4	25.5	23.2	5.2	1.5	0.06	4.6	28.4	0.50	0.10	5.0	3.2
30-36"	23.7	24.6	51.7	33.0	28.9	27.1	25.7	5.3	1.3	0.05	4.1	28.3	0.38	0.12	4.4	2.9
Ave.	25.3	27.7	47.0	32.9	28.6	25.9	22.9	5.5	4.2	0.12	10.1	27.9	0.95	0.08	6.7	3.2
ML 2C																
0-4"	34.0	28.2	37.9	37.6	32.0	26.4	22.4	5.8	9.8	0.27	27.5	32.5	1.34	0.05	9.7	3.4
4-10"	31.8	24.9	43.3	34.1	29.0	24.9	21.4	5.9	3.7	0.18	8.0	28.6	1.20	0.05	7.8	2.7
12-16"	29.3	25.4	45.3	32.6	29.2	25.0	22.0	5.7	2.3	0.10	4.6	26.2	1.00	0.05	6.4	2.7
22-26"	28.8	24.2	47.0	32.9	28.9	25.0	22.8	5.4	1.8	0.07	4.6	25.7	0.92	0.05	5.8	3.3
30-36"	25.5	23.4	51.1	34.5	-	-	-	5.3	1.4	0.06	3.4	28.4	0.78	0.10	5.5	3.3
Ave.	29.9	25.2	44.9	34.3	29.8	25.4	22.1	5.6	3.8	0.13	9.6	28.3	1.05	0.06	7.0	3.1

TABLE 18. Continued.

	Soil Physical Characteristics							Soil Chemical Characteristics								
	Soil Texture			Moist. Equiv.	MC % for Tension Values-Pressure Membrane Determ.				Org. Mat	Tot. N	Avail. P_2O_5	Exchange Capacity	K	Na	Ca	Mg
	Sand	Silt	Clay	MC %	2 Atm.	5 Atm.	15 Atm.	pH	%	%	ppm		me/100 gm. OD Soil			
ML 2																
0-4"	31.6	27.7	40.6	36.5	30.3	25.5	22.0	5.8	8.7	0.24	23.1	31.8	1.49	0.05	9.4	3.5
4-10"	27.8	26.5	43.6	33.0	28.5	24.8	21.2	5.7	4.0	0.16	8.5	28.1	1.23	0.05	7.3	2.8
12-16"	25.8	27.9	46.2	31.2	27.2	24.4	20.8	5.6	2.9	0.11	6.2	25.8	0.92	0.06	6.3	3.0
22-26"	25.7	26.4	47.9	31.5	27.4	24.5	22.5	5.2	1.5	0.06	4.4	27.0	0.69	0.07	5.3	3.3
30-36"	25.3	24.2	50.8	33.9	29.1	25.2	25.0	5.1	1.4	0.05	3.9	28.8	0.57	0.11	4.8	3.1
Ave.	27.2	26.5	45.8	33.2	28.5	24.9	22.3	5.5	3.7	0.12	9.2	28.3	0.98	0.07	6.6	3.1

TABLE 19. ML-2 Stand Statistics Acre Basis Douglas Fir Site Index 130 Birth Date 1930

Subarea	A	A	A	A	B	B	B	B	C	C	C	C
Age	25	27	29	31	25	27	29	31	25	27	29	31
						Spring						
Year of Measurement	1956	1958	1960	1962	1956	1958	1960	1962	1956	1958	1960	1962
Stand Statistics												
Before Thinning:												
No. of trees	1516	1214	992	832	1514	368	366	362	2080	1906	1676	1462
Ave. DBH. inches	3.9	4.4	5.0	5.5	3.9	6.4	7.1	7.8	3.3	3.6	4.1	4.4
Height. feet	36	39	46	52	37	47	51	57	33	35	41	49
Total volume. cu. ft.	2132	2207	3072	3534	2252	1560	2571	3222	2019	2315	3456	3875
Basal area. sq. ft.	126	127	135	138	131	84	103	121	125	140	153	161
Removed in Thinning:												
No. of trees	252	100	84	36	1142							
Ave. DBH. inches	3.5	3.9	5.2	6.6	3.1							
Height. feet	35	35	48	55	33							
Total volume. cu. ft.	284	138	289	220	1024							
Basal area. sq. ft.	17	8	13	8	64							
Percent basal area	14	7	9	6	49							
After Thinning:												
No. of trees	1264	1114	908	796	372	368	366	362				
Ave. DBH. inches	3.9	4.4	5.0	5.4	5.7	6.4	7.1	7.8				
Height. feet	37	39	47	52	45	47	51	57				
Total volume. cu. ft.	1848	2069	2783	3314	1229	1560	2571	3222				
Basal area. sq. ft.	109	119	122	130	67	84	103	121				

Soil Profile Description

Silty Clay Loam

This profile was examined on May 28, 1957, by Ray C. Roberts, Ray Austin, Bob Strand, and Chet Youngberg and is located in the Crown Zellerbach Forest Production Research Area ML 2 in Sec 28, T5S, R3E, Clackamas County, Oregon. The soil is a Reddish-Brown Latosol developed from andesite residuum in an area having 50 inches annual precipitation at an elevation of 1450 feet on a level to very gently sloping upland. This soil had many rock fragments in the B_2 horizon and is well drained with moderate permeability. Soil moist when examined.

A_{00}	1-1/2 - 0"	Leaf litter
A_{11}	0 - 4"	Dark reddish brown (5 YR 3/2) moist, silty clay loam, strong very fine and fine granular, very friable, slightly sticky and slightly plastic, roots abundant, high shot content, pH 6. 0.
A_{12}	4 - 11"	Dark reddish brown (5 YR 3/3) moist, silty clay loam, strong fine granular, very friable, slightly sticky, and slightly plastic, roots abundant, high shot content, pH 5. 7.
B_1	11 - 22"	Dark reddish brown (5 YR 3/4) moist, silty clay loam, moderate fine and medium subangular blocky, friable, slightly sticky and slightly plastic, roots common, high shot content, pH 5. 2.

B_2	22 - 34"	Yellowish red (5 YR 4/8) moist, silty clay, weak fine and medium subangular blocky with weak clay flows on ped surfaces, firm sticky and plastic, roots few, pH 5. 2.
B_2DR	38+"	This horizon is similar to B_2 in color, texture, structure and consistence but with a high percentage of andesite rock fragments.

Stand Specifications

Treatment Objectives - ML 2

Subarea ML 2A - Crown Thinning

1. Maximum silvicultural stand improvement.
2. Crown thinning.
3. Maintain maximum practical total growth rate per acre on high quality trees.
4. Reduce density carefully, whenever necessary, by frequent light cuts, to an optimum level for this stand.
5. Maintain steady growth rate on individual "crop" trees.

Subarea ML 2B - Minimum Growing Stock Thinning

1. Reduce growing stock to minimum level consistent with reasonably good growth rate per acre.
2. Obtain maximum possible growth rate on individual trees.
3. Only one "weeding" to be done, and "leave" trees to be free of excessive competition until the first commercial thinning is made.
4. Produce high-quality wood by pruning selected "leave" trees.

Subarea ML 2C

1. No thinning or disturbance.

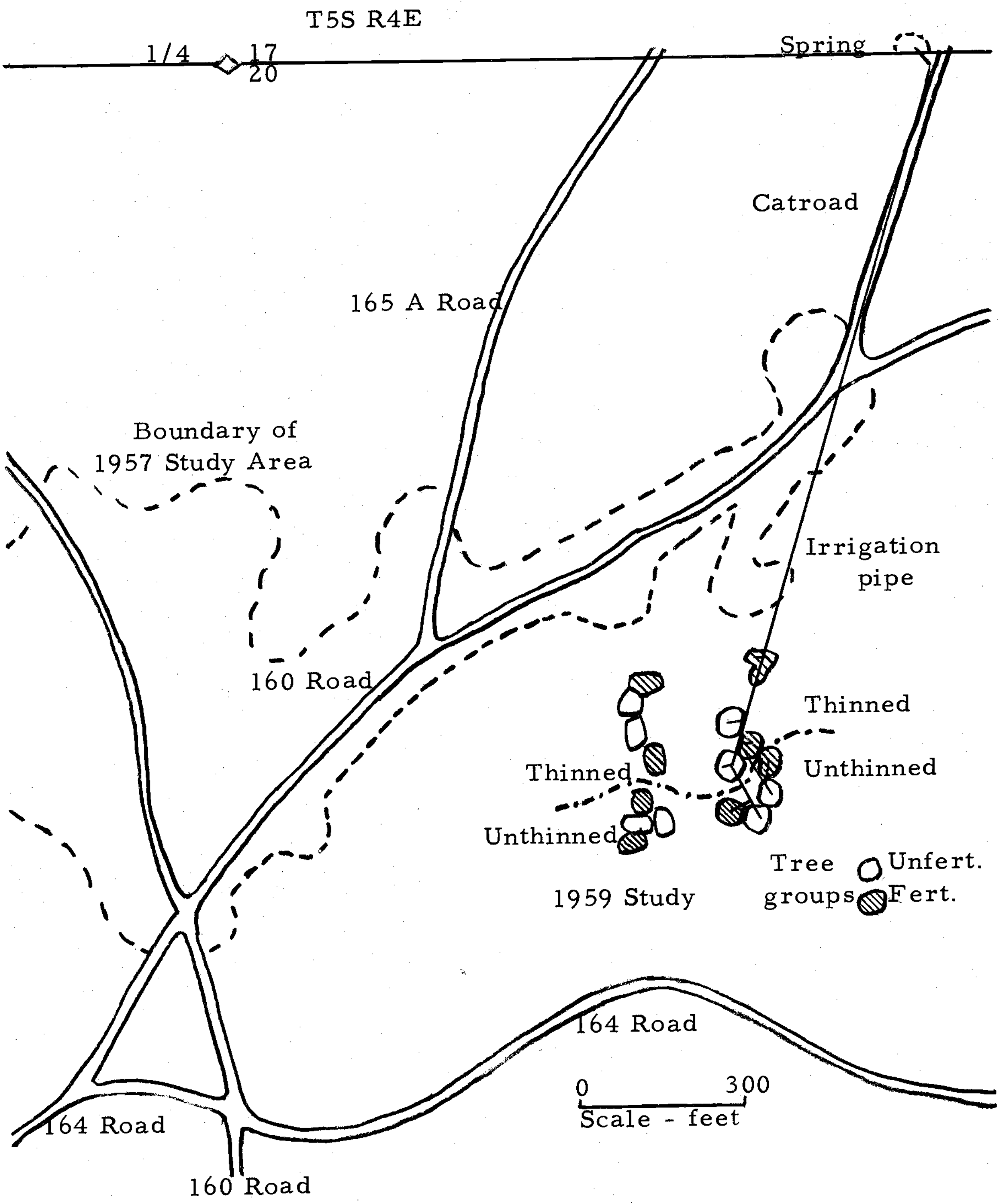

FIGURE 38. Layout of HESPA, 20-year-old Douglas-fir seed production area at high elevation at Clackamas Tree Farm.

FIGURE 39. Study trees at HESPA.

TABLE 20. Soil analysis of samples from various depths in the profile at HESPA, 20-year-old Douglas-fir stand.

Soil Physical Characteristics							Soil Chemical Characteristics								
			MC % for Tension Values - Pressure Membrane Determ.												
Soil Texture			1/3	2	5	15		Org. Mat	Tot. N	Avail. P_2O_5	Exchange Capacity	K	Na	Ca
Sand	Silt	Clay	Atm.	Atm.	Atm.	Atm.	pH	%	%	ppm	me/100 gm. OD Soil			
35.0	59.7	5.3	42.9	32.8	26.6	23.8	5.7	15.7	0.23	5.2	31.4	0.78	0.36	2.65
32.3	51.0	16.7	43.0	31.2	24.9	18.8	5.8	6.5	0.13	2.2	24.5	0.26	0.28	0.79
27.8	38.7	33.4	38.6	29.0	24.1	20.2	5.8	1.0	0.03	1.4	18.3	0.20	0.45	0.78
26.9	38.6	34.5	42.7	32.3	26.3	22.2	5.6	0.8	0.02	1.3	21.5	0.28	0.33	0.78
30.4	38.7	30.8	47.8	36.0	29.5	22.7	5.3	0.7	0.02	1.2	24.6	0.36	0.28	0.79

Soil Profile Description

High Elevation Seed Production Area (HESPA)

Kinney (tentative)

This soil is an uncorrelated Sol Brun Acide developed on andesite residuum at an elevation of 3100 feet under a cover of Douglas-fir, western hemlock, and noble fir and a rainfall of 65 - 70 inches a year. It is situated on a gentle mountain slope (bench) on a SE exposure and a 20 percent slope. The understory vegetation consists of bracken fern, fireweed, trailing blackberry, violet, star-flower, huckleberry, elderberry, and scattered rhododendron. Oregon grape and salal were also observed on the seed production area. The soil is well-drained with moderate permeability and is stony throughout the profile. Roots were abundant in the A_1 and A_3, few in the B_1 and B_2 and sparse below. The A_1 and A_3 horizons were dry when observed and the horizons below were moist.

A_{00}	3/4 - 0"	Scattered leaf litter
A_1	0 - 5"	Brown (10 YR 4/3 dry) and dark brown (10 YR 3/3 moist) shot loam; moderate fine granular; loose when dry, very friable when moist; slightly sticky and slightly plastic when wet; pH 5. 2; boundary is abrupt and smooth.
A_3	5 - 20"	Yellowish brown (10 YR 5/4 dry) dark yellowish brown (10 YR 3/4 moist) shot loam; moderate medium granular and fine subangular blocky; soft when dry,

		friable when moist; slightly sticky and slightly plastic when wet; pH 5. 2; boundary gradual wavy.
B_1	20 - 32"	Dark brown (10 YR 4/3 moist) silty clay loam; weak fine subangular blocky; friable when moist, sticky and plastic when wet; pH 5. 0; boundary gradual wavy.
B_2	32 - 38"	Dark yellowish brown (10 YR 5/4 moist) silty clay loam on light clay; weak fine subangular blocky; firm when moist, sticky and plastic when wet; pH 4. 8; boundary clear wavy.
B_3C	38+"	Dark yellowish brown (10 YR 4/4 moist) gritty clay loam; massive; firm when moist, sticky and plastic when wet; pH 4. 8.

The organic matter content in the A_1 appeared to be lower than normal for a Sol Brun Acide with the rainfall associated with the elevation. It is possible that this is a result of fire since charcoal was observed in the soil profile.

TABLE 21. Average amount and chemical composition of forest litter fall material samples from ML 1 and ML 2 (45-and 30-year-old Douglas-fir stands) for different collection dates by area and by subarea (1959) - Clackamas tree farm - Molalla, Oregon.

	Twigs & Branches O. D. Wt. Lbs/A	Needles O. D. Wt. Lbs/A	Tw & Br + Need. O. D. Wt. Lbs/A	N %	P %	K %	Na %	Ca %	Mg[1] %
December, 1958									
April 10, 1959									
ML 1									
A	294	272	566	0.86	0.19	0.29	0.13	0.61	0.15
B	282	271	553	0.81	0.20	0.30	0.11	0.64	0.13
C	285	218	503	1.03	0.15	0.39	0.12	0.79	0.19
ML 2									
A	258	259	517	1.04	0.15	0.24	0.10	0.45	0.15
B	253	237	490	0.98	0.15	0.23	0.22	0.21	0.23
C	264	262	526	1.05	0.16	0.30	0.15	0.34	0.14
August 27, 1959									
ML 1									
A	61	318	379	0.73	0.11	0.28	0.14	0.36	0.22
B	64	281	345	0.71	0.10	0.24	0.13	0.36	0.19
C	315	398	713	0.80	0.11	0.21	0.10	0.36	0.15
ML 2									
A	44	286	330	0.70	0.10	0.20	0.13	0.37	0.14
B	22	286	308	0.72	0.11	0.17	0.13	0.42	0.21
C	129	367	496	0.83	0.17	0.20	0.14	0.34	0.14
October 12, 1959									
ML 1									
A	328	551	879	0.80	0.13	0.17	0.13	0.43	0.24
B	116	504	620	0.65	0.10	0.11	0.12	0.88	0.27
C	178	902	1081	0.70	0.11	0.20	0.10	0.86	0.04
ML 2									
A	4	836	840	0.42	0.08	0.17	0.09	0.88	0.19
B	4	709	713	0.44	0.10	0.10	0.09	1.01	0.14
C	18	709	727	0.52	0.08	0.12	0.08	0.82	0.16
October 30, 1959									
ML 1									
A	1	194	195	0.52	0.11	0.11	0.09	1.12	0.18
B	1	245	246	0.50	0.10	0.11	0.09	1.21	0.13
C	6	345	351	0.51	0.12	0.14	0.08	0.96	0.33
ML 2									
A	2	118	120	0.51	0.13	0.11	0.10	0.86	0.18
B	1	146	147	0.53	0.10	0.12	0.13	0.79	0.13
C	7	193	200	0.60	0.11	0.11	0.14	0.85	0.33

[1] Magnesium determinations had appreciable variation. Therefore, differences between dates of collection, and subareas should probably be discounted.

TABLE 21. Continued

	Twigs & Branches O. D. Wt. Lbs/A	Needles O. D. Wt. Lbs/A	Tw & Br + Need. O. D. Wt. Lbs/A	N %	P %	K %	Na %	Ca %	Mg[1] %
December 11, 1959									
ML 1									
A	70	191	261	0.73	0.11	0.13	0.11	0.81	0.18
B	24	212	236	0.64	0.10	0.12	0.10	0.70	0.15
C	70	289	359	0.73	0.11	0.13	0.09	0.71	0.19
ML 2									
A	4	139	143	0.82	0.10	0.12	0.13	0.66	0.25
B	4	109	113	0.69	0.10	0.11	0.14	0.46	0.24
C	12	138	150	0.75	0.11	0.14	0.15	0.66	0.24
May 3, 1960									
ML 1									
A	468	686	1154	0.97	0.14	0.18	0.10	0.83	0.17
B	282	356	638	1.04	0.13	0.13	0.08	1.06	---
C	750	510	1260	0.95	0.14	0.19	0.08	0.83	0.09
ML 2									
A	40	170	210	0.76	0.11	0.13	0.08	0.72	0.20
B	12	130	142	0.98	0.10	0.12	0.08	1.10	---
C	67	245	312	1.00	0.11	0.16	0.09	0.64	0.13
August 29, 1960									
ML 1									
A	17	318	335	0.66	0.10	0.10	0.07	0.83	0.29
B	97	297	394	0.69	0.10	0.12	0.08	0.87	0.12
C	441	668	1109	0.69	0.12	0.17	0.08	0.76	0.01
ML 2									
A	11	522	533	0.49	0.12	0.15	0.08	0.92	0.07
B	10	353	363	0.45	0.12	0.14	0.07	1.10	0.14
C	58	567	625	0.50	0.11	0.14	0.07	0.76	0.30
October 14, 1960									
ML 1									
A	38	581	619	0.49	0.12	0.13	0.09	1.24	0.08
B	40	703	743	0.50	0.11	0.14	0.09	1.15	0.13
C	94	772	866	0.49	0.12	0.15	0.08	1.15	---
ML 2									
A	14	630	644	0.52	0.10	0.10	0.08	1.15	0.12
B	14	782	796	0.51	0.11	0.11	0.10	0.88	0.42
C	94	739	833	0.63	0.12	0.20	0.10	1.01	0.06
December 9, 1960									
ML 1									
A	200	262	462	0.71	0.11	0.16	0.08	1.16	0
B	354	430	784	0.72	0.13	0.21	0.08	1.06	0.09
C	417	605	1022	0.79	0.11	0.24	0.10	0.99	0.04
ML 2									
A	21	176	197	0.48	0.08	0.09	0.08	1.01	0.06
B	18	194	212	0.44	0.07	0.14	0.08	1.33	---
C	94	305	399	0.72	0.10	0.14	0.08	1.34	---

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[1] Magnesium determinations had appreciable variation. Therefore, differences between dates of collection, and subareas should probably be discounted.

TABLE 22. Average amount and chemical composition of forest litter fall material sampled from ML 1 and ML 2 (45- and 30-year-old Douglas-fir stands) for different collection dates, for different years, and for different thinning intensities.

	Twigs & Branches	Needles	Tw & Br + Need.	N	P	K	Na	Ca	Mg[1]
					Mineral constituents				
	Dry weight in pounds per acre								
Ave. 1959-60									
Dec - ML 1	393	386	779	3.7	0.6	0.9	0.4	3.1	0.6
April ML 2	149	217	366	2.1	0.3	0.5	0.3	1.1	0.4
April - ML 1	166	380	546	2.7	0.4	0.7	0.4	2.3	0.5
August ML 2	46	397	443	2.3	0.4	0.6	0.4	2.8	0.7
August- ML 1	132	669	801	4.7	0.9	1.2	0.8	7.9	1.2
Oct ML 2	25	734	759	4.1	0.8	1.1	0.8	7.6	1.3
Oct- ML 1	191	462	653	2.5	0.4	0.6	0.3	3.1	0.3
Dec ML 2	27	253	280	0.8	0.2	0.3	0.2	1.8	0.2
ML 1 Total/Yr.	882	1897	2779	13.6	2.3	3.4	1.8	16.4	2.6
ML 2 Total/Yr.	247	1601	1848	9.9	1.8	2.4	1.6	13.3	2.6
ML 1 1959-60									
/Yr. A medium	739	1687	2425	11.5	2.1	2.9	1.8	13.7	2.9
B light	630	1650	2280	11.8	2.1	2.8	1.7	13.2	2.5
C control	1278	2354	3632	17.4	2.8	4.5	2.1	20.2	2.3
ML 2 1959-60									
/Yr. A light	199	1568	1767	9.0	1.6	2.5	1.5	13.2	2.9
B heavy	169	1473	1642	8.4	1.6	1.9	1.6	12.6	2.5
C control	372	1762	2134	11.9	2.0	2.9	1.8	14.0	2.3

[1] Magnesium determinations had appreciable variation. Therefore, differences between dates of collection, areas, and subareas should probably be discounted.

TABLE 23. Average weight of forest floor material and its constituent elements sampled from ML 1 and ML 2 (1958).

	Weight in pounds per acre						
	Total	N	P	K	Na	Ca	Mg[1]
ML 1A	14,820	117.1	22.2	13.3	14.8	133.3	16.3
1B	12,440	150.5	18.6	12.4	17.4	144.3	16.1
1C	17,700	152.2	24.7	14.1	17.7	168.1	31.8
2A	17,230	153.3	19.0	15.5	17.2	163.7	32.7
2B	26,200	217.5	31.4	21.0	28.8	207.0	52.4
2C	12,100	130.7	15.7	10.9	14.5	140.4	19.4
ML 1	14,987	139.9	21.8	13.3	16.6	148.6	21.4
ML 2	18,510	167.2	22.0	15.8	20.2	158.4	34.8

[1] Magnesium determinations had appreciable variation. Therefore, differences between subareas and areas should probably be discounted.

TABLE 24. Average available soil moisture in inches on the thinned and control subareas at ML 1 and ML 2 for the date of greatest depletion (1957-1962).

	Thinned Subarea A Depth in Inches				Thinned Subarea B Depth in Inches				Control Subarea C Depth in Inches			
Year	0-10	10-20	20-36	0-36	0-10	10-20	20-36	0-36	0-10	10-20	20-36	0-36
1957-23 Sept.												
ML 1	0.22	0.23	0.73	1.18	0.00	0.31	1.07	1.38	0.27	0.31	0.69	1.27
1957-24 Sept.												
ML 2	0.12	0.12	0.46	0.70	0.22	0.15	0.85	1.22	0.19	0.25	0.82	1.26
1958-8 Sept.												
ML 1	0.28	0.24	0.75	1.27	0.00	0.21	0.83	1.04	0.34	0.33	0.75	1.42
1958-10 Sept.												
ML 2	0.44	0.46	1.09	1.99	0.31	0.15	0.85	1.31	0.01	0.00	0.40	0.41
1959-27 Aug.												
ML 1	0.50	0.33	0.87	1.70	0.08	0.44	1.17	1.69	0.52	0.37	0.89	1.78
1959-27 Aug.												
ML 2	0.28	0.19	0.64	1.11	0.49	0.26	0.93	1.68	0.41	0.32	0.89	1.62
1960-15 Aug.												
ML 1	0.57	0.36	0.88	1.81	0.19	0.45	1.21	1.85	0.62	0.49	0.88	1.99
1960-15 Aug.												
ML 2	0.31	0.21	0.69	1.21	0.28	0.27	0.91	1.46	0.45	0.40	0.96	1.81
1961												
ML 1	--	--	--	--	--	--	--	--	--	--	--	--
1961-25 Aug.												
ML 2	0.30	0.20	0.66	1.16	0.46	0.26	0.85	1.57	0.39	0.37	0.91	1.67
1962												
ML 1	--	--	--	--	--	--	--	--	--	--	--	--
1962-7 Sept.												
ML 2	0.43	0.27	0.77	1.47	0.54	0.31	0.89	1.74	0.51	0.43	0.98	1.92

TABLE 25. Analysis of variance. Average available soil moisture in inches on the thinned and unthinned subareas for 45-year-old and 30-year-old Douglas-fir at ML 1 and ML 2 (1957-1960).

Source of variation	Sum of Squares	df	MS	"F"	Sig.
Area	0.0561	1	0.0561	2.42	NS
Depth	0.7203	2	0.3602	15.59	***
Thin. Treatment	0.1176	2	0.0588	2.55	NS
Area by Depth	0.0415	2	0.0208	<1	NS
Area by Treatment	0.0753	2	0.0376	1.63	NS
Depth by Treatment	0.0780	4	0.0195	<1	NS
Area by Depth by Treatment	0.1987	4	0.0497	2.12	NS
Error	1.2451	54	0.0231		

*** Significant at the 0.001 level.

TABLE 26. Analysis of variance. Average soil-moisture tension at the date of greatest soil-moisture depletion for thinned and unthinned Douglas-fir trees at ML 2 (30-year-old) and HESPA (20-year-old) (1961-1962).

Source of variation	Sum of Squares	df	MS	F	Sig.
Area	30.15	1	30.15	6.51	*
Depth	13.00	2	6.50	1.40	NS
Thin. Treatment	3.92	1	3.92	<1	NS
Area by Depth	4.52	2	2.26	<1	NS
Area by Treatment	13.65	1	13.65	2.95	NS
Depth by Treatment	3.60	2	1.80	<1	NS
Area by Depth by Treatment	3.36	2	1.68	<1	NS
Error	55.60	12	4.63		

* Significant at the 0.05 level.

TABLE 27. Average soil temperature[1] in °F over the growing season for the thinned and control subareas at ML 1, ML 2, and HESPA (1957-1962).

	Thinned Subarea A			Thinned or Subarea B			Unthinned or Subarea C		
	depth in inches			depth in inches			depth in inches		
	5	15	28	5	15	28	5	15	28
1957									
ML 1	54.2	52.4	50.2	52.5	51.6	49.8	48.8	49.8	48.8
ML 2	52.3	51.3	49.3	53.8	52.8	51.0	51.8	51.4	48.9
1958									
ML 1	56.0	53.9	51.6	54.5	53.1	51.7	52.8	51.6	50.4
ML 2	54.2	53.6	51.8	55.4	54.4	52.6	53.5	53.6	50.9
1959									
ML 1	51.2	50.6	49.2	50.4	50.1	49.1	49.1	48.7	48.2
ML 2	50.0	50.2	50.2	51.5	51.2	50.0	50.2	50.2	48.9
1960									
ML 1	51.8	51.3	49.4	50.4	50.3	49.0	49.1	48.9	48.4
ML 2	50.0	50.6	49.2	51.4	51.0	48.4	50.0	50.0	48.4
1961									
HESPA	---	---	---	51.1	50.7	48.3	48.0	46.5	45.7
ML 2	52.9	52.5	50.5	53.2	52.4	50.8	52.5	52.3	49.8
1962									
HESPA	---	---	---	49.3	49.1	47.4	46.6	46.4	45.1
ML 2	51.5	51.8	50.8	52.3	51.5	49.9	51.5	51.8	49.0

[1] Based on 13 readings spaced between late April and early to mid-October.

TABLE 28. Analysis of variance. Average soil temperature[1] in degrees Fahrenheit over the growing season for thinned and unthinned Douglas-fir stands, ML 1 (45-year-old) and ML 2 (30-year-old) at three depths (1957-1960).

Source of variation	Sum of Squares	df	MS	"F"	Sig.
Area	3.51	1	3.51	6.05	*
Depth	57.04	2	28.52	49.17	***
Thin. Treatment	38.06	2	19.03	32.81	***
Area by Depth	1.58	2	0.76	1.31	NS
Area by Treatment	2.87	2	1.44	2.48	NS
Depth by Treatment	2.35	4	0.59	1.02	NS
Area by Depth by Treatment	2.65	4	0.66	1.14	NS
Error	31.52	54	0.58		

[1] Based on 13 measurements spaced between late April to mid-October.

* Significant at the 0.05 level.

*** Significant at the 0.001 level.

TABLE 29. Analysis of variance. Average soil temperature[1] in degrees Fahrenheit over the growing season for thinned and unthinned Douglas-fir stands, ML 2B, ML 2C (30-year-old) and HESPA (20-year-old) at three depths (1961-1962).

Source of variation	Sum of Squares	df	MS	"F"	Sig.
Area	150.87	1	150.87	127.25	***
Depth	36.22	2	18.11	15.09	***
Thin. Treatment	47.00	1	47.00	39.17	***
Area by Depth	16.93	2	8.46	7.05	*
Area by Treatment	0.67	1	<1	<1	NS
Depth by Treatment	0.05	2	<1	<1	NS
Area by Depth by Treatment	1.57	2	<1	<1	NS
Error	43.14	36	1.20		

* Significant at the 0.05 level.
*** Significant at the 0.001 level.

[1] Based on 13 measurements spaced between late April to mid-October.

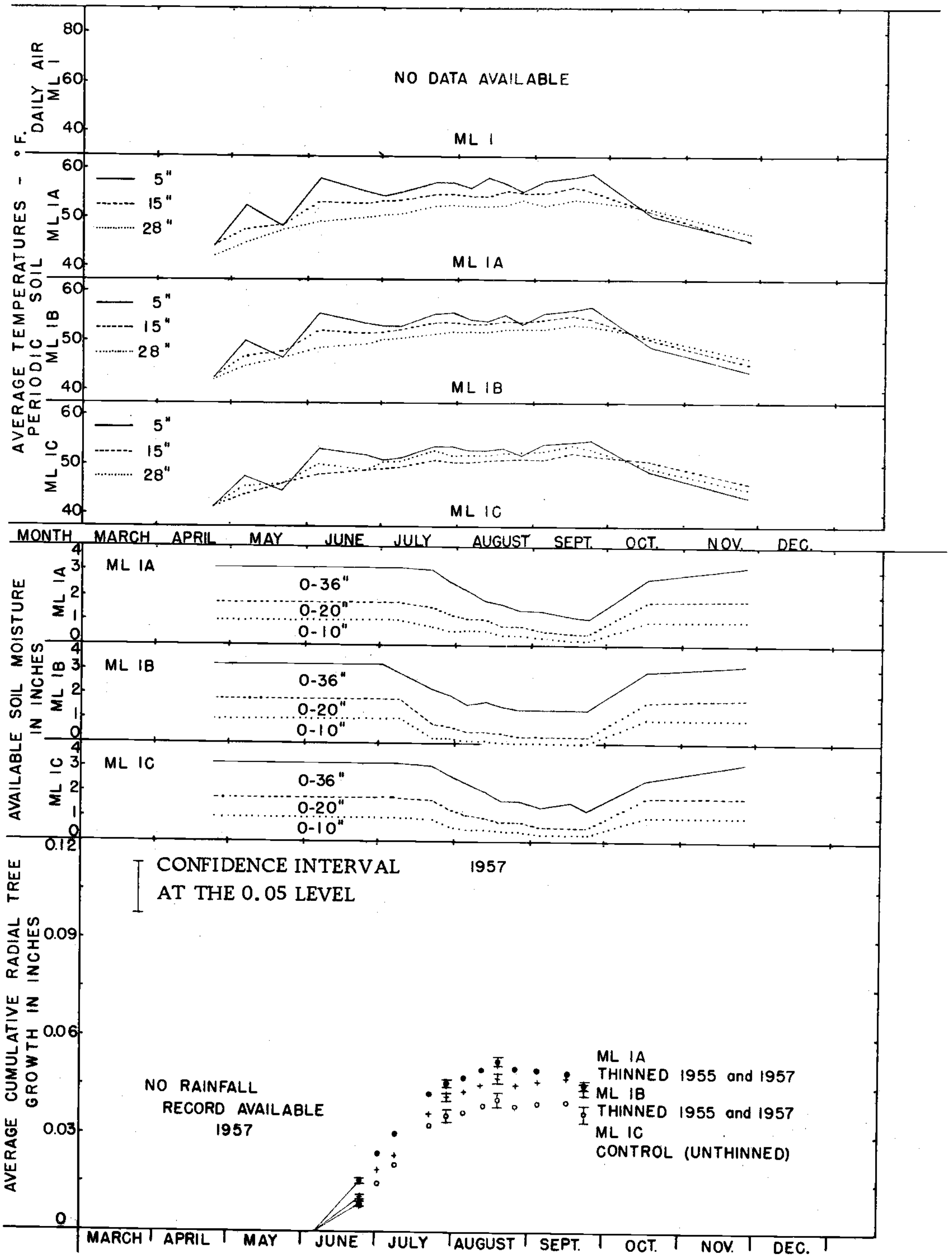

FIGURE 40. Average soil moisture and temperature - average air temperature and periodic rainfall in relation to average cumulative radial growth on 45-year-old Douglas-fir trees for different thinning intensities at ML 1 (1957).

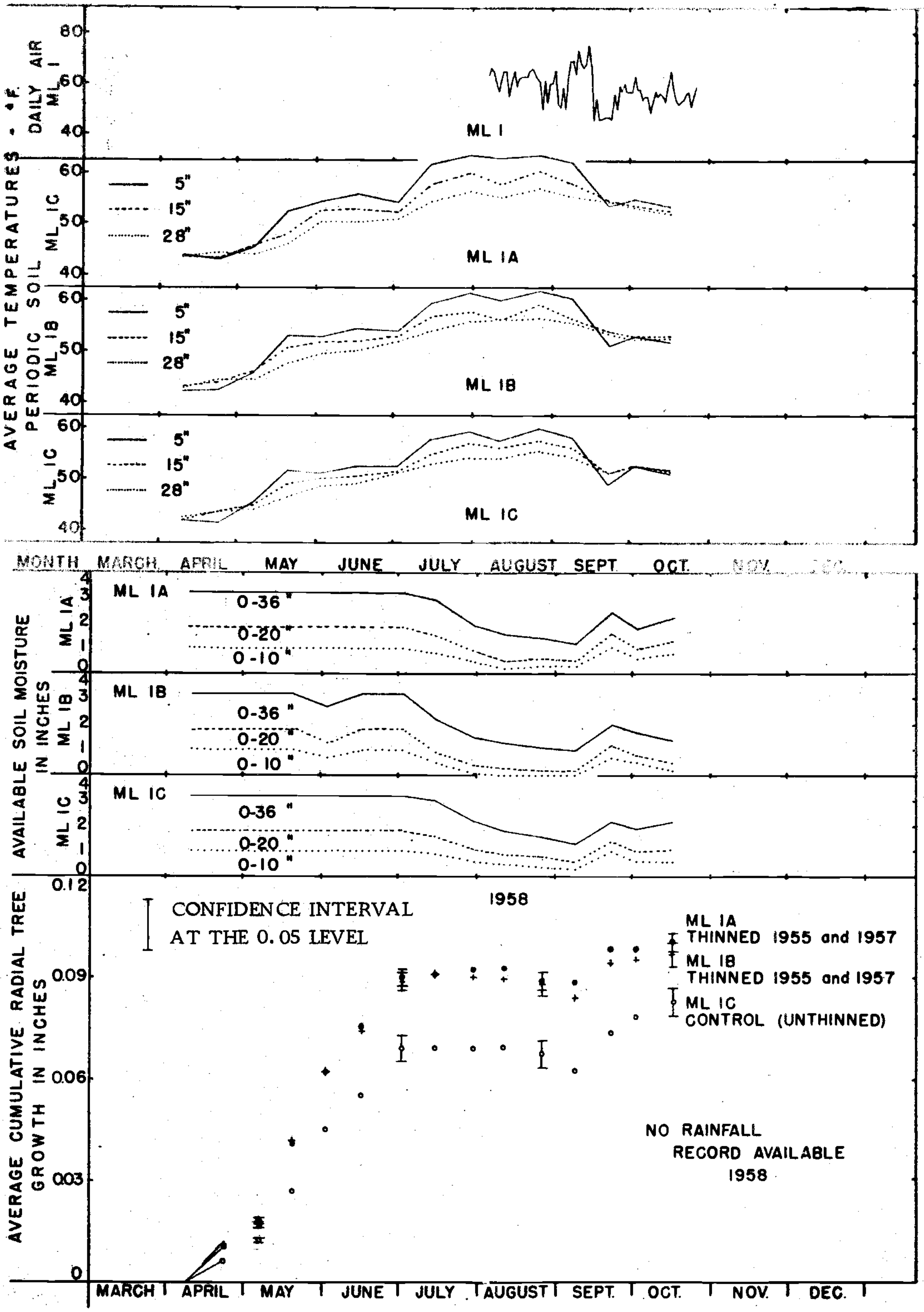

FIGURE 41. Average soil moisture and temperature - average air temperature and periodic rainfall in relation to average cumulative radial growth on 45-year-old Douglas-fir trees for different thinning intensities at ML 1 (1958).

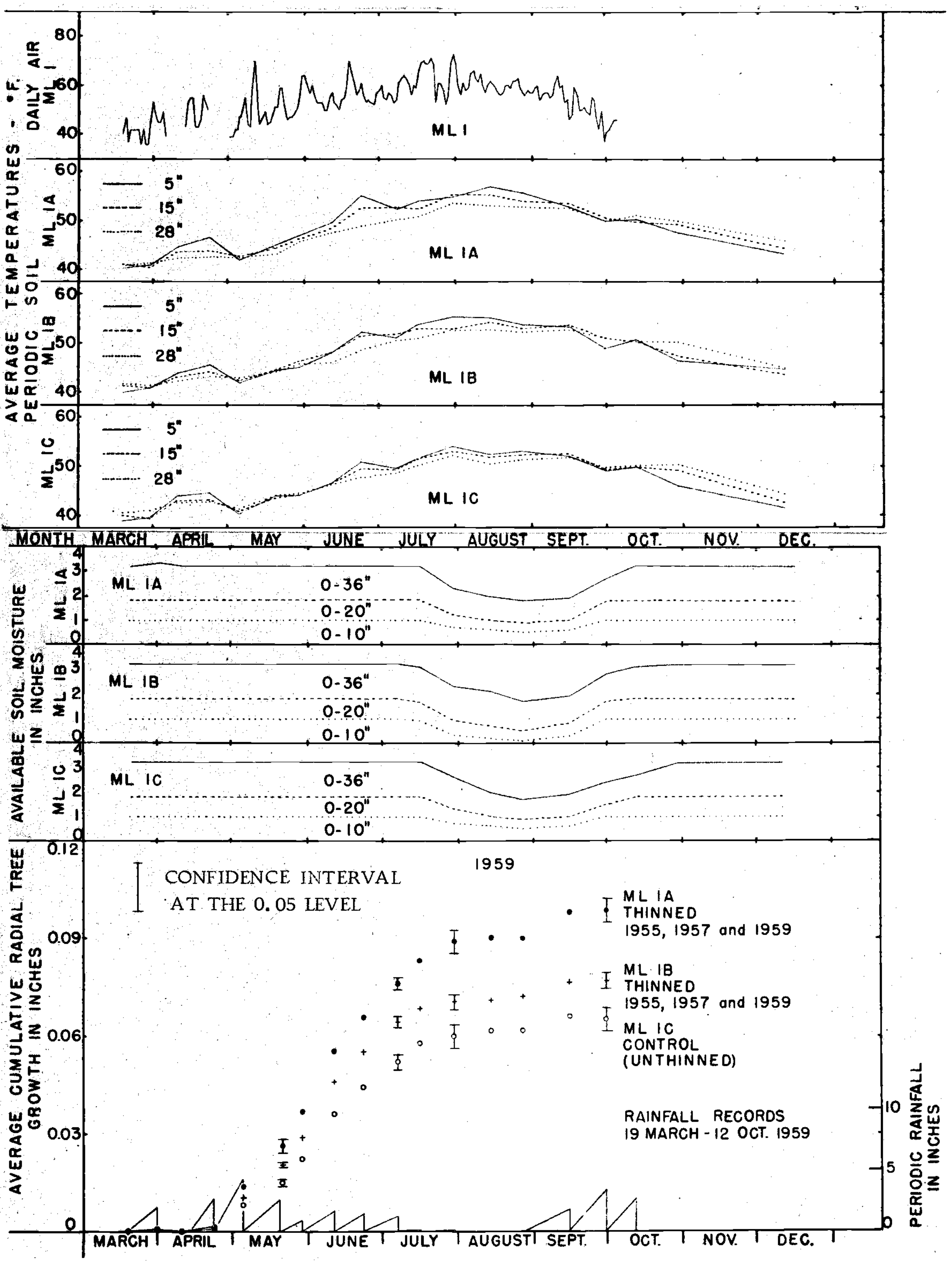

FIGURE 42. Average soil moisture and temperature - average air temperature and periodic rainfall in relation to average cumulative radial growth on 45-year-old Douglas-fir trees for different thinning intensities at ML 1 (1959).

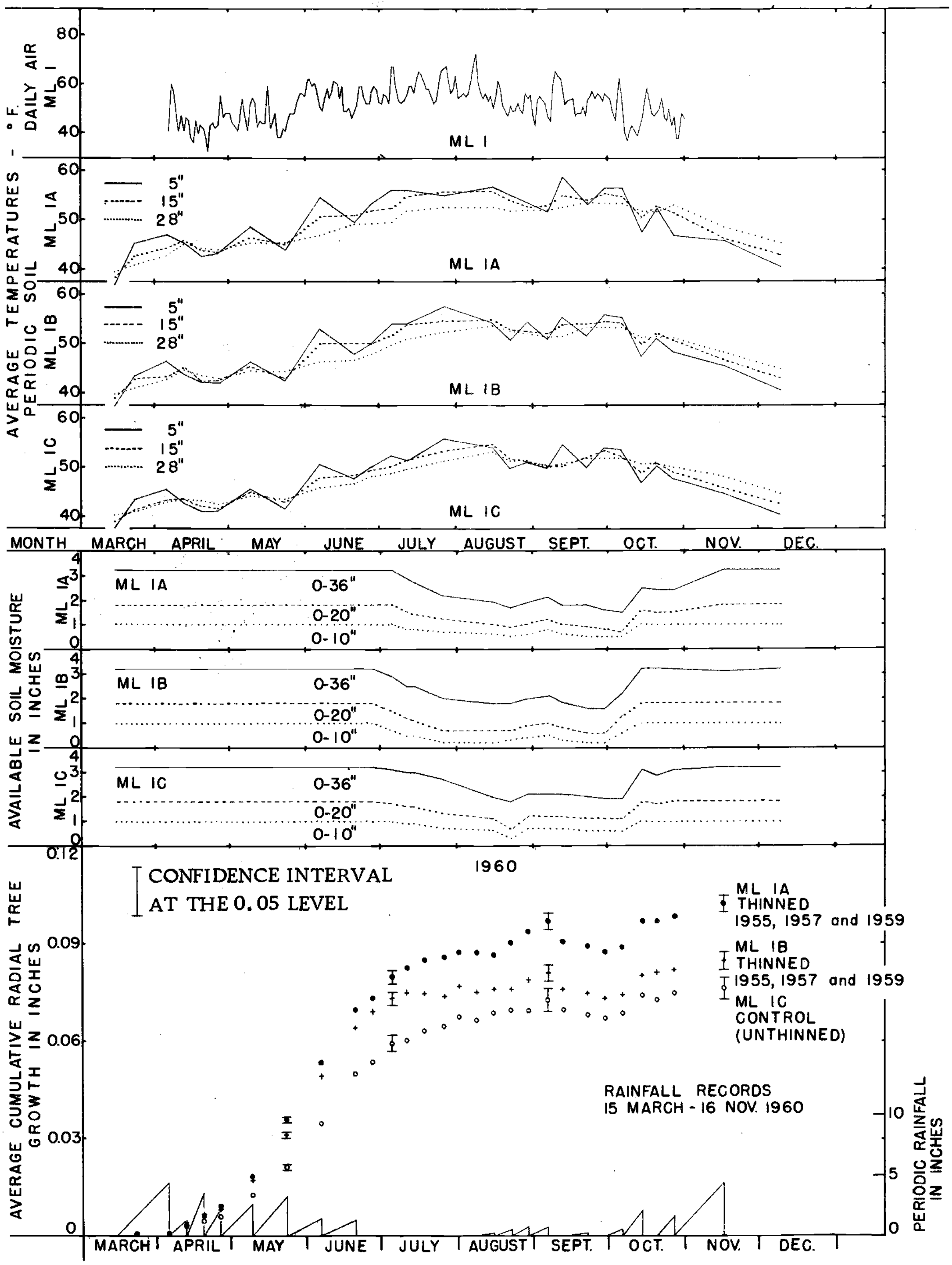

FIGURE 43. Average soil moisture and temperature - average air temperature and periodic rainfall in relation to average cumulative radial growth on 45-year-old Douglas-fir trees for different thinning intensities at ML 1 (1960).

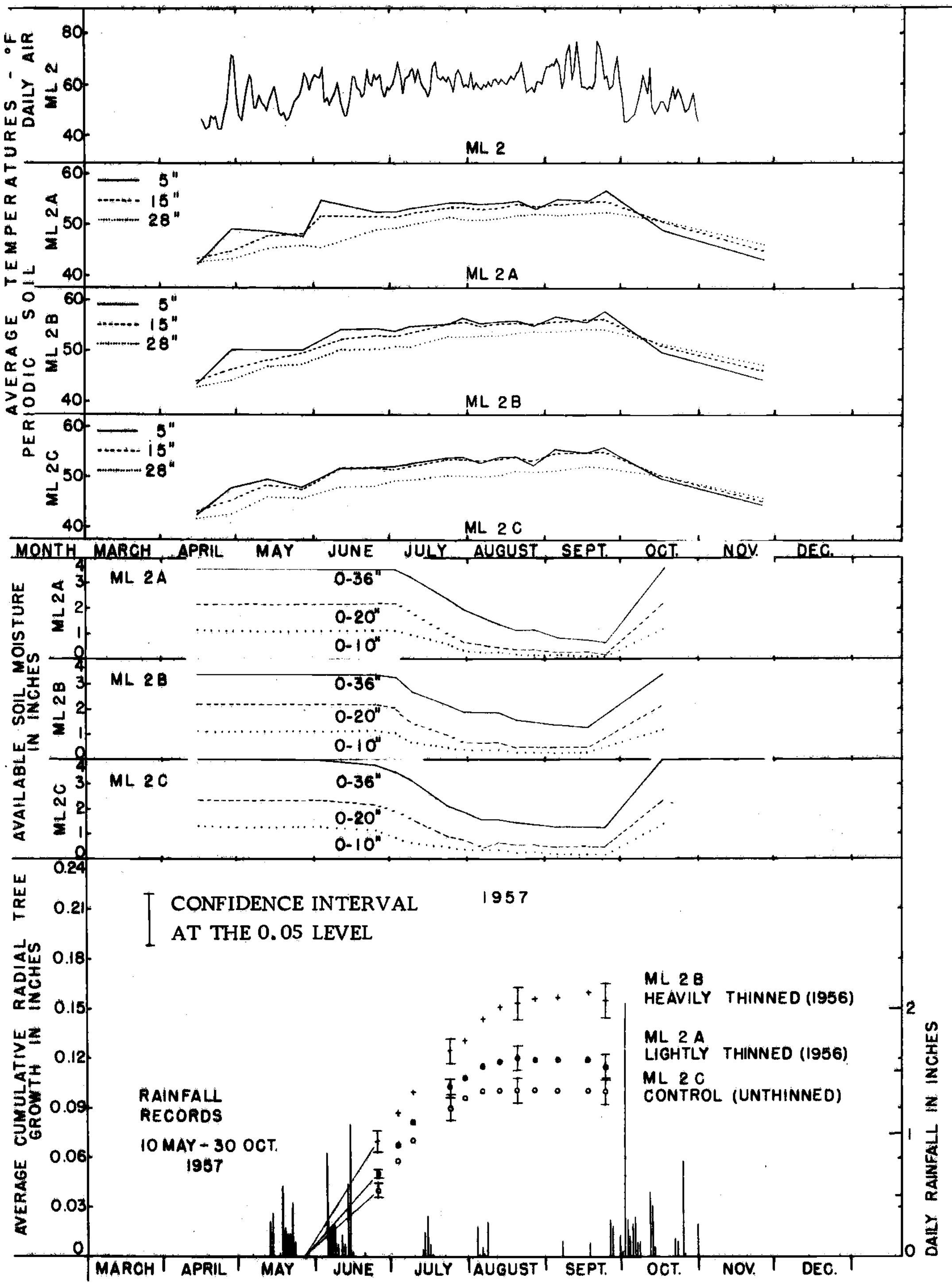

FIGURE 44. Average soil moisture and temperature - average air temperature and periodic rainfall in relation to average cumulative radial growth on 30-year-old Douglas-fir trees for different thinning intensities at ML 2 (1957).

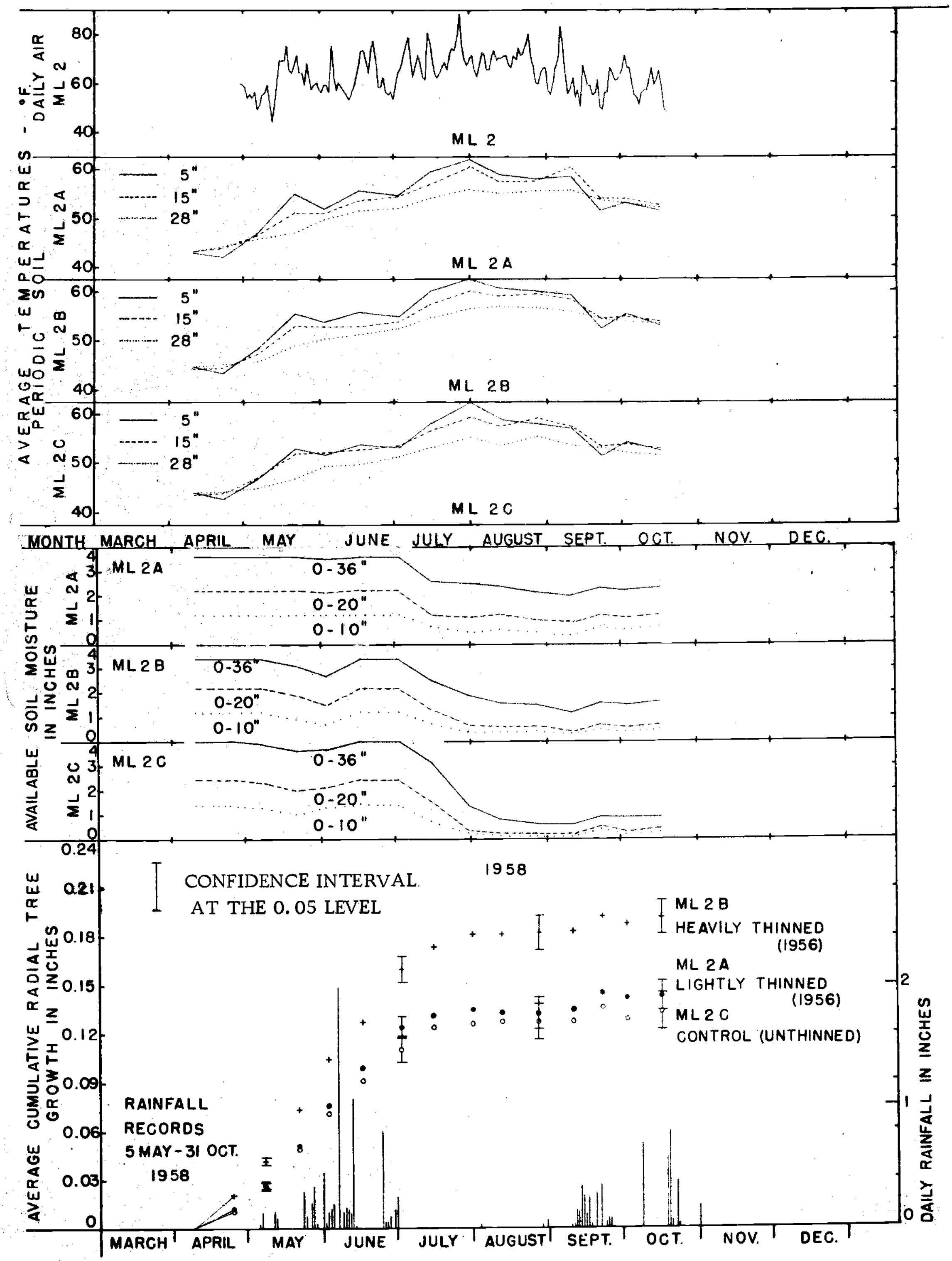

FIGURE 45. Average soil moisture and temperature - average air temperature and periodic rainfall in relation to average cumulative radial growth on 30-year-old Douglas-fir trees for different thinning intensities at ML 2 (1958).

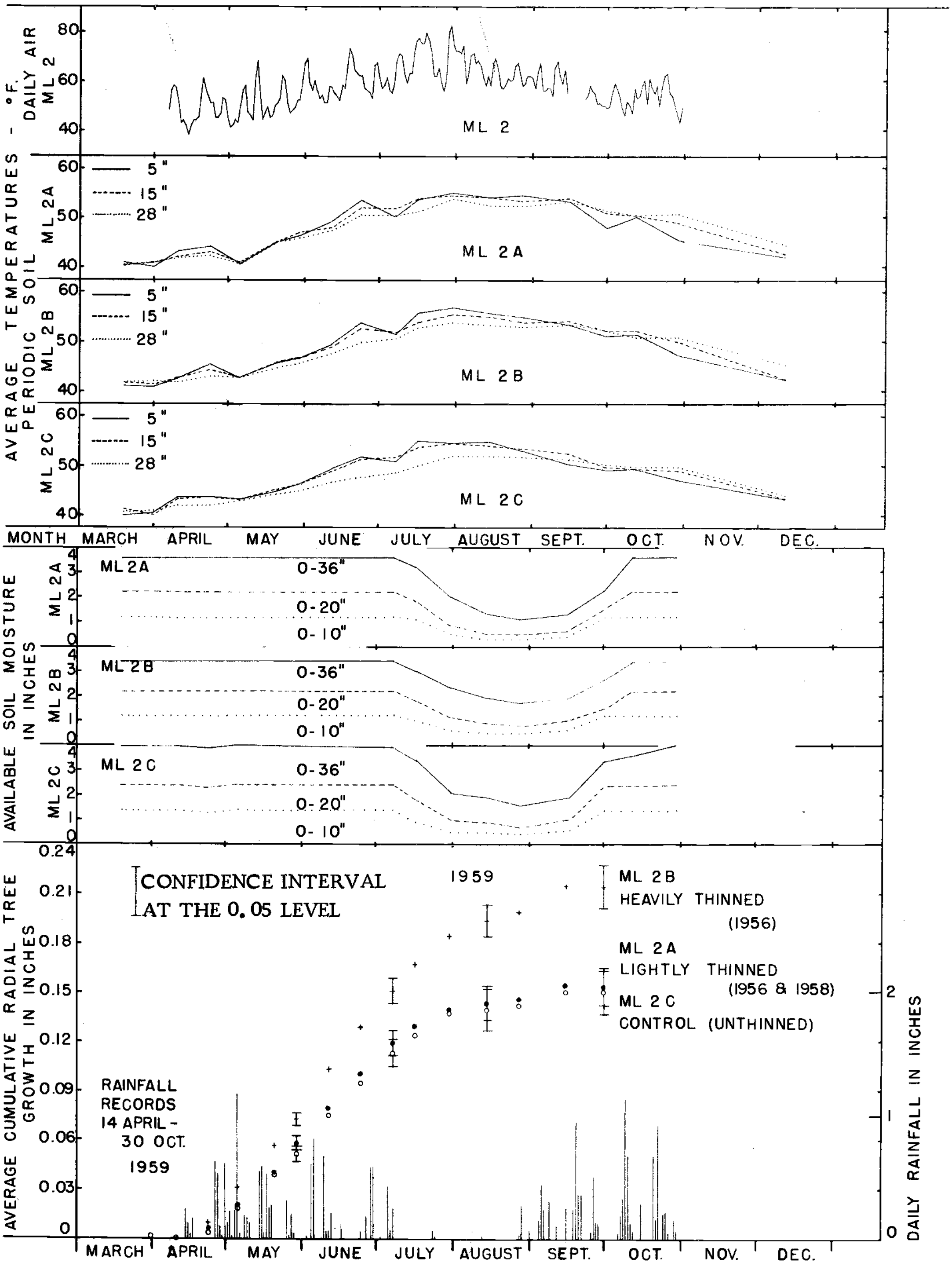

FIGURE 46. Average soil moisture and temperature - average air temperature and periodic rainfall in relation to average cumulative radial growth on 30-year-old Douglas-fir trees at ML 2 for different thinning intensities (1959).

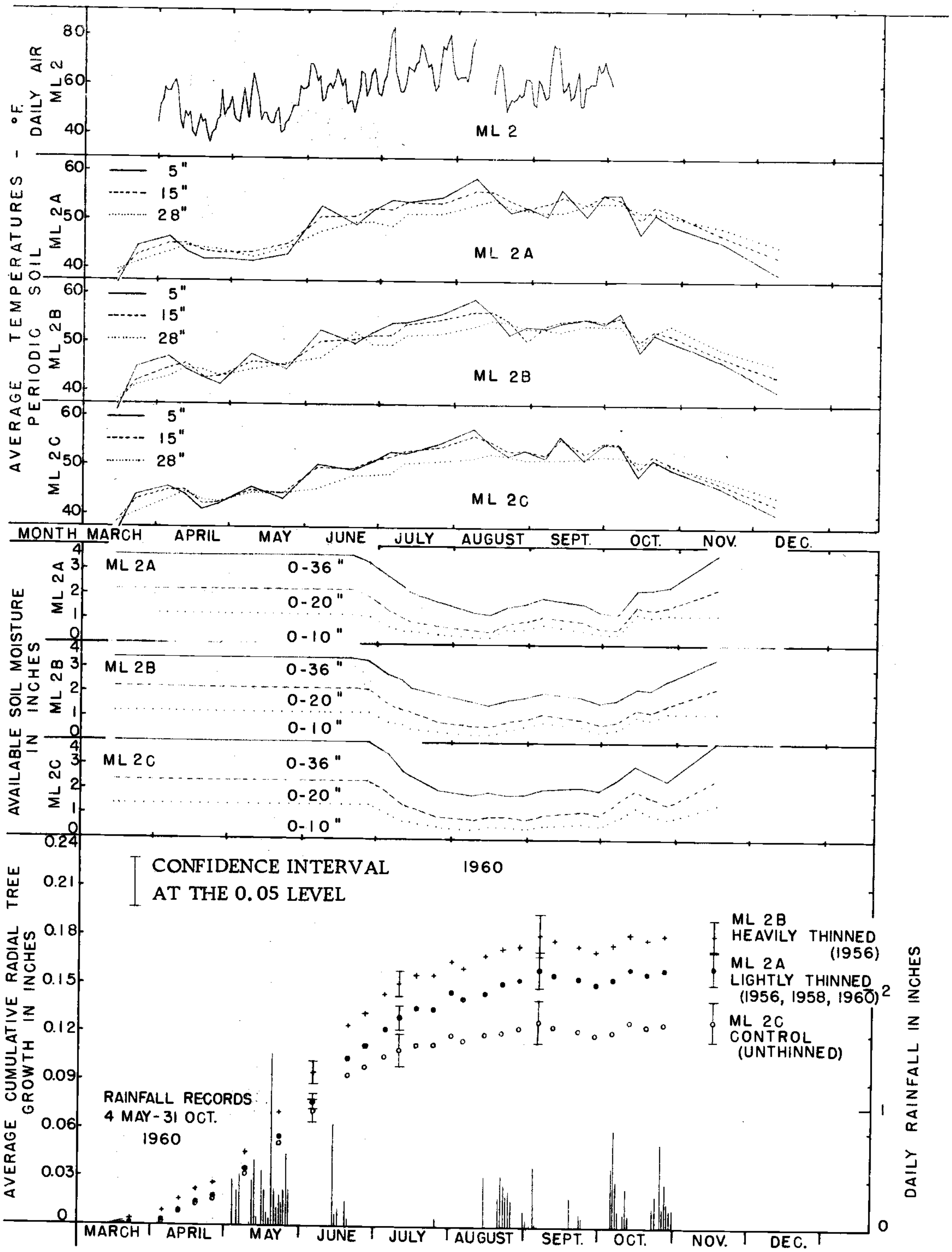

FIGURE 47. Average soil moisture and temperature - average air temperature and periodic rainfall in relation to average cumulative radial growth on 30-year-old Douglas-fir trees at ML 2 for different thinning intensities (1960).

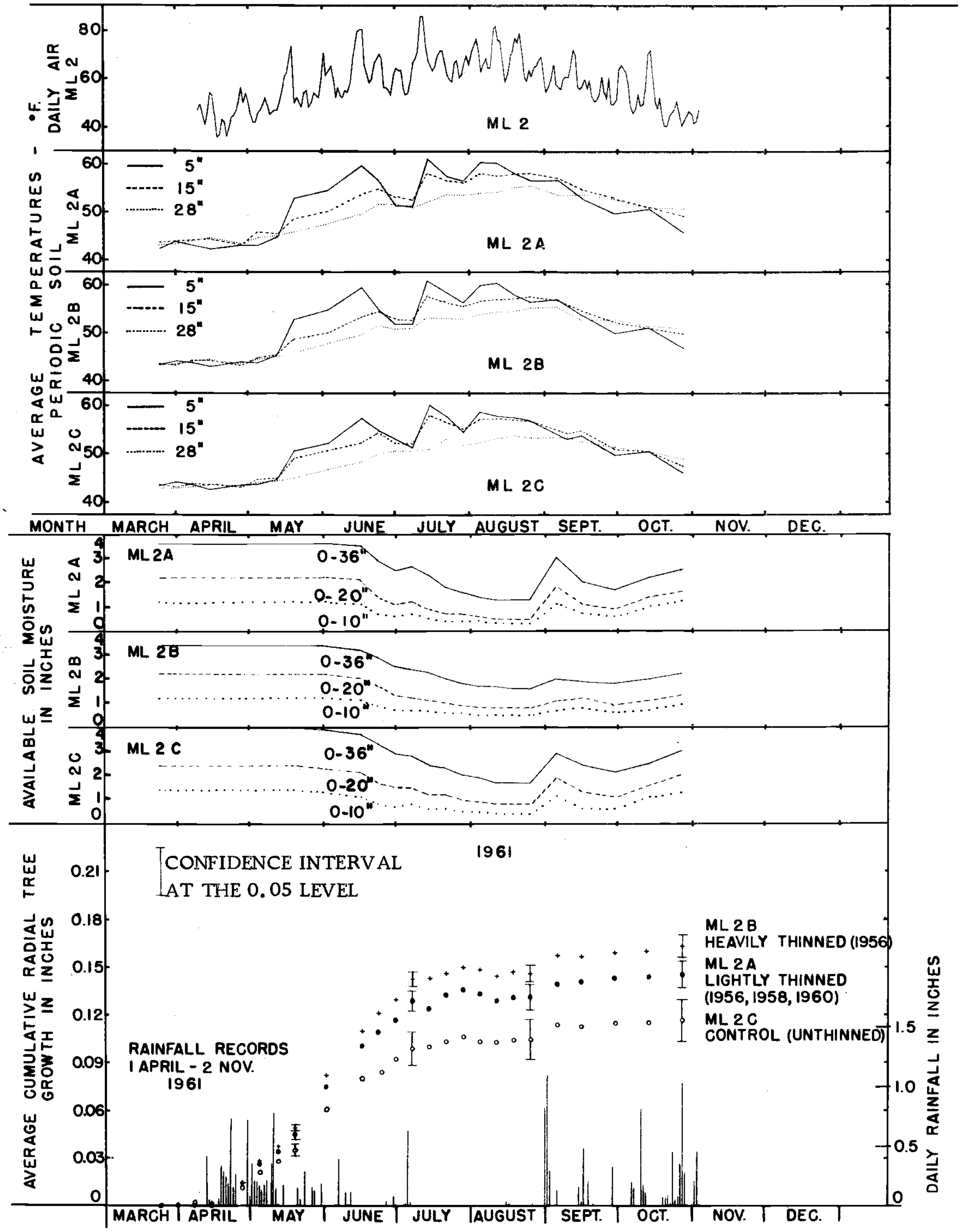

FIGURE 48. Average soil moisture and temperature - average air temperature and periodic rainfall in relation to average cumulative radial growth on 30-year-old Douglas-fir trees at ML 2 for different thinning intensities (1961).

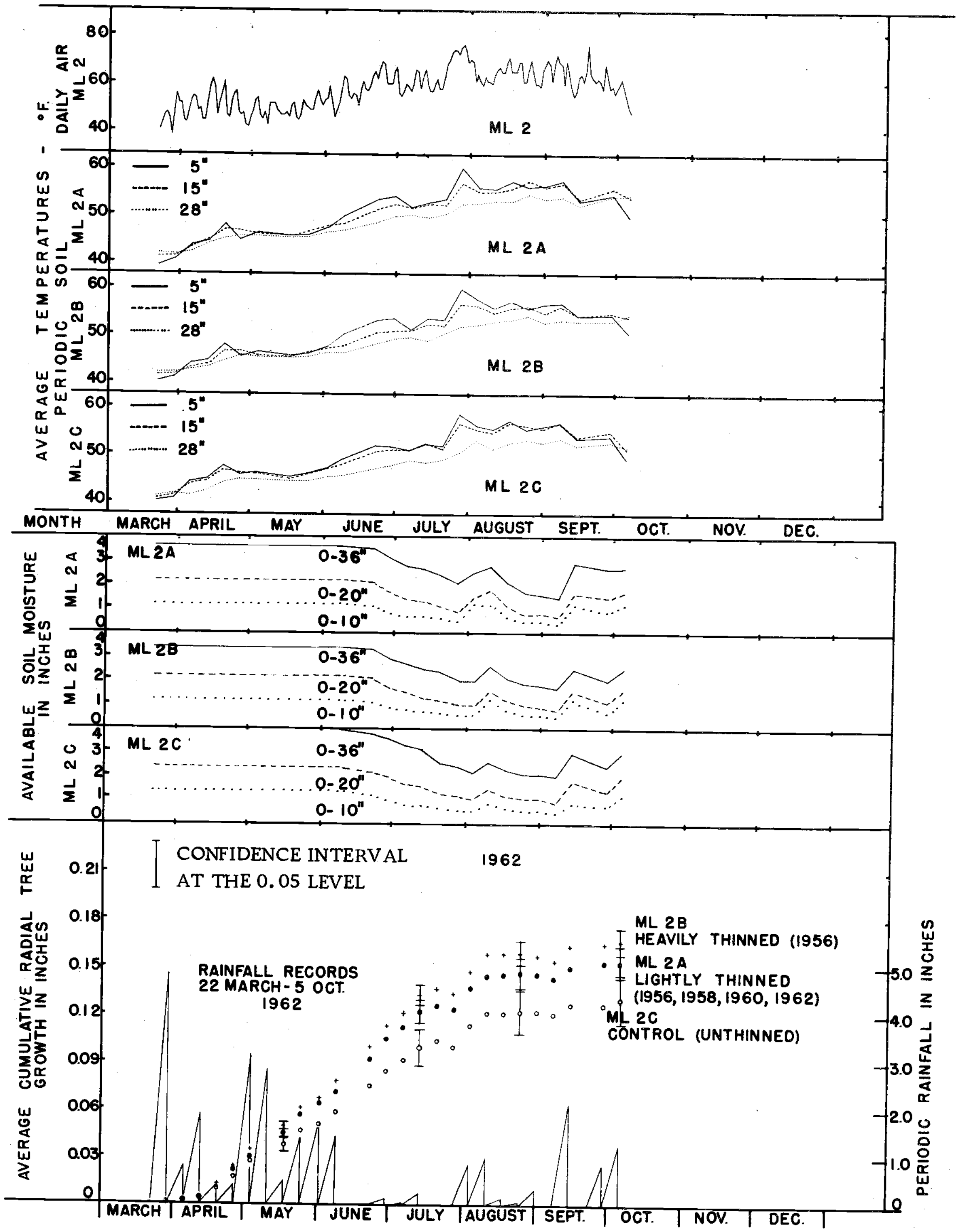

FIGURE 49. Average soil moisture and temperature - average air temperature and periodic rainfall in relation to average cumulative radial growth on 30-year-old Douglas-fir trees at ML 2 foe different thinning intensities (1962).

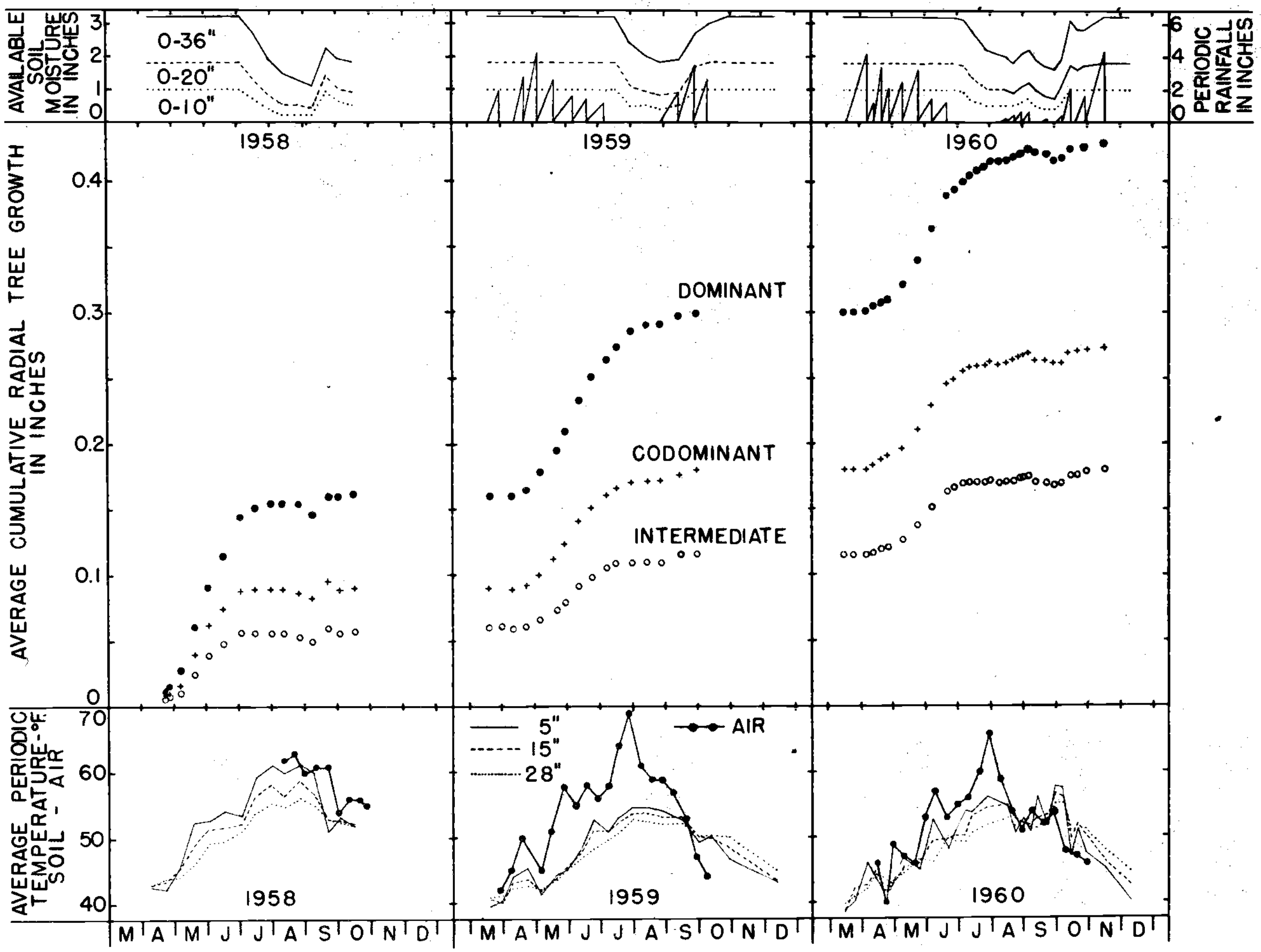

FIGURE 50. Average cumulative radial growth for various crown classes of 45-year-old Douglas-fir at ML 1 (1958-1960). Average soil moisture and temperature - average air temperature and periodic rainfall.

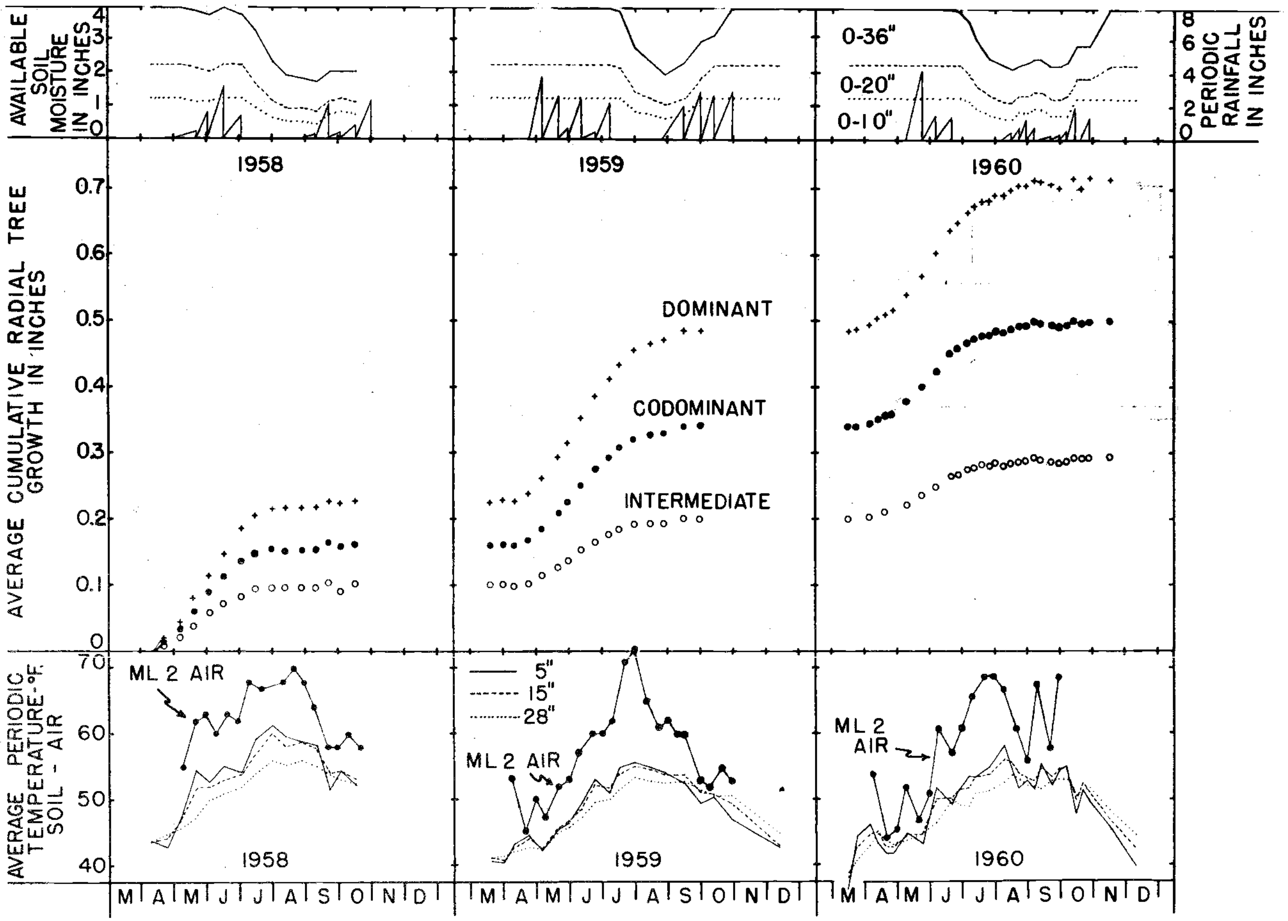

FIGURE 51. Average soil moisture and temperature - average air temperature and periodic rainfall in relation to average cumulative radial growth on 30-year-old Douglas-fir trees at ML 2 for different crown classes (1958-1960).

TABLE 30. Results of pot fertility tests ML 1, ML 2, and HESPA. Top weight in grams per pot (five seedlings per pot).

Treat. No.	Treat.[1] Code N, P_2O_5, S	ML 1 - M. pine Soil horizon			ML 2 - M. pine Soil horizon			HESPA-DF Treat.[2] Code N, P_2O_5	Horizon
		A1	B1	B2	A1	B1	B2		A1
1	111	4.88	2.10	1.12	4.77	1.33	0.95	11	56.66
2	115	6.62	2.59	1.29	5.89	1.71	0.95	13	53.87
3	133	6.67	2.35	1.22	6.29	1.24	1.03	15	56.78
4	151	6.50	2.63	1.22	7.68	1.46	0.94	22	76.66
5	155	8.21	2.93	1.34	7.72	1.67	0.98	24	79.01
6	222	7.52	3.87	3.38	7.70	6.87	4.40	31	59.18
7	224	8.46	5.19	3.44	7.93	6.21	4.46	33	55.42
8	242	9.31	7.53	5.62	10.64	7.99	6.50	35	77.31
9	244	8.66	7.29	4.90	10.91	7.92	6.87	42	71.09
10	313	4.90	3.03	2.41	4.72	2.93	2.03	44	61.23
11	331	4.38	3.10	2.43	6.14	5.73	4.81	51	44.31
12	333	6.37	5.37	4.31	8.81	7.10	4.98	53	70.31
13	335	8.21	5.88	4.51	8.94	6.90	5.47	55	66.05
14	353	10.94	8.60	6.03	12.81	8.97	7.46		
15	422	4.25	3.46	2.47	8.16	4.91	3.45		
16	424	3.95	4.28	2.86	7.92	4.50	2.74		
17	442	7.41	5.26	4.22	9.93	7.13	6.38		
18	444	5.13	5.60	4.28	8.96	7.14	6.21		
19	511	2.55	2.60	1.79	3.66	2.24	2.15		
20	515	3.40	3.24	3.02	6.53	5.18	5.26		
21	533	3.19	2.92	1.90	4.93	2.90	2.41		
22	551	3.73	3.17	2.46	5.63	5.56	4.82		
23	555	5.95	5.16	3.27	6.88	6.16	4.17		

[1]

Levels of fertilizers:	1	2	3	4	5
pounds per acre N, P_2O_5	0	400	800	1600	3200
S	0	100	200	400	800

[2]

Levels of fertilizers:	1	2	3	4	5
pounds per acre, N, P_2O_5	0	100	200	400	800

TABLE 31. Average dry weight per pot of Monterey pine and Douglas-fir seedlings for different levels of nitrogen and phosphorus in a pot fertility comparison.

N	Fertilizer lbs./acre P_2O_5	S	Average top dry wt. Monterey pine gm.	Average top dry wt. Douglas-fir gm.	Ratio MP/DF
0	0	0	4.0	2.6	1.5
0	800	200	4.4	4.7	1.0
800	0	200	26.7	12.2	2.2
800	800	0	34.3	23.9	1.4
800	800	200	35.1	21.0	1.7
800	800	800	31.8	24.1	1.3
800	3200	200	37.5	34.7	1.1
3200	800	200	29.6	10.6	2.8
3200	3200	800	37.9	20.0	1.9

TABLE 32. Analysis of variance. Average dry weights of seedling tops per pot for Monterey pine and Douglas-fir grown on the B1 horizon soil from ML 1 (45-year-old Douglas-fir stand) with selected treatments of N and P fertilizers.

Source of variation	Sum of Squares	df	MS	"F"	Sig.
Replication	0.85	2			
Fertilizer	377.52	8	47.19	5.81	**
Species	148.60	1	148.60	18.30	***
Fertilizer by Species	64.96	8	8.12	6.77	***
Error	40.65	34	1.20		

** Significant at the 0.01 level.

*** Significant at the 0.001 level.

Procedures for Pot Fertility Studies for ML 1 and ML 2 Soil

Soils: Soil of three horizons (A1, B1 and B2) at ML 1 and ML 2 were collected and screened moist through a 1/2-inch mesh screen. The soil was placed still at field-moisture content into seven-inch polyethylene pots each holding the equivalent of two kilograms oven-dry soil.

Seedlings: Monterey pine seed was sowed onto the soil surface and covered by a 1/4-inch layer of quartz sand. A native California seed source was used in the first study series, and it was thinned to five seedlings per pot. The next series, Monterey pine and Douglas-fir comparison, a New Zealand seed source was used and the stands thinned to eight seedlings per pot. The Douglas-fir seed source was at 1000 to 1500 feet elevation in Columbia County, Oregon.

Fertilizers: Nitrogen (NH_4NO_3), phosphorus (H_3PO_4), and sulphur (H_2SO_4) of the desired combination were added to each pot in a half-liter solution. Five levels of each element were selected with a maximum rate of 800 pounds per acre and a geometric progression sequence. Unfortunately, the factor for converting ppm to pounds per acre (1/2) was reversed and the high level extended to 3200 pounds per acre. The actual applied levels are shown as follows:

	1	2	3	4	5
N and P_2O_5	0	400	800	1600	3200 lbs. /A
S	0	100	200	400	800 lbs. /A

Light: Supplementary illumination was provided by a light bank of mixed fluorescent bulbs, standard daylight and deluxe warm white, for a period of 16 hours (0800 to 2400).

Temperature: The temperature was controlled for a 12 hour day at 70°F and a 12 hour night at 60°F. Warm sunny days, however, brought temperatures as high as 85 to 90°F.

Procedure for Pot Fertility Study for HESPA Soil

Seedlings: Seedlings were grown in the greenhouse from seed collected from Rayonier Corporation's Promised Land Seed Production Area, Tree no. 77, and transplanted to five gallon pots.

Fertilizers: Nitrogen (NH_4NO_3) and phosphorus (H_3PO_4) were blended with the soil in the desired combination. Five levels of each element were selected with a geometric progression sequence as follows:

1	2	3	4	5
0	100	200	300	400 lbs. /A

Climatic Regime: Seedlings received natural day and night temperature and day length but a 50 percent shading screen was used during the summer to avoid high temperature damage. Supplementary watering was also carried out in the summer.

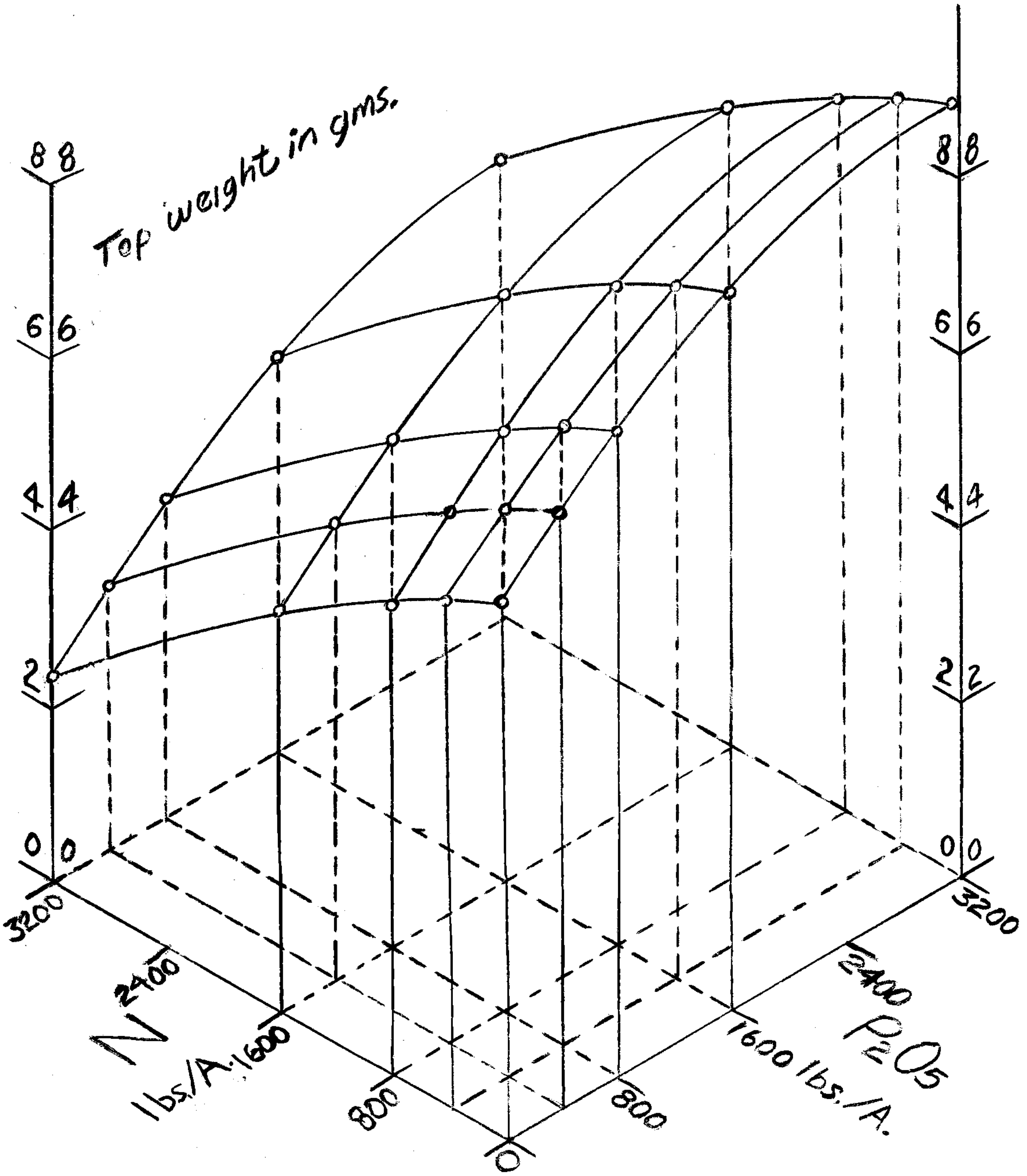

FIGURE 52. Response surface for top weight of Monterey pine seedlings grown in ML 1, A1 horizon soil in pot fertility test involving five levels of N and P_2O_5 fertilizer. S held at 200 pounds per acre level. (1962-1963).

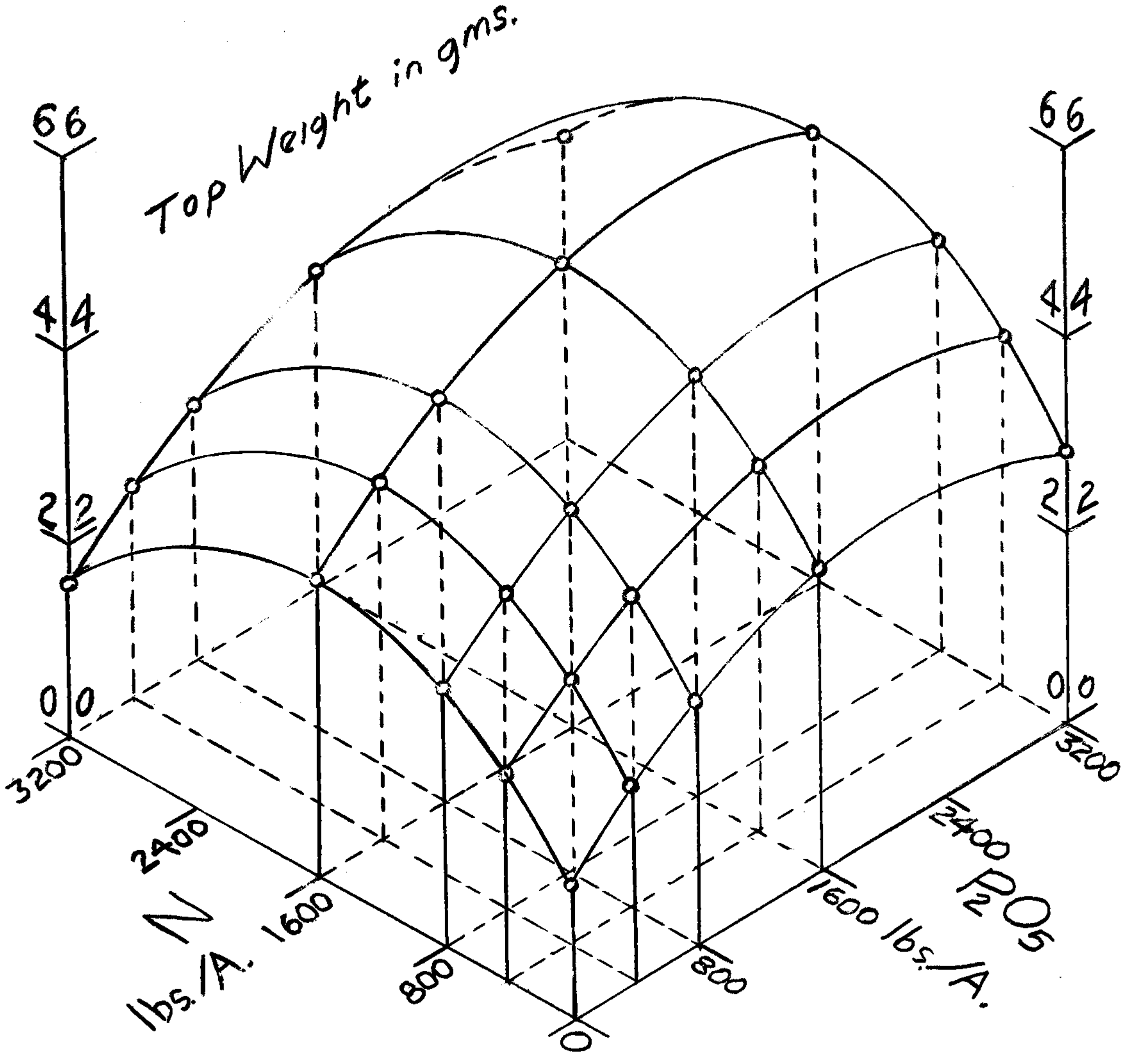

FIGURE 53. Response surface for top weight of Monterey pine seedlings grown in ML 1, B2 horizon soil in pot fertility test involving five levels of N and P_2O_5 fertilizer. S held at 200 pounds per acre level. (1962-1963).

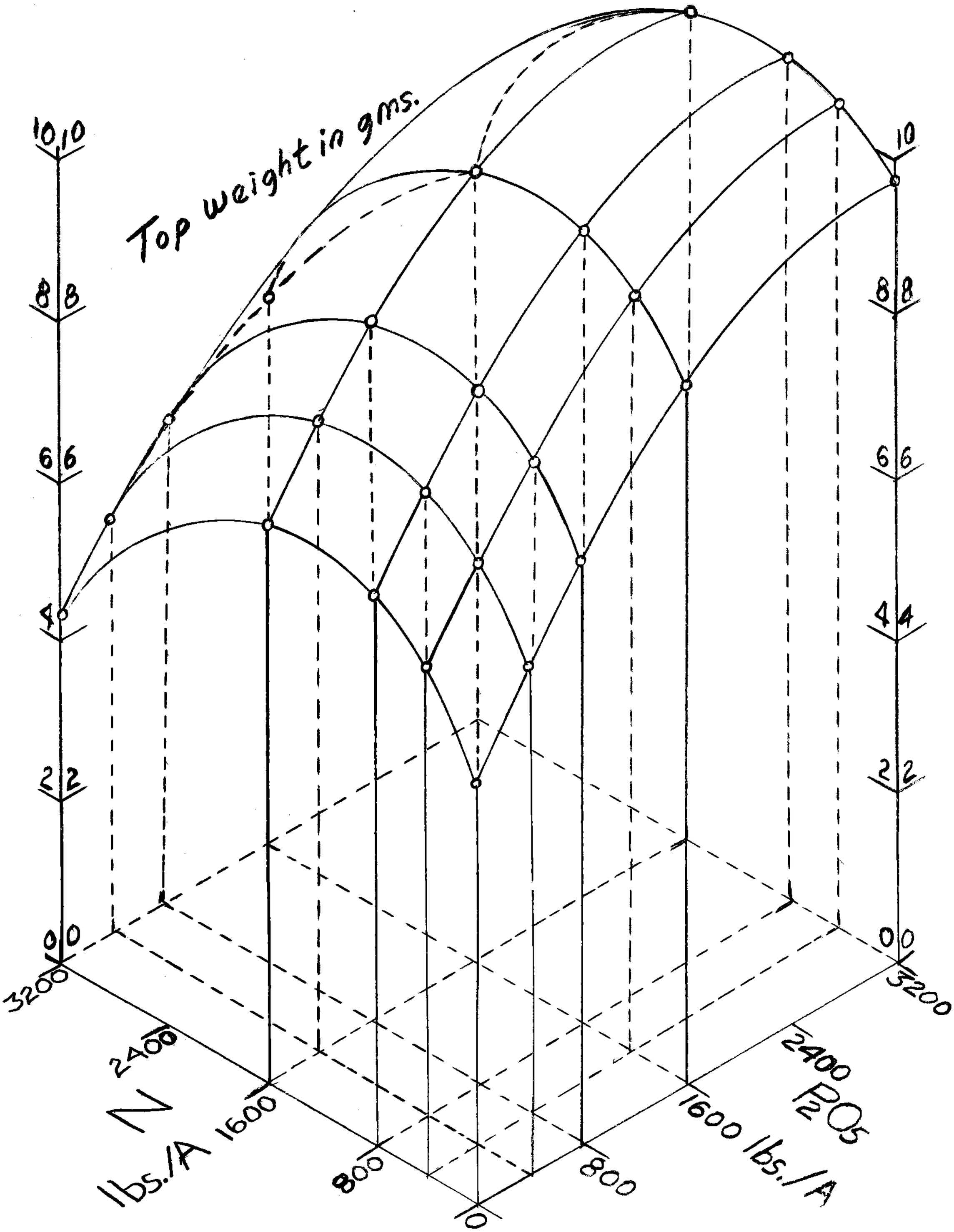

FIGURE 54. Response surface for top weight of Monterey pine seedlings grown in ML 2, A1 horizon soil in pot fertility test involving five levels of N and P_2O_5 fertilizer. S held at 200 pounds per acre level. (1962-1963).

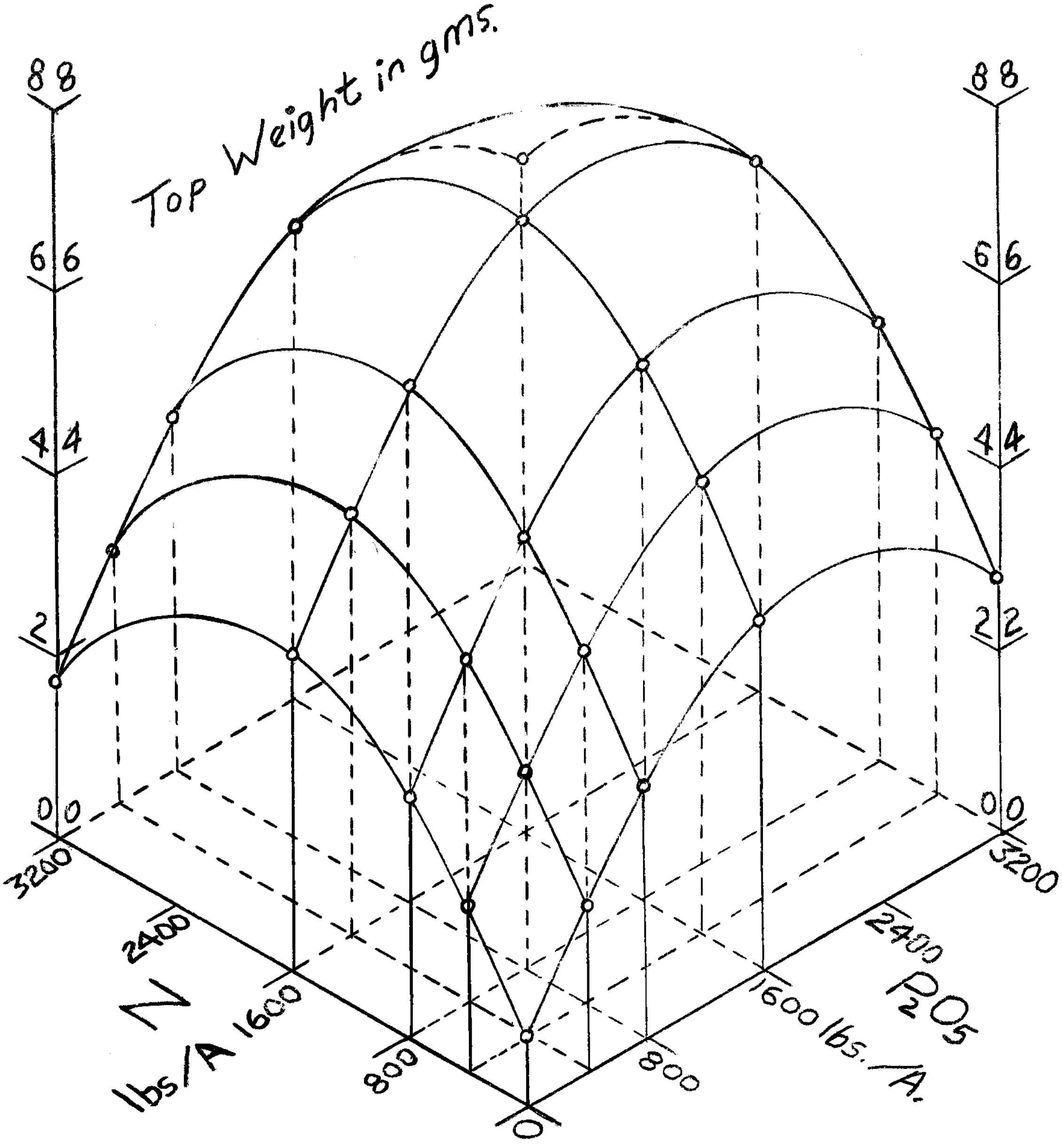

FIGURE 55. Response surface for top weight of Monterey pine seedlings grown in ML 2, B2 horizon soil in pot fertility test involving five levels of N and P_2O_5 fertilizer. S held at 200 pounds per acre level. (1962-1963).

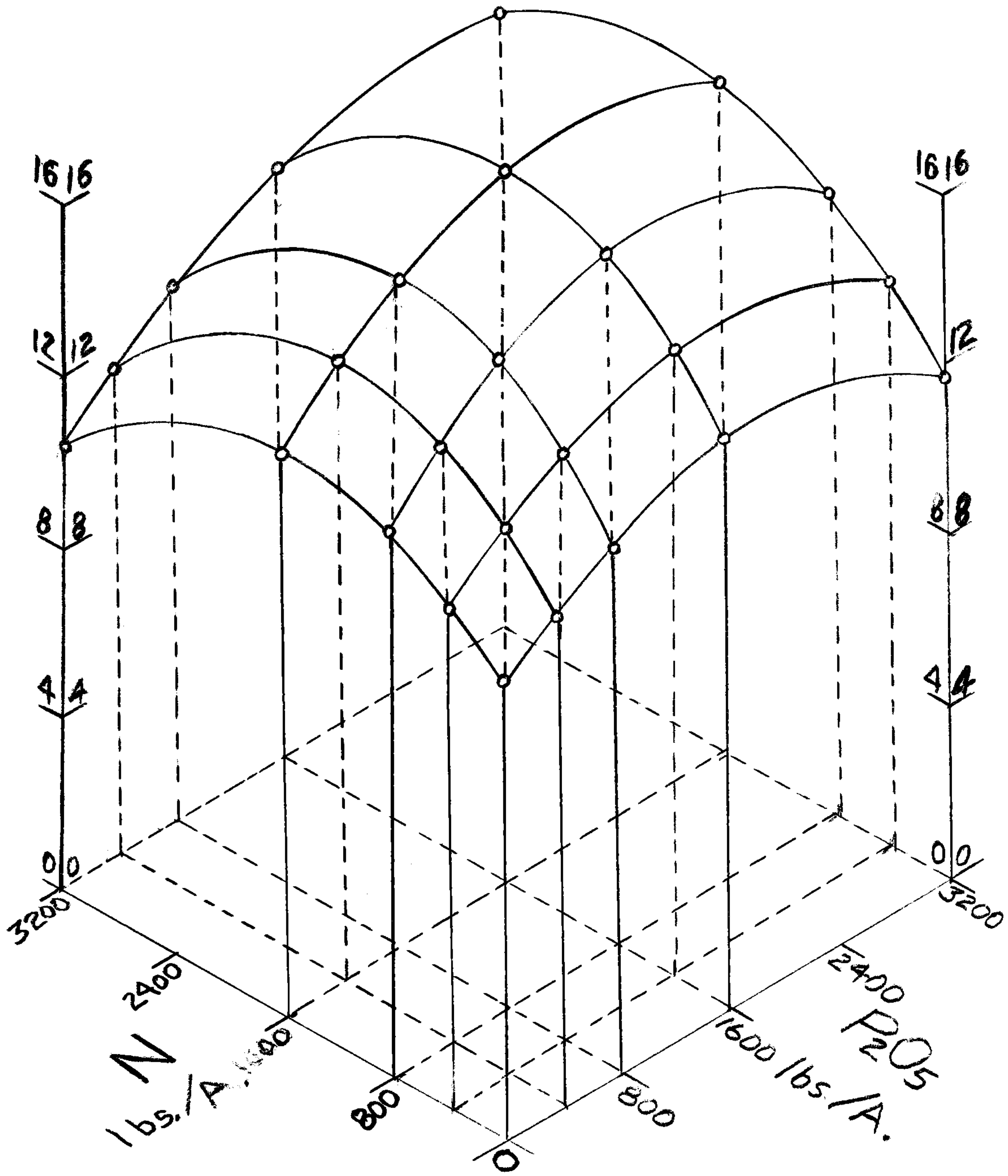

FIGURE 56. Response surface for top weight of Douglas-fir seedlings grown in HESPA, A1 horizon soil in pot fertility test involving five levels of N and P2O5 fertilizer. (1962-1963).