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Tree Growth and Soil Relations at the 1925 Wind River Spacing Test in Coast Douglas-Fir

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Abstract

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The 1925 Wind River spacing test is the earliest field trial seeking to determine the most appropriate spacing for planting Douglas-fir. Spacing treatments were not replicated, although individual spacings were subsampled by two to four tree-measurement plots. Previously, greater growth occurred at the wider spacings (10 and 12 ft) than at the closer spacings (4, 5, 6, and 8 ft). We considered three possible explanations: (1) close spacing eventually retarded growth, (2) soil quality may be better in the 10- and 12-ft spacings than at closer spacings, and (3) tree spacing and soil quality combined affected growth. To test these explanations, we (1) measured and mapped several site factors (topographic relief, depth to bedrock, and soil properties) and (2) related these factors to tree and stand growth. We infer from the strong correlation between spacing and soil variables that the influence of soil and spacing cannot be separated; differences in soil depth and available water capacity confound spacing effects and vice versa. Because soils in the wider spacings are generally deeper and have more available water capacity than do soils in the closer spacings, we conclude that some of the superior tree growth attained in the 10- and 12-ft spacings is due to more favorable soil conditions. Visual comparisons of tree size, however, suggest that spacing is probably the stronger factor affecting tree growth at this location.

Keywords: Douglas-fir, tree spacing, tree size, stand yields, soil depth, available water capacity, site productivity.

Summary

The 1925 Wind River spacing test is the earliest field trial that compares various spacings and their effects on growth and yield of planted Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco). In April 1925, 2-year-old seedlings (1-1) were planted at six square spacings: 4, 5, 6, 8, and 10 ft (each within 2.8-acre blocks), and at 12 ft (within a 0.52-acre block) on a broad flat along the Wind River in southwest Washington near Carson. These seedlings had been grown at the local USDA FS Wind River Nursery from nonlocal, low-elevation seed. Growth trends through plantation age 50 years indicated that greatest cubic-volume yield (total stem) gradually shifted from the 4- to the 10-ft spacing (Reukema 1979) and since age 50, the superior yields at the 10- and 12-ft spacings have increased further.

Spacing treatments are not replicated in the Wind River spacing test. Instead, individual spacings are subsampled on two to four plots. Such subsampling is pseudoreplication. We speculated that some within-spacing variation in growth is due to differences in soil properties, and hence soil differences also could affect among-spacing variation. We investigated these speculations by (1) mapping or measuring some site factors in the test area (topographic relief, depth to bedrock, and soil physical properties) and (2) relating these site factors to tree and stand growth data.

Soils in the study area are developing on pumiceous alluvium over nonfractured basalt bedrock. Soil horizons are weakly developed. We described soil characteristics in 37 pits and collected samples to confirm soil textures. Using a computer program to integrate a contour map and depth-to-bedrock measurements (from excavation, boring, or seismic procedures), we estimated for each tree-measurement plot (1) average depth to the underlying bedrock and (2) average available water-holding capacity based on soil

characteristics. Within and near measurement plots, depth to bedrock varied between 1 and 14 ft. Depth to bedrock exceeded 10 ft in six of the 37 pits. In some pits, bedrock was covered by 1 to 2 in of gravel. In others, the nonfractured bedrock was covered directly by finer alluvial material that ranged in particle size from clay to popcorn-size pumice. Cobbles were infrequent except near a dry stream channel. Deep deposits of rounded gravel and cobbles in and near the former stream channel often prevented accurate determination of bedrock depth. The surface of the underlying, nonweathered basalt is not smooth, and can have at least 5 ft of difference in elevation within 40 ft of horizontal distance. Variation in soil depth affects volume available for rooting. We usually found roots near the bedrock, indicating the importance of soil depth to tree growth. Besides differing in depth, soil profiles and horizons also differed in particle size (from clay to popcorn-size pumice, to gravel- and cobble-sized andesite and basalt). Volume available for rooting is further reduced by volume of these hard gravels and cobbles. Differences in water-holding capacity of these stream deposits and the soils developing from them influence tree growth. Clay content generally increased with soil depth, and in some profiles, clay was 30 to 40 percent by weight of the <0.008-in (<2-mm) fraction near either the underlying basalt or a thin layer of gravel that occasionally covered it. Even in the dry, late summer (1992), the thick, clay-rich layer above bedrock at one pit (13 E in the 10-ft spacing) was wet and rooted by Douglas-fir. We infer that water accumulating locally atop the bedrock may further explain superior growth in some plots.

Tree growth differed among spacings. Lowest site index at age 68 was associated with 4- and 5-ft spacings; greatest site index was associated with wider spacings, especially the 10- and 12-ft spacings. Despite greater cumulative losses of trees, close spacings retained more live trees per acre than wider spacings. These trees were smaller, and stand volumes were less both in total cubic feet and especially in cubic volume to a 6-in top. In the last three decades, live stand volume in the 10-ft spacing averaged about 10 to 15 percent more than in the 12-ft spacing.

We considered three possible explanations for differences in tree growth among the spacings: (1) more intense between-tree competition and winter damage eventually retarded growth in the closer spacings, (2) there was better soil quality in the 10- and 12-ft spacings than in closer spacings, and (3) both wider spacing and better soil quality led to exceptionally good growth in the 10- and 12-ft spacings. The strong correlation between spacing and soil variables, however, suggests that the influence of the two variables cannot be separated; soil differences confound spacing effects and vice versa. We suspect that spacing of the planted seedlings (both initial and replacement) is probably the stronger factor affecting tree growth in this study area. This opinion is supported by visual comparisons of tree size where no or minimal differences in soil quality are likely. For example, near the east-west boundary, trees are larger on the 10-ft-spacing side than in the adjacent 4-ft spacing. Secondly, the outermost trees planted at the close spacings are near open conditions outside the plantation and are much larger than their planted counterparts to the interior of the same planting. Because soils in the wider spacings are generally deeper and have more available water capacity than do soils in the closer spacings, we conclude that a gradient of soil quality exists in the study area, and that more favorable soil conditions partially explain the greater tree growth attained in the 10- and 12-ft spacings.

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Introduction

The Wind River spacing test is the earliest field trial to compare the effects of initial spacings on growth and yield of planted Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco). Established in 1925 by the USDA Forest Service (Pacific Northwest Forest and Range Experiment Station) on a broad flat along the Wind River in southwest Washington near Carson, the trial includes square spacings of 4, 5, 6, 8, 10, and 12 ft (fig. 1). Growth trends through plantation age 50 years indicated that greatest cubic-volume yield (total stem) per acre gradually shifted from the 4- to the 10-ft spacing (Reukema 1979). Since age 50, the superior yields at the 10- and 12-ft spacing have increased further.

Conclusions from field trials are valid when no significant differences in soil quality exist within the study area or when randomly allocated replications of each treatment ensure that all treatments equally sample soil variation. If significant differences in soil or site quality exist, then some adjustment of basic growth and yield data is necessary to estimate the true effect of spacing or other treatments. Such covariance adjustment of observed treatment means is feasible only if individual treatments are replicated. In the Wind River test, treatments are not replicated. Instead, individual spacings are subsampled by two to four plots; such subsampling is pseudoreplication.

Past Comparisons Within and Among Spacings at Wind River

Field observations in 1961 and laboratory analyses of soils from one soil pit in each of four spacings suggested unusually uniform site conditions.[1] Soil uniformity could not be confirmed by a later USDA report for Skamania County (Haagen 1990) because the soil survey did not include this study area. Moreover, it is unlikely that such conventional mapping would have been sufficiently detailed to provide reliable evidence of soil uniformity in the test area.

Growth comparisons among plots that subsample individual spacings provided a measure of site uniformity within the Wind River spacing test. Differences in mean height of dominant and codominant trees or in volume growth within individual spacings would support the assumption that differences in site quality also might exist among spacings and, therefore, that nonuniformity of a site could constrain interpretations about spacing effects. Reukema (1979) reported that height growth trends in the 8-ft spacing during the first 17 years indicated a generally lower site quality in this spacing; also that plot 17 had been added close to the south boundary (where growth was better) to replace original plot 12. Analysis of 1967 data showed that height-diameter curves differed significantly within and between spacings (Curtis and Reukema 1970).

Study Objectives

We speculated that some within-spacing variation in growth is due to differences in soil properties, which also could account for among-spacing growth variation. We tested these speculations by (1) measuring and mapping some site factors in the experimental area (topographic relief, depth to bedrock, and soil physical properties) and (2) relating tree and stand growth to these site factors.

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[1] Steinbrenner, G. 1963. Personal communication. Soil scientist, Weyerhaeuser Company, 505 North Pearl, Centralia, WA 98531.

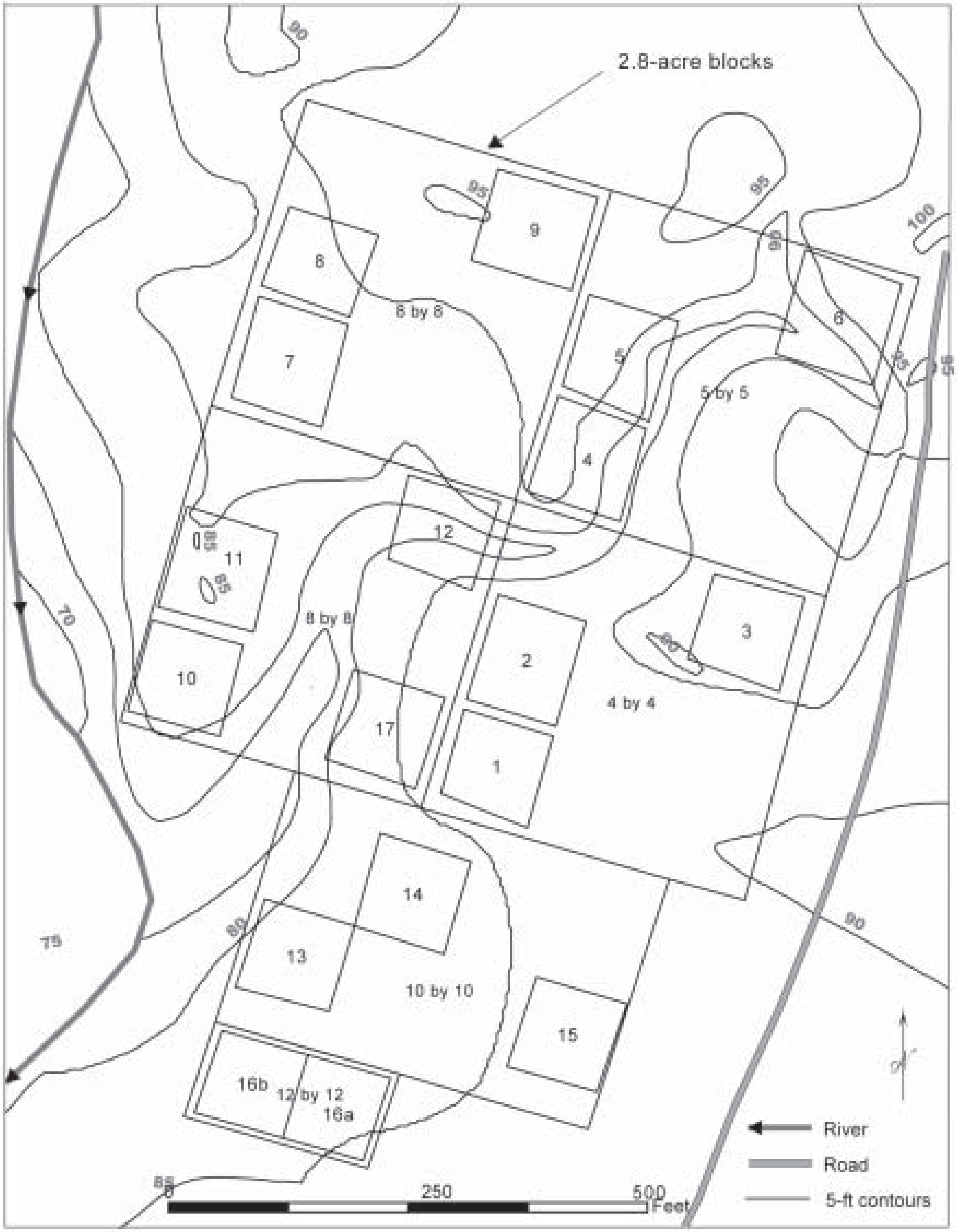

Figure 1—The 15-acre study area showing spacings, subplots, and topography.

Methods

Study Area

The original forest that was clearcut in early summer 1920 consisted of well-stocked, overmature Douglas-fir with some western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), western redcedar (*Thuja plicata* Donn ex D. Don), and western white pine (*Pinus monticola* Dougl. ex D. Don). Wildfire swept the area that August before logs were removed. Salvable logs were yarded by cable to spar trees, then loaded on railroad cars for transport. Four years later (June 1924), a second wildfire in the future study area destroyed natural regeneration and much of the duff and debris above the mineral soil.[2]

The Spacing Test

The test is located on a level terrace dissected by a dry, former stream channel that exposes basalt bedrock and boulders. Wind River is 100 to 200 ft west of the study area and flows rapidly in a southerly direction paralleling the longer dimension of the trial area (fig. 1). Wind River has cut 15 to 20 ft into the basalt that underlies the study area. Because the study area is located near the river and is dissected by a former stream channel leading to the Wind River, differences in soil depth and particle size within the study area are likely.

Plantation establishment—In April 1925, 2-year-old seedlings (1-1) were planted at six square spacings: 4, 5, 6, 8, and 10 ft (each within 2.8-acre blocks), and at 12-ft spacing within a 0.34-acre block (fig. 1). In October 1926, the original 12-ft spacing was expanded to its current 0.52-acre size with 3-year-old stock that had been grown at the Wind River Nursery from nonlocal, low-elevation seed collected near Roy, Washington.[3] Because of two recent fires, most of the forest floor and fine fuels in the planting area had burned; charred tree boles were prevalent either lying on the soil or standing as snags (figs. 2 and 3). Rain occurred before and during planting of the 4- and 5-ft spacing, but extremely hot dry weather followed planting of the other spacings (see footnote 2). Early researchers noted that many seedlings died despite careful planting. Losses were particularly great (1) where “scab rock” was close to the surface (5- and 8-ft spacings) and (2) wherever soil had a “burned-out” appearance from wildfire (see footnote 3). Analysis of soil samples (0- to 7.5-in depth) taken in April 1928 showed 50 percent less organic matter concentration and almost no total nitrogen in samples from heavily burned spots.[4]

To maintain the targeted spacing, trees that died during the first 5 years were replaced with stock from several seed lots (table 1). In the first year after planting, 37 percent of the original seedlings were replaced in March 1926 with comparable planting stock (1-2). A second replacement planting occurred in October 1926 after the second growing season; most of these 3,300 seedlings (16 percent of initial planting) replaced former replacement seedlings.[5] Like the initial seedlings, replacement seedlings were from

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[2] Isaac, L.A.; Kummel, J.F. 1926. Work plan and progress report no. 1. Spacing in Douglas-fir plantations. Unpublished report. On file with: USDA Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, 3625 93rd Ave., Olympia, WA 98512-9193.

[3] Isaac, L.A.; Meagher, G.S. 1936. Progress report no. 2. Spacing in Douglas-fir plantations. Unpublished report. On file with: USDA Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, 3625 93rd Ave., Olympia, WA 98512-9193.

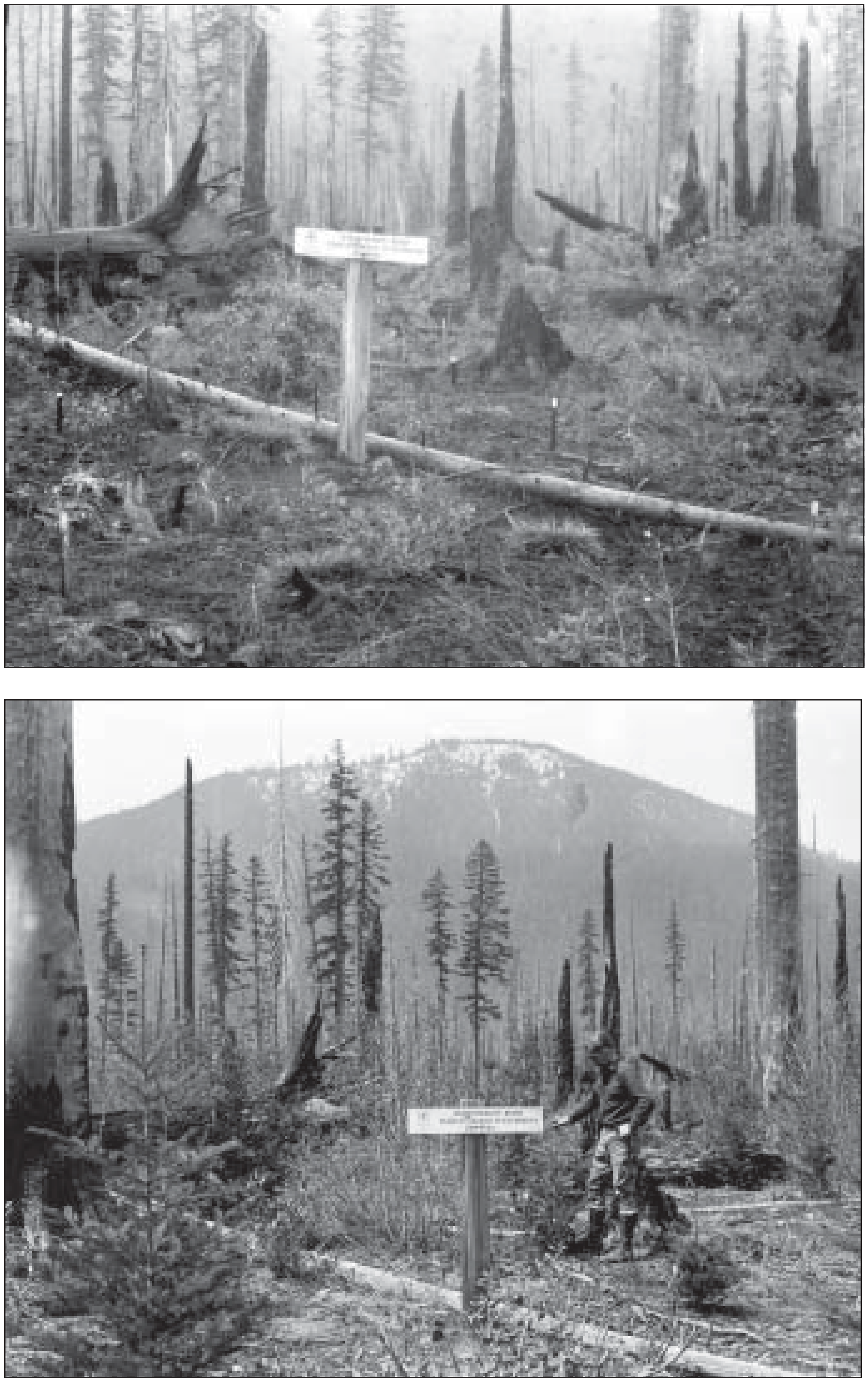
[4] Isaac, L.A. 1931 (1 June). Memo to the files. On file with: USDA Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, 3625 93rd Ave., Olympia, WA 98512-9193.

[5] Isaac, L.A. 1926 (28 October). Unpublished report. On file with: USDA Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, 3625 93rd Ave., Olympia, WA 98512-9193.

A

B

Figure 2—The 4- by 4-ft spacing: (A) initial site conditions and (B) at year 10 after planting.



A

B

Figure 3—The 10- by 10-ft spacing: (A) initial site conditions and (B) at year 7 after planting.

Table 1—Number of seedlings planted initially in 1925 and subsequently as replacements at Wind River, by test spacing

Square spacing			Trees planted						
			Originally[a]	As replacements[b]					
			1925	1926 (Mar.)	1926 (Oct.)	1928	1929	1930	All
Feet	*No. per acre*	*Acres*	*Number*						
4	2,722	2.8	7,744	—	930	—	—	—	930
5	1,742	2.8	4,900	—	1,020	—	—	—	1,020
6	1,210	2.8	3,422	—	630	—	—	—	630
8	681	2.8	1,936	—	450	—	—	—	450
10	436	2.8	1,247	—	210	—	—	—	210
12	302	.32	144	—	30[c]	—	—	—	30
Total[b]			19,393	7,200	3,270	1,000	730	630	3,270
Percent			37	16	5	4	3	66	

— = no data.

[a] From Kummel, J.F.; Isaac, L.A. 1926. Spacing in Douglas-fir plantations. Progress Rep. No. 1 Unpublished report. On file with: Forestry Sciences Laboratory, 3625 93rd Ave., Olympia, WA 98512-9193.

[b] From Isaac, L.; Meagher, G. 1936. Spacing in Douglas-fir plantations. Progress Rep. No. 2. 15 p. + photos. Unpublished report. On file with: Forestry Sciences Laboratory, 3625 93rd Ave., Olympia, WA 98512-9193.

[c] Fifty-four additional seedlings were planted when four rows of trees (0.18 acre) were added later to the original area of the 12-ft spacing.

nonlocal seed; most originated from seed collected near Roy, Washington. Unfortunately, we do not know to what extent this early soil sampling or seedling replacement occurred on the tree-measurement plots that were established in 1945.

Sampling and measurements—Different sampling systems were used to document tree performance. At ages 7, 12, and 17 (years from seed germination), seedling heights were measured on selected rows in each spacing (Isaac 1937). Beginning in 1945 (23 years from seed), each spacing (4 through 12 ft) was subsampled on permanent plots. Natural regeneration remaining after earlier cleanings was cut. Most spacings were sampled by three approximately 0.25-acre square plots. Each plot was about 104 ft on a side, and the initial corner post was placed midway between the rows; the plot boundary paralleled the row regardless of cardinal direction. The three subplots in the 4-, 5-, 6-, and 8-ft spacings were located in the same relative position within their respective block because the same randomization was used for these four spacings (fig. 1). At the time these plots were installed, "…it was realized that two of the plots [11 and 12] in this 8- by 8-ft plantation fell on areas of rocky, shallow soil and were not comparable with the other plots. The growth data substantiate this."[6] A fourth subplot (no. 17) was established in 1951 in the 8-ft spacing to replace plot 12, which was located on

[6] Munger, T.T.; Fredde, G.P. 1945. Establishment report for 16 permanent plots on the spacing test plantations. Unpublished report. On file with: USDA Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, 3625 93rd Ave., Olympia, WA 98512-9193.

poorer quality soil. The three subplots in the 10-ft spacing were located in a different randomization pattern. The final area of the 12-ft spacing (0.52 acre) was separated into two abutting 0.21-acre subplots for data summary.

Since 1951 (total age 29), diameters at breast height (d.b.h.) of all trees in plots were measured at approximately 5-year intervals (age 29, 34, 38, 43, 48, 53, 58, 63, and 68 years). Heights were measured on varying numbers of trees distributed across the entire d.b.h. range; the minimum number in any year was 10 per plot. To ensure a well-distributed sample, each plot was gridded at age 48 into 16 squares, and the height of the largest tree in each square was measured. Heights of previous sample trees also were remeasured then and in subsequent years if these survived.

All volumes for the period 1951-90 were computed from tariff equations (Brackett 1973). Cubic-volume total stem (CVTS) of all trees measured for height was computed by using the equation derived by Bruce and DeMars (1974), from which tariffs were computed; these individual tree tariffs were averaged for each plot. Total and merchantable volumes of each tree were computed by d.b.h. and tariff, summed to give volumes per plot, and expanded to volumes per acre.

Soil Investigations

1968 to 1971–A contour map of the 15-acre study area was prepared in summer 1968 by using a steel tape and compass-theodolite. Elevations were measured systematically on a 100-ft grid with additional elevations measured at intervening topographic breaks. The base elevation (assumed as 100 ft, but really about 1,400 ft) was at exposed basalt bedrock near the northeast corner of the study area.

A detailed soil survey was done in 1970 to determine and document variation in soil properties in the study area.[7] Sixteen pits were excavated around the perimeter of the study area by a backhoe or near interior subplots by hand (fig. 4). Soil and rooting characteristics were described at all pits, and specific soil horizons were sampled at four pits (app., table 4).

A seismic survey was completed in 1971 for the north two-thirds of the study area by using the seismic refraction method (Dobrin 1960) at some of the 100- by 100-ft topographic grid stations. Unfortunately, equipment malfunction precluded completion of the southern one-third of the area (10- and 12-ft spacings). The seismic method gave integrated velocities and depth over the length of a transect, which was roughly three to four times the estimated depth to the underlying bedrock. Detailed field and office procedures are described in the instruction manual for the “Terra Scout” portable refraction seismograph.[8] As a check on depth estimates, depths computed from velocities and resistivities measured during the survey were compared with the profile descriptions acquired at nearby soil pits. Seismic depth data at some measurement stations were rejected because resistant soil was detected instead of the basalt bedrock.

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[7] Meyer, L.C. 1971. Soil survey, Wind River Douglas-fir spacing study on the Gifford Pinchot National Forest. Unpublished report. On file with: USDA Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, 3625 93rd Ave. SW, Olympia, WA.

[8] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

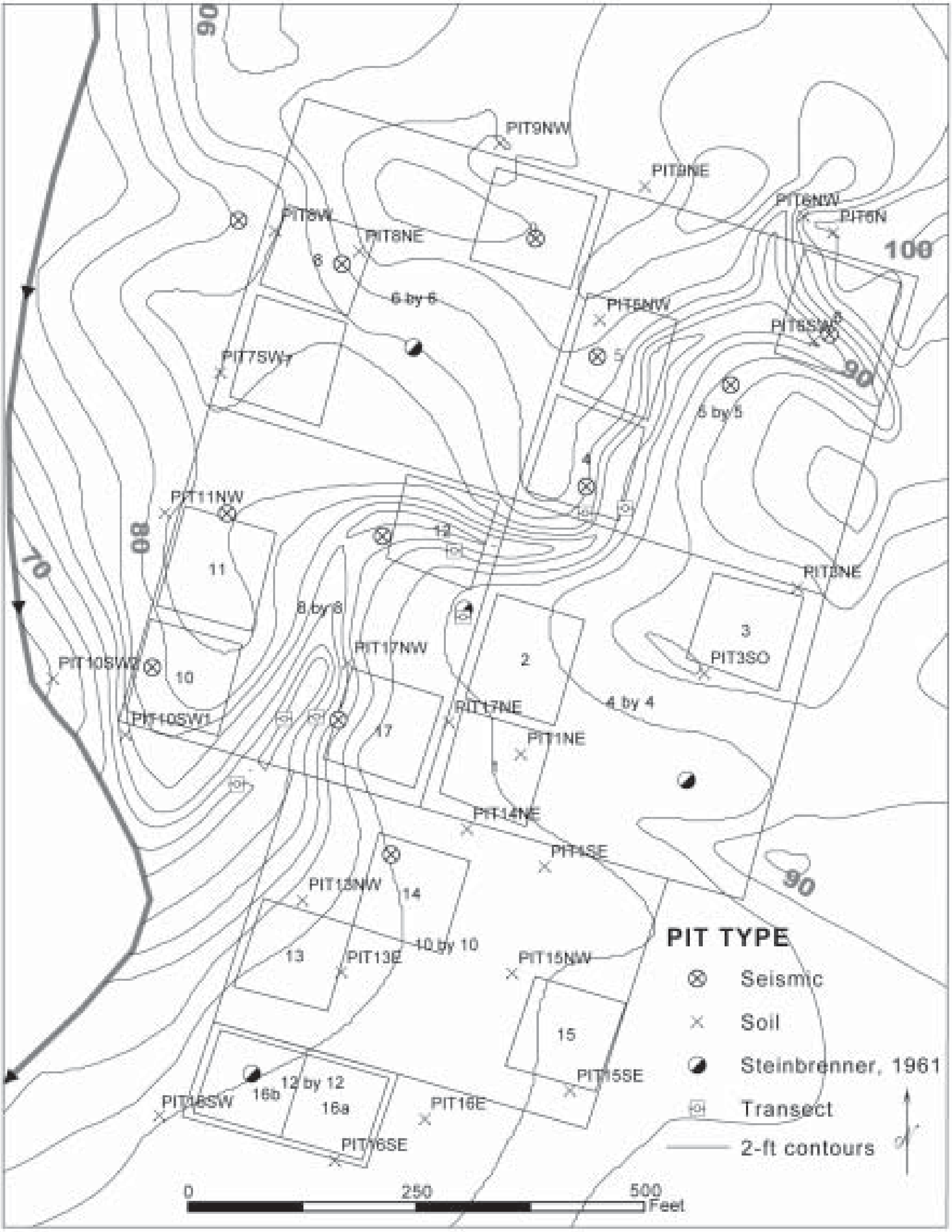

Figure 4—Location of soil pits and seismic measurements.

1993 and 1994–An additional 21 pits were excavated by hand to increase the total number of pits in the study area to 37 (fig. 4). Soil and rooting characteristics were described, and for most pits, soil texture was determined in a 4-in layer immediately above bedrock (or above a 2- to 3-in-thick layer of gravel atop the bedrock at some locations). Original data about surface and bedrock elevations, and about pit and plot locations were verified, corrected, or supplemented; data were recorded for summary.

Data Summary

Using the original contour map (1-ft vertical interval and 1 in = 100 ft on horizontal scale) and depth-to-bedrock measurements from excavation, boring, or seismic "Terra Scout" procedures, we estimated elevations and contours of the underlying bedrock by using computer programs of ArcInfo.[9]

Surface elevation grid—Ground-surface contours were created by scanning a hard-copy site map and extracting all contour line information into an ArcInfo line map. The contour lines were then attributed with elevation data. The TOPOGRID command, which generates a hydrologically correct grid of elevations, created a continuous surface, digital elevation grid.

Rock-surface elevation grid—Using the Geostatistical Analyst extension to ArcInfo, we generated a continuous rock-surface elevation grid by performing a kriging analysis of the known rock-surface elevations at 48 separate locations.

Depth to bedrock—Mean soil depth for each subplot was estimated by subtracting the rock-surface elevation grid from the ground-surface elevation grid. In a similar procedure, mean effective depth of soil was estimated by subtracting the mean cumulative depth-equivalent of coarse-fragment volume from total soil depth.

Available water capacity—Available water capacity (AWC) refers to the amount of soil water potentially available for plant growth. It is usually considered the amount of water retained in a soil between an upper limit (termed field capacity or FC) and a lower limit, termed permanent wilting percentage (PWP) (USDA NSSC 1995). The preferred way to estimate moisture content at FC is by in situ measurements of volumetric moisture within 1 to 3 days after the soil has been thoroughly wetted by rain or irrigation, and when drainage of gravitational water has become very slow. Alternatively, field capacity can be estimated in the laboratory by using tension tables or a pressure-membranes apparatus that simulate the tension that develops during drainage in the field. Although the correct tension or pressure to apply in these simulations is debatable, values ranging from 0.05 to 0.33 bar (5 to 33 kPa) are generally accepted as appropriate (USDA NSSC 1995). "Available water capacity only approximates the soil's ability to retain or store water and does not provide an estimate of the supplying capacity of a soil or even the amount that plants extract. The actual supplying capacity depends on numerous other factors (e.g., rooting depth and intensity, hydraulic conductivity, plant species)" (USDA NSSC 1995: 58-59).

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[9] ArcInfo Version 8.1 Copyright © 1982-2001 Environmental Systems Research Institute, Inc., 380 New York Street, Redlands, CA 92373-8100, USA.

The AWC was estimated for individual horizons by using the following formula (USDA NSSC 1995: 60), then summarized for the entire profile:

$$AWC\ (\text{horizon}) = \frac{(W_{.2} - W_{15}) \times BD \times Cm \times Pw}{100},$$

where

AWC = volume fraction of water retained in the whole soil between 0.2- and 15-bar suction, reported in $cm \cdot cm^{-1}$ (equivalent to inch of water per inch of soil);

$W_{.2}$ = weight percentage of water retained at 0.2-bar suction on the <2-mm fraction;

W_{15} = weight percentage of water retained at 15.0-bar suction on the <2-mm fraction;

BD = dry bulk density of the <2-mm soil at 0.2-bar water content (We used *BD* at time of sampling);

Cm = coarse fragment (>2-mm) conversion factor. Calculated as percentage of volume <2-mm soil per percentage of volume of >2-mm particles or (1 – decimal fraction > 2 mm); and

Pw = density of water ($1 \cdot cm^3 \cdot g^{-1}$).

We used three procedures to estimate AWC for each horizon or distinctive layer within soil profiles. For 22 soil samples collected from modal profiles in the 1970-71 soil survey, volumetric AWC could be estimated from measured gravimetric moisture retention in sieved soil and bulk density. Specifically, the water retention (weight percentage) at 0.2-bar pressure minus that at 15-bars pressure was multiplied by average *BD* of the three cores associated with each bulk soil sample. Duplicate retention analyses of sieved soil from each horizon were completed at the Forest Hydrology Laboratory in Wenatchee, Washington. For horizons in the remaining soil profiles, only laboratory-determined textures or field-estimated texture classes were available. We estimated AWC for these horizons through the following steps:

1. Using laboratory-analyzed data from the original 22 samples (gravimetric water retention at 0.2 and 15.0 bars, *BD*, and percentage of sand, silt, and clay), we estimated correlation coefficients between pairs of these variables.

2. We selected the strongest predicting variable to estimate gravimetric moisture percentage at FC and PWP, and fine-soil *BD*. Percentage of silt proved the strongest predictor ($r^2 = 0.13–0.20$) for these characteristics.

3. For horizons with laboratory-determined percentage of silt, we used linear regression to estimate gravimetric water-retention difference ($W_{.2} - W_{15}$) and *BD*.

4. For horizons with both field-estimated texture class, and laboratory-determined percentage of silt, we first derived an average percentage of silt for each texture class, then entered that average into our estimating equations to estimate gravimetric water-retention difference and *BD*.

5. We then assigned the difference in gravimetric water percentage (at FC and PWP) to field-estimated texture classes. The mean AWC for each texture class was then compared to published values for the same texture classes. Results follow:

USDA texture class	Observed mean silt	AWC (volume) The study area	Geist and Strickler 1978[11]	Rawls and Pachepsky 2002[12]
			Percent	
Sand	5	13.3	—	6.8
Loamy sand	15	17.2	—	8.0
Sandy loam	25	21.8	—	12.5
Loam	41	29.0	17.1 (basalt)	14.5
Silt loam	69	45.3	30.5 (ash)	19.4
Silty clay loam	56	37.3	—	15.8
Clay loam	34	25.6	—	14.6

— = no data.

[11] 0.1-bar minus 15-bars water retention = AWC. Means of 0- to 15-cm depth in 22 basalt-derived and 35 ash-derived soil profiles.

[12] Based on numerous soil parent materials; 0.33-bar minus 15-bar water retention = AWC.

Our data support an earlier generalization that volumetric water-holding capacity of soils derived from ash and pumice is about twice that of similar textured soils derived from other parent materials (Geist and Cochran 1991). The lower tension (0.1 bar) that we used to simulate FC also explains the consistently greater moisture percentage (AWC) that we estimated compared to Rawls and Pachepsky (2002).

Data Analysis

The unreplicated spacing treatments in this trial preclude valid statistical testing, e.g., regression and variance analyses and inferences (Freese 1974). Consequently, we based our inferences on plottings and simple correlation that measured the degree of linear association between stand and soil variables. We accepted that nonrandom sampling and pseudoreplication precluded valid tests of significance among correlation coefficients.

Results

Tree and Stand Characteristics, Within and Among Spacings

Trends of stand density–-Commonly used measures of stand density include number of trees per acre (TPA) and relative density (RD) (Curtis 1982). In recent decades through 1990, mean number of live TPA remained nearly unchanged in widest spacings but declined markedly in initially closer spacings (fig. 5). In the 4- and 5-ft spacings, suppression of small trees and periodic tree losses from top breakage and blowdown associated with snow accumulation and wind created large openings devoid of trees. Heavy damage was documented in winters 1936-37 and 1959-60. Although severe losses also occurred in winter 1993-94 (fig. 6), these losses occurred after our last re-measurement (1990). Among the two to four plots that are subsamples of each spacing, the three plots in the 4-ft spacing show largest difference in number of live trees (fig. 7). In past decades, individual plots in each spacing have maintained parallel trends in number of live trees, with the exception of plot 8 in the 6-ft spacing, which had more rapid losses of trees in recent decades for no apparent reason (fig. 7).

Trends of mean RD reflect greater tree losses in close spacing (fig. 8). Relative density is a function of both TPA and mean tree diameter. In even-aged, naturally regenerated Douglas-fir stands, RD70 corresponds to the stand density at which mortality from suppression is imminent. The plantation spaced at 4 ft attained RD80 when trees were about 40 years old, then dropped to RD63 by age 68 (fig. 8). Stands planted at wider spacings attained peak RD at progressively later ages; hence, the 5-ft spacing reached RD70 at age 55 years, but 8- and 12-ft spacings attained only RD60 at about age 68. Spacings of 5 by 5 and 10 by 10 ft are currently at about RD70, so further mortality is anticipated.

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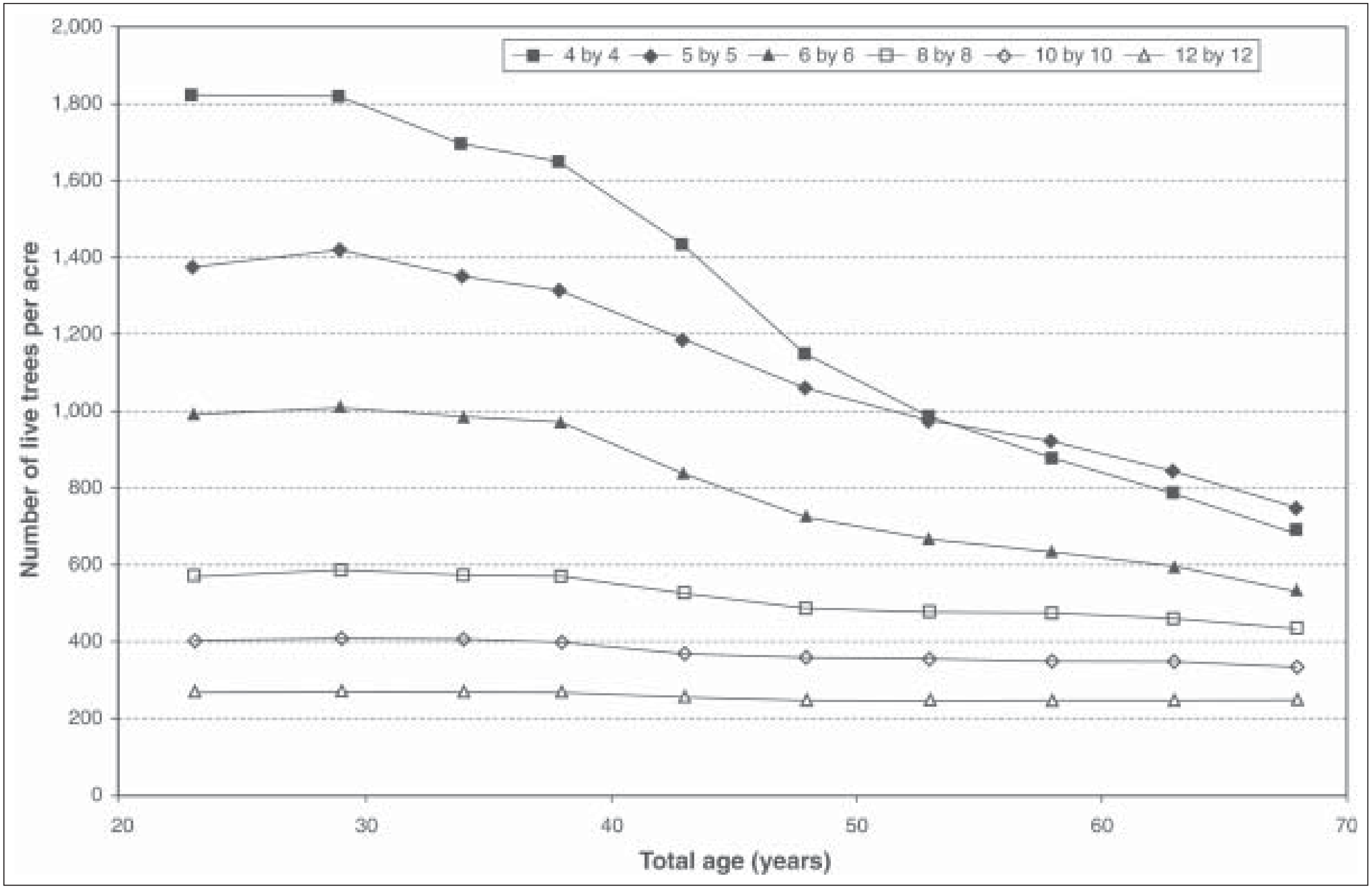

Figure 5—Trends of mean number of live trees per acre, by spacing.

A

B

Figure 6—Photo of blowdown of 1993-94 (age 71 years) in the (A) 4 by 4 spacing (top) and (B) 5 by 5 spacing (bottom).

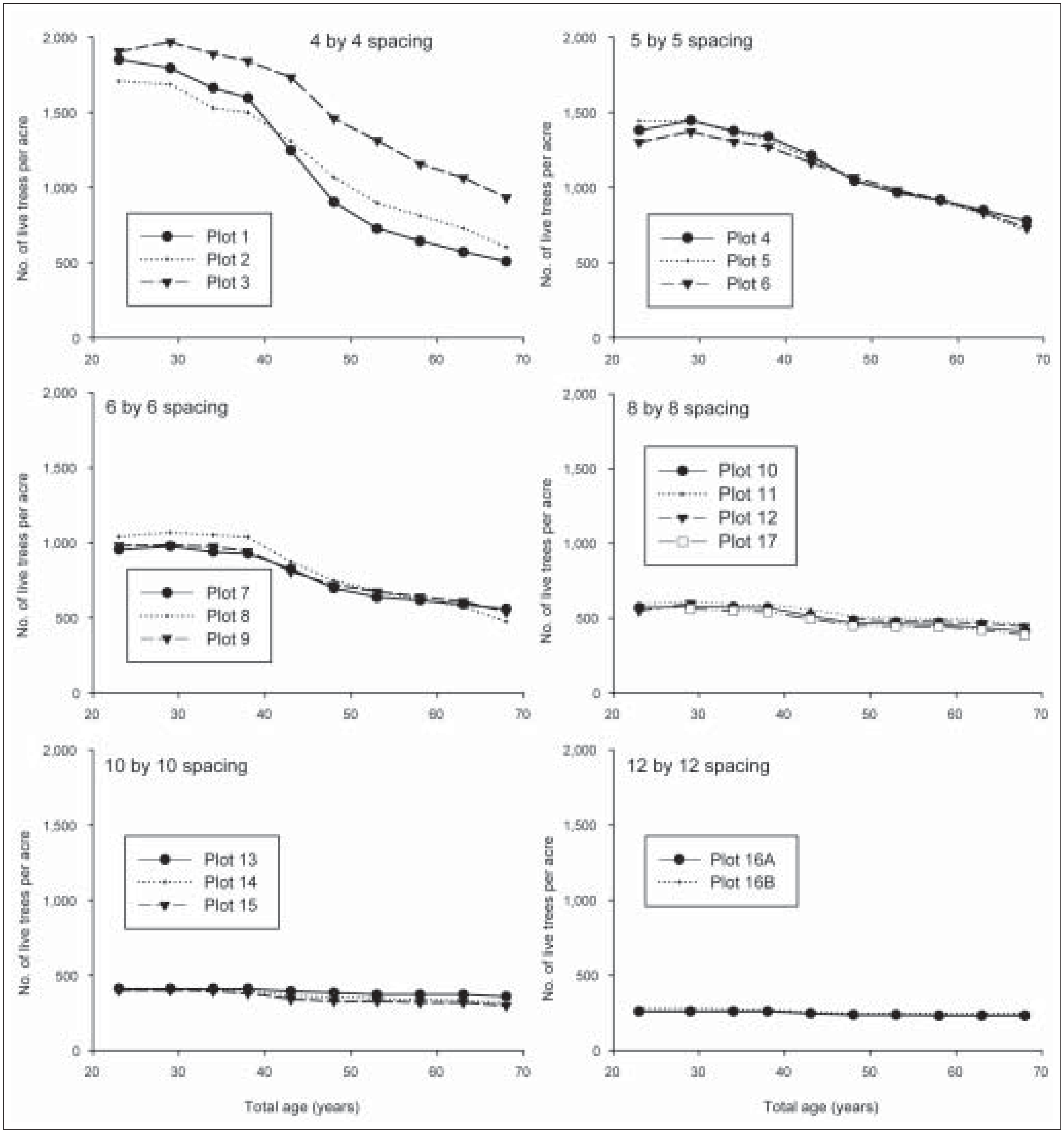

Figure 7—Trends of number of live trees per acre on individual subplots within specified spacings.

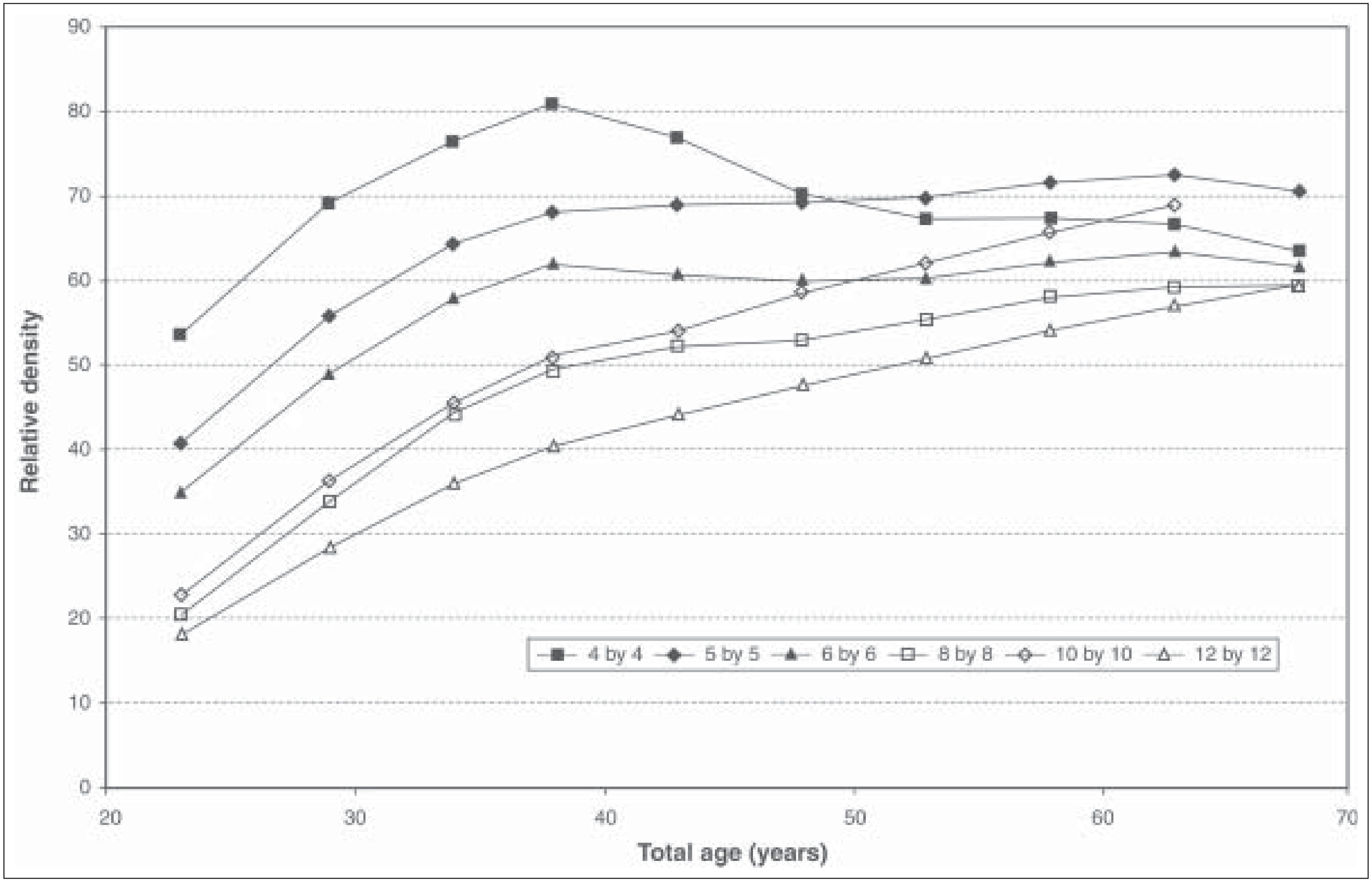

Figure 8—Trends of mean relative density, by spacing.

Trends of mean diameter, largest 40 trees (by d.b.h.) per acre (D40)—Tree d.b.h. was directly related to wider tree spacing (fig. 9). At total age of about 68 years, d.b.h. of the 40 largest trees per acre (D40) averaged about 10.5 in in the 4- and 5-ft spacings, compared to nearly 17 in in the 10- and 12-ft spacings. Trees in the 8-ft spacing were intermediate in D40.

Trends of mean height, largest 40 trees per acre (top height or H40)—By about age 35 years, mean top height (H40) was directly related to tree spacing (fig. 10). By age 68, H40 averaged about 75 ft in close spacings and 115 ft in the 10- and 12-ft spacings. Mean H40 in the 10- and 12-ft spacings was similar, despite nearly 50 percent more growing area per tree at the wider spacing (144 vs. 100 ft^2). Trends of top height among the closer spacings (4 to 8 ft) also indicated taller trees are associated with wider spacings. The addition of plot 17 (to replace plot 12) in the 8-ft spacing substantially increased mean H40 of that spacing.

Large differences in trends of H40 exist among the sample plots within some spacings, especially the 4-, 6-, and 8-ft spacings (fig. 11). In contrast, differences in H40 among plots are small in the 10- and 12-ft spacings. Because few large trees were lost in any of the spacing, a simple arithmetic increase in H40 and D40 from mortality does not explain these different trends among spacings. As will be discussed later, however, soil quality is more uniform and better in the widest spacings. Moreover, H40s on 8- and 4-ft spacing plots closest to the widest spacings are greater than other plots in these close spacings (figs. 1 and 11).

Trends of site index among spacings—Site index (50-year-base age) was calculated from estimated breast-height age and height of the H40. Between ages 23 and 68 years, mean site index gradually declined at close spacings (fig. 12). Lowest mean site index at age 68 is associated with 4- and 5-ft spacings; greatest site index is associated with the 10- and 12-ft spacings (table 2). Mean site index in the 8-ft spacing remained intermediate between these extremes.

Trends of stand volume among spacings—Because number of live trees and tree size are related to spacing, their product (stand volume) also is related to spacing. In 1945 when the plantation was 23 years from seed, live stand volume averaged greater at closer than wider spacings (table 2, fig. 13). Subsequent volume growth increased with increased spacing through 1990 (68 years from seed). Tree mortality at closer spacings substantially reduced live stand volume (table 2). Although close spacings consistently had more live trees per acre than wider spacings, these trees were smaller and stand volumes were less both in total cubic feet total stem (CVTS) (fig. 13) and especially in cubic volume to a 6-in top (CV6) (fig. 14). Trends of mean live volume among spacings support an inference that yields per acre generally increase with progressively wider initial spacing. The extraordinarily large increase in yield at the 10- and 12-ft spacing is remarkable. Moreover, in the last three decades, live stand volume in the 10-ft spacing averaged about 10 to 15 percent more than that in the 12-ft spacing. As will be discussed later, those apparent superior benefits of 10- and 12-ft spacings could be explained partially by soil differences.

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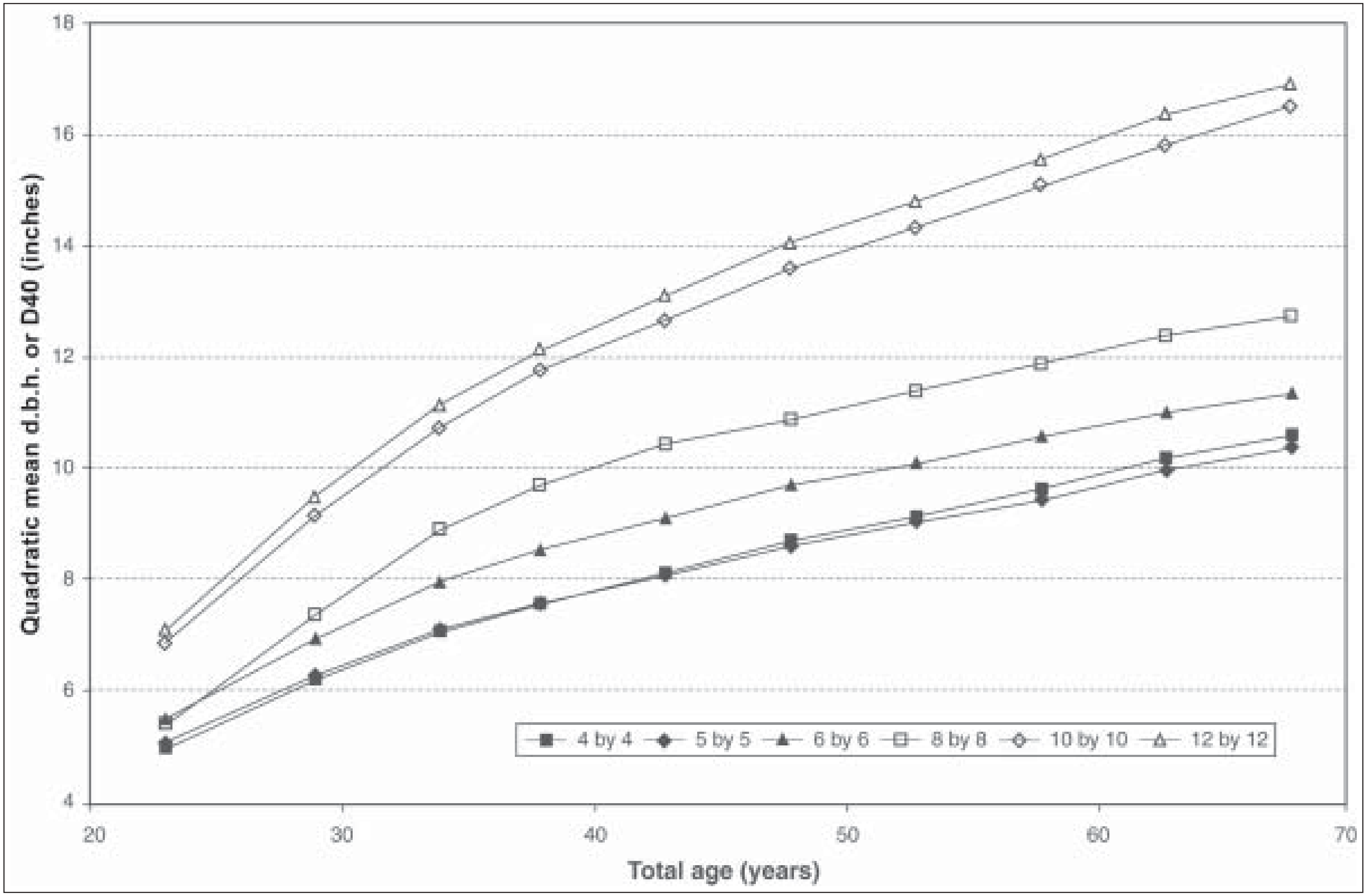

Figure 9—Trends of quadratic mean diameter at breast height (d.b.h) of the 40 largest trees per acre, by spacing.

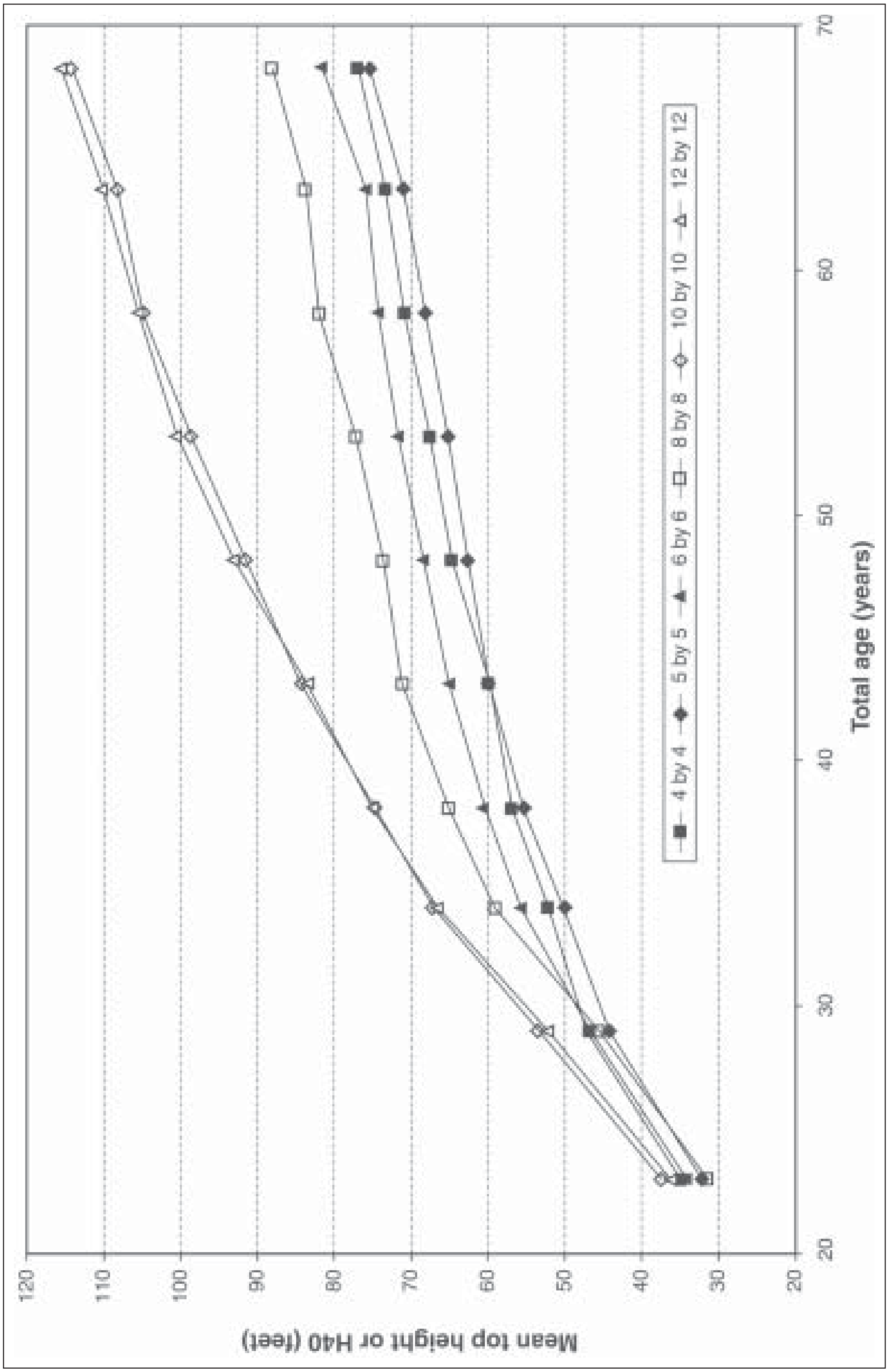

Figure 10—Trends of mean top height of the 40 largest trees per acre (H40), by spacing.

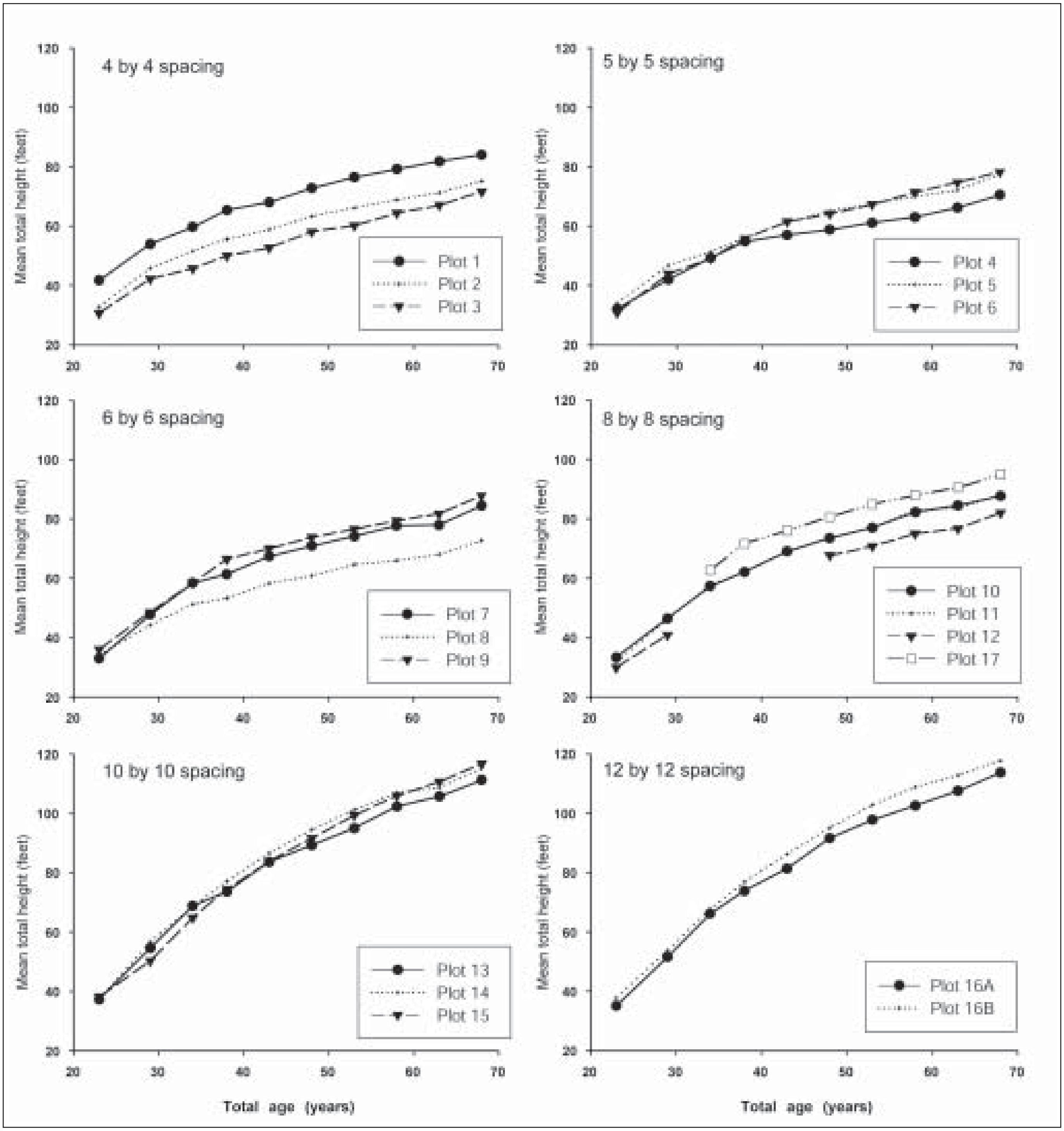

Figure 11—Trends of mean top height of the 40 largest trees per acre on individual subplots within specified spacings.

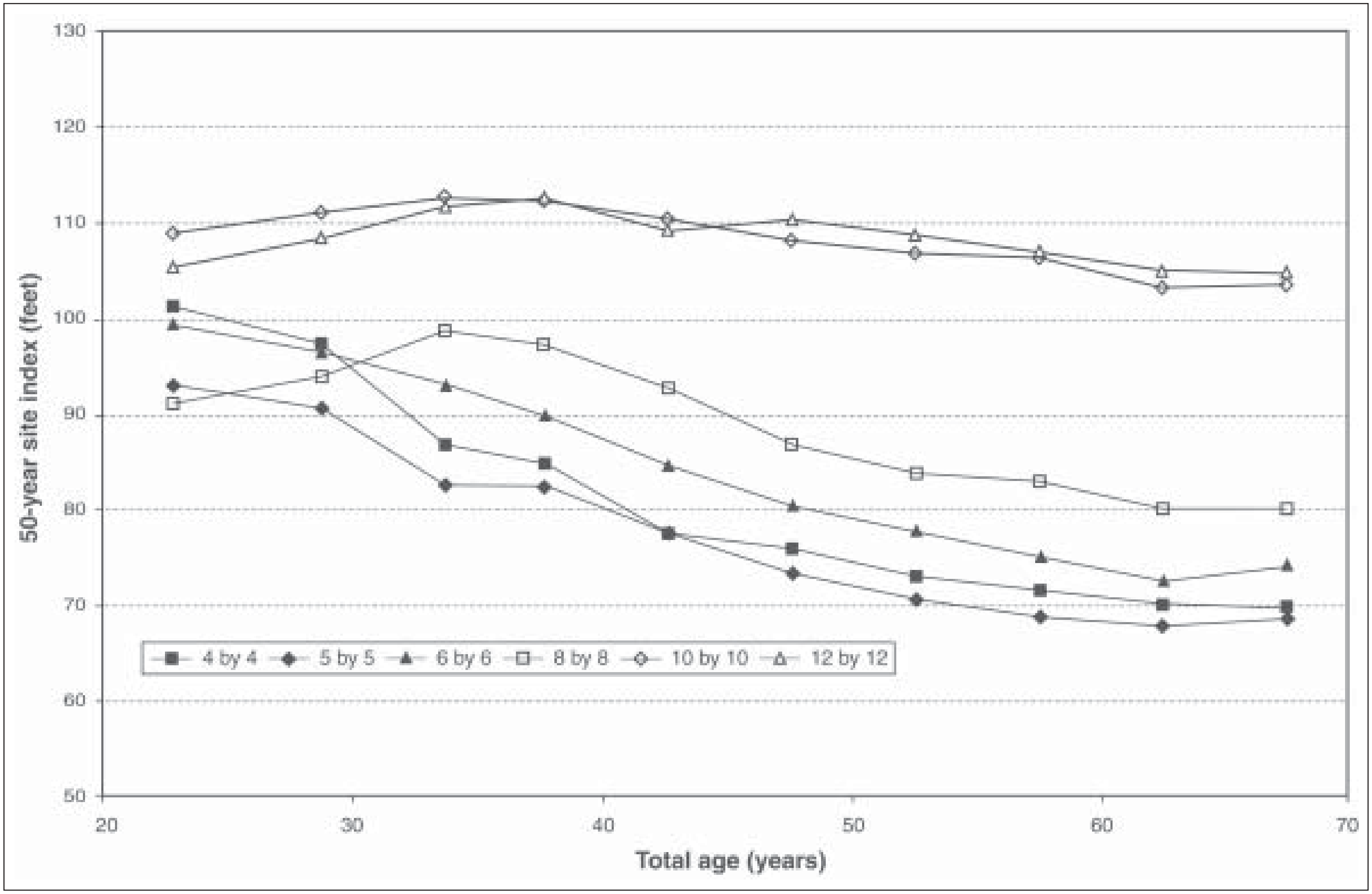

Figure 12—Trends of mean 50-year site index, by spacing.

Table 2—Site index (50-year-base age) and live volume per acre by spacing, plot, and year

Spacing	Plot no.	Site index 1945	Site index 1990	Site index Diff.	Live stand 1945	Live stand 1990	Live stand Diff.	Dead 1945	Dead 1985-90
		Feet			*Cubic feet*[a]				
4 by 4	1	122	76	-46	1,560	5,027	3,467	0	207
	2	95	68	-27	1,160	4,073	2,913	0	455
	3	88	65	-23	1,010	4,478	3,468	0	295
5 by 5	4	93	64	-29	690	4,032	3,342	0	94
	5	98	70	-28	942	5,293	3,351	0	230
	6	89	71	-18	831	5,278	4,447	0	347
6 by 6	7	96	77	-19	723	5,609	4,886	0	66
	8	99	66	-33	767	3,391	2,624	0	349
	9	104	80	-24	937	6,026	5,089	0	213
8 by 8	10	96	80	-16	571	5,625	5,054	0	188
	11	92	80	-12	425	5,367	4,942	0	128
	12	86	75	-11	322	4,554	4,232	0	57
	17[b]	—	86	—	—	6,350	—	—	277
10 by 10	13	108	101	-7	676	9,332	8,556	0	79
	14	108	104	-4	813	11,097	10,284	0	140
	15	111	106	-5	572	9,247	8,675	0	166
12 by 12	16A	102	103	1	520	8,208	7,688	0	0
	16B	110	107	-3	654	9,232	8,578	0	0

— = no data.

[a] Includes entire stem of all trees 1.5 in diameter at breast height and larger.

[b] Plot 17 was established in 1951, hence, no data for 1945.

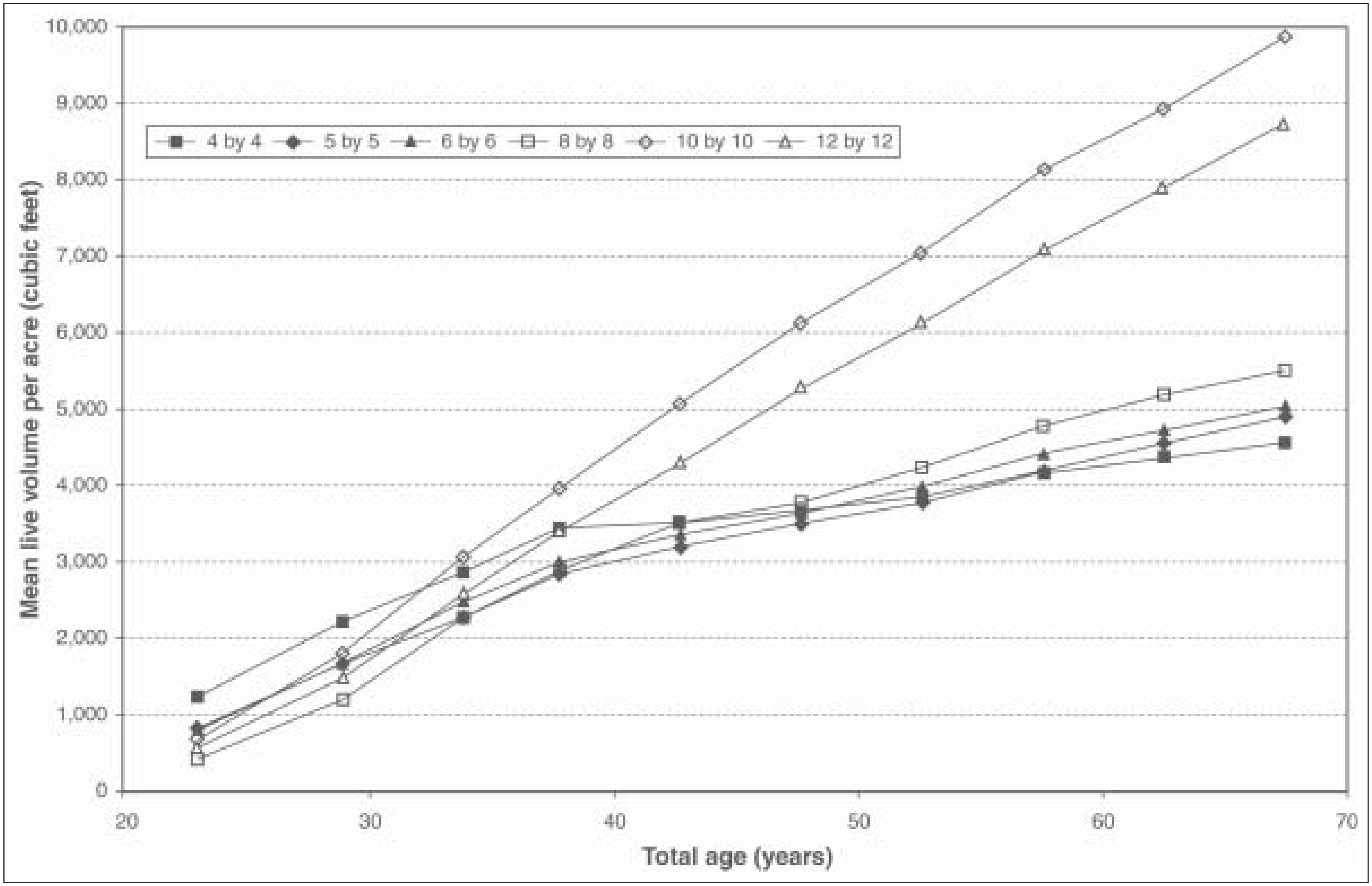

Figure 13—Trends of mean live stand volume per acre (CVTS, total stem, trees 1.5 in diameter at breast height and larger) by spacing.

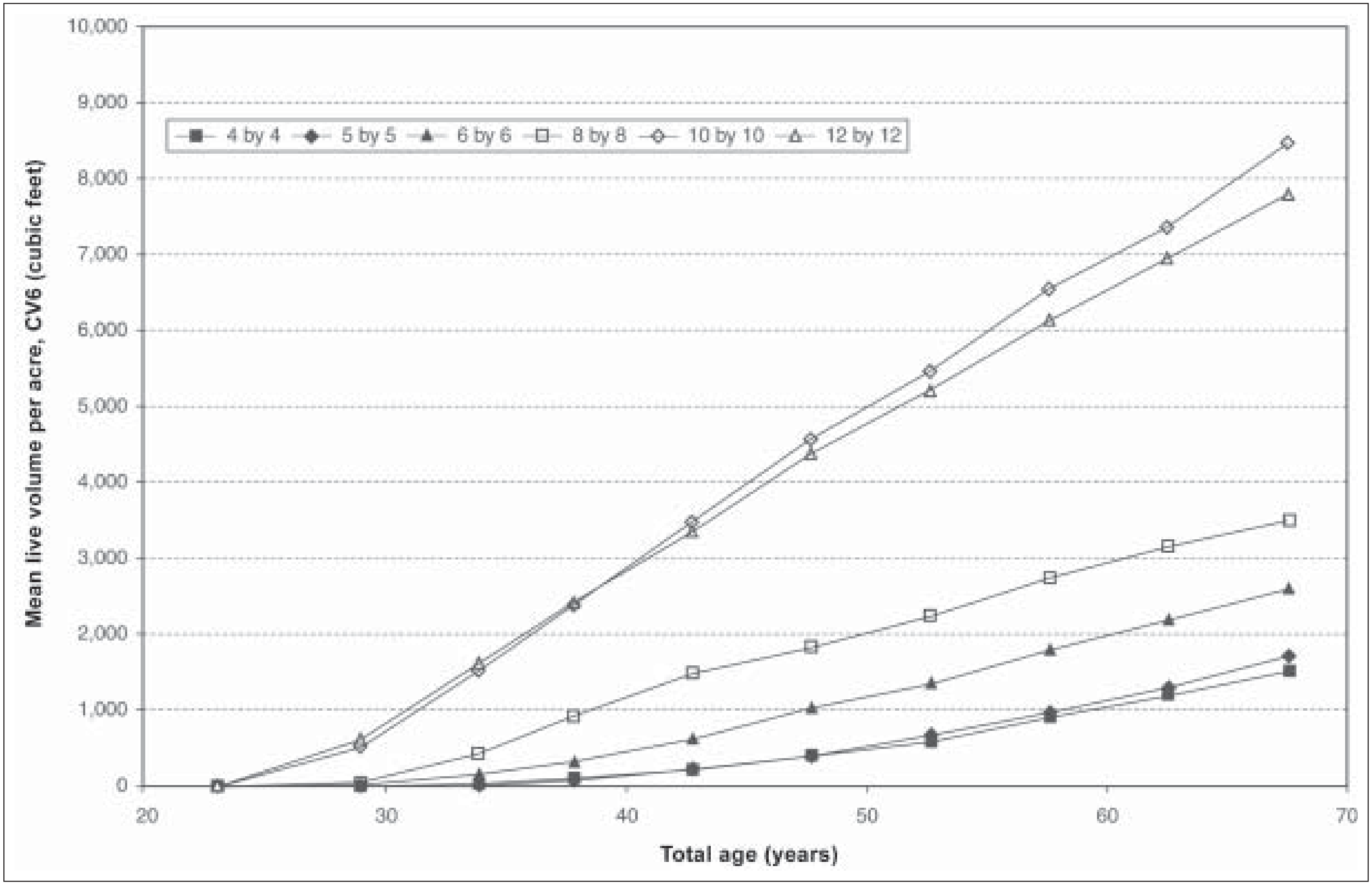

Figure 14—Trends of mean live volume per acre (CV6, trees 7.6 in diameter at breast height and larger to a 6-in top) by spacing.

Soil Investigations

The soil survey–-A preliminary soils map showed three soils (phases) in the area (app., fig. 19). Distinguishing field characteristics were as follows:

	Soil number		
Item	**1**	**2**	**3**
Depth to bedrock (ft)	5-10	3-14	1-4
Subsurface resistance	Weak to moderate	Moderate to strong	None

Soils 1 and 2 were similarly deep to bedrock, but soil 2 was more resistant to digging and boring. Fewer roots were observed in and below these moderate to strongly resistant soil horizons, suggesting reduced root penetration and exploitation of soil moisture and nutrients (see footnote 7). The preliminary mapping boundary between soils 1 and 2 was estimated by probing with a 3-in diameter borer systematically on both sides of a suspected boundary. The average depth to strong resistance in soil 2 was 41 in; however, some subsequent soil profiles failed to validate the originally mapped boundary between soils 1 and 2.

Soil origin and depth—Fieldwork from 1993 through 1994 confirmed that soils in the study area had weakly developed horizons derived from pumiceous alluvium. Some soil profiles had alternating, thin layers of unweathered sand or silt at lower depths suggesting deposition by water. Subsequent field observations in the study area suggest that several inches of airborne ash and lapilli from nearby Red Mountain or more distant Mount St. Helens may overlay this alluvium.[10]

Within and near measurement plots, depth to bedrock varied between 1 and 14 ft (fig. 15). Depth to bedrock equaled or exceeded 10 ft in 6 of the 36 pits (app., table 5). Rounded gravel and cobbles of andesite often prevented accurate determination of bedrock depth near the former stream channel dissecting the study area. Roots were observed to bedrock in most pits (app., table 5). Observations or borings within and near some pits revealed that the surface of the nonweathered basalt bedrock was not smooth as originally assumed, but could have 1 to 2 ft of relief within 2 ft of horizontal distance (Pit 3 NE) and 5 ft or more of relief within 40 ft horizontal distance (Pit 16 SE vs. Pit 16 E). In some pits, bedrock was covered by 1 to 2 in of rounded gravel. In others, the basalt was covered directly by finer material that ranged in particle size from clay to popcorn-size pumice. Cobbles were infrequent, except near the dry stream channel.

Soil texture and resistance—Soil horizons within profiles differed in texture and inherent resistance to excavation with a shovel or auger. These differences in resistance (consistence) also were noted in soil profile descriptions by Meyer (see footnote 7). Blocklike specimens from surface horizons failed under very slight force applied between the thumb and forefinger; rupture classes in both dry and moist states were loose. In contrast, material from lower horizons was usually hard when dry and very firm when moist, especially where strong “compaction” was noted. Nearly all pits had sandy loam textures and 0- to 30-percent coarse fragments (>2 mm) in the upper 6 to 12 in. Pits near the dry stream channel had 40 percent or more of rounded gravel or cobbles by volume throughout; only plots 4, 5, 6 (5-ft spacing), and 12 (8-ft spacing) sampled this very gravelly soil (soil 3). Some deep pits usually had a high percentage of clay

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[10] High, T. 2001. Personal communication. Soil scientist, USDA Forest Service, Gifford Pinchot National Forest, 6926 E. 4th Plain Blvd., Vancouver, WA 98668-8944.

Figure 15—Estimated mean depth to bedrock based on interpolation of known rock-surface elevations.

within 4 to 6 in of the basalt bedrock; clay was frequently 30 to 40 percent of the weight of the <2-mm fraction (app., fig. 20). A few deep pits also had a large percentage of clay within several feet above bedrock. In the dry, late summer of 1992, the deep, clay-rich layer in Pit 13E (10-ft spacing) was moist and well rooted by Douglas-fir.

Soil resistance at the 30- to 50-in depth was readily detected by shovel when pits were excavated (app., fig. 21). Below about 3 ft in many pits, soil resistance was frequently moderate to severe. This resistance restricted but did not stop root penetration. Characteristics of this firm layer meet criteria of fragipans (Smeck and Ciolkosz 1989). Our seismic survey also detected this resistant soil. Bulk density measured by soil cores, however, failed to indicate substantial differences in BD (soil density) in the resistant layers (which slaked rapidly when immersed in water) and the overlying less resistant layers (app., table 4). Lindbo and others (1994) reported poor correlation between soil resistance and soil BD in loess soils and suggested that other physical or chemical properties must contribute to soil resistance.

Available moisture capacity—Soils were not only deeper at the south end of the study area (fig. 15) but also had greater storage capacity of potentially available water for tree growth. Available water-holding capacity is greater in the 10- and 12-ft spacings (fig. 16). Conversely, plots in the 5-ft spacing were located near the gravelly dry stream channel and on soil with the poorest AWC.

Relation of Tree Growth to Soil Properties

We considered three possible explanations for among-spacing differences in tree growth: (1) more intense between-tree competition and winter damage eventually retarded growth in the closer spacings, (2) better soil quality in the 10- and 12-ft spacings than at closer spacings promoted among-spacing differences, and (3) wider spacing and better soil quality combined determined the superior growth in the 10- and 12-ft spacings. We infer from the strong correlation between spacing and soil variables ($r = 0.77$ to 0.80; table 3) that the influence of the two variables cannot be separated; soil differences confound spacing effects and vice versa.

Top height—By age 48, the H40 were tallest at the widest spacing and where AWC was greater (fig. 17). Within some spacings, H40 was greater on plots located where mean AWC was greater (fig. 17). Mean top height was related positively to both spacing and soil variables (depth and AWC) at ages 29, 48, and 68 years (table 3). Correlation coefficients, r, indicated that 38 to 77 percent of the variation in top height is associated positively with these soil variables; the association was strongest after age 48 years (table 3). During this 40-year period (1951-90), site index at 10- and 12-ft spacings remained about 110 ft, but site index at narrower spacings declined from about 90 to 70 ft (fig. 12).

Bole volume, all trees (CVTS)—Also during the last 40 years, bole volume of all live trees (1.6-in d.b.h. and larger) increased from about 1,500 $ft^3 \cdot acre^{-1}$ to more than 9,000 $ft^3 \cdot acre^{-1}$ in the 10- and 12-ft spacings (fig. 13). Tree losses from competition and especially winter breakage help explain the lesser amount of live stand volume in close spacings. Poorer yields at close spacings at age 48 years also could be explained by shallower and more gravelly soils, and less available water capacity (fig. 17). At 23 and 29 years, stand volume was weakly related to these soil variables ($r = -0.29$ to 0.17; table 3). At age 68 years, however, 56 to 74 percent of the variation in plantation volumes was associated with soil depth, effective depth, or AWC.

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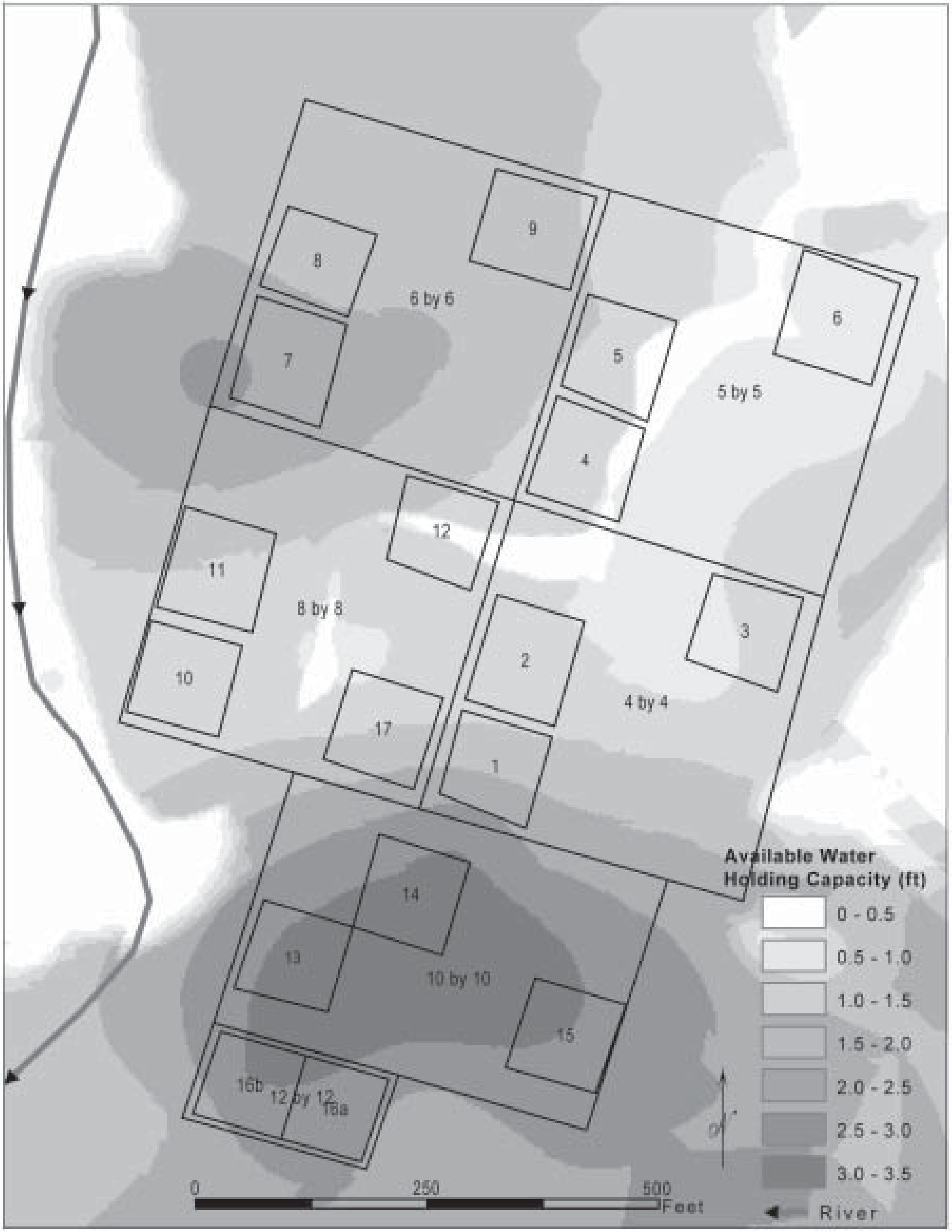

Figure 16—Estimated amounts of available water-holding capacity within the study area.

Table 3—Correlation coefficients and mean values of stand and soil variables

Variable		Space	Total depth	Effective depth	AWC	H40 (top height), by age 23	29	48	68	CVTS, by age 23	29	48	68
			r										
Space		—	0.77[a]	0.80	0.77	0.38	0.60	0.90	0.92	-0.57	-0.30	0.71	0.82
Total depth			—	1.00	.82	.64	.77	.85	.83	-.25	-.01	.67	.75
Effective depth				—	.83	.62	.76	.87	.85	-.29	.03	.68	.77
AWC[a]					—	.71	.83	.88	.88	-.16	.17	.80	.86
H40	-23					—	.87	.65	.61	.40	.60	.66	.58
	-29						—	.85	.81	.20	.51	.85	.82
	-48							—	.99	-.29	.03	.85	.95
	-68								—	-.33	-.02	.85	.95
CVTS[b]	-23									—	.92	-.05	-.24
	-29										—	.29	.12
	-48											—	.91
		Feet²/tree	*Feet*							*Cubic feet/acre*			
Mean		59.7	7.0	6.7	1.8	34.5	48.0	74.7	90.6	778	1,664	4,218	6,234
CV[c]		71	35	39	45	9	10	17	19	38	26	28	36

— = no data.

[a] AWC = available water-holding capacity (in feet).

[b] CVTS = cubic volume total stem in trees 1.6-inch diameter at breast height and larger.

[c] CV = coefficient of variation = (standard deviation/mean) X 100.

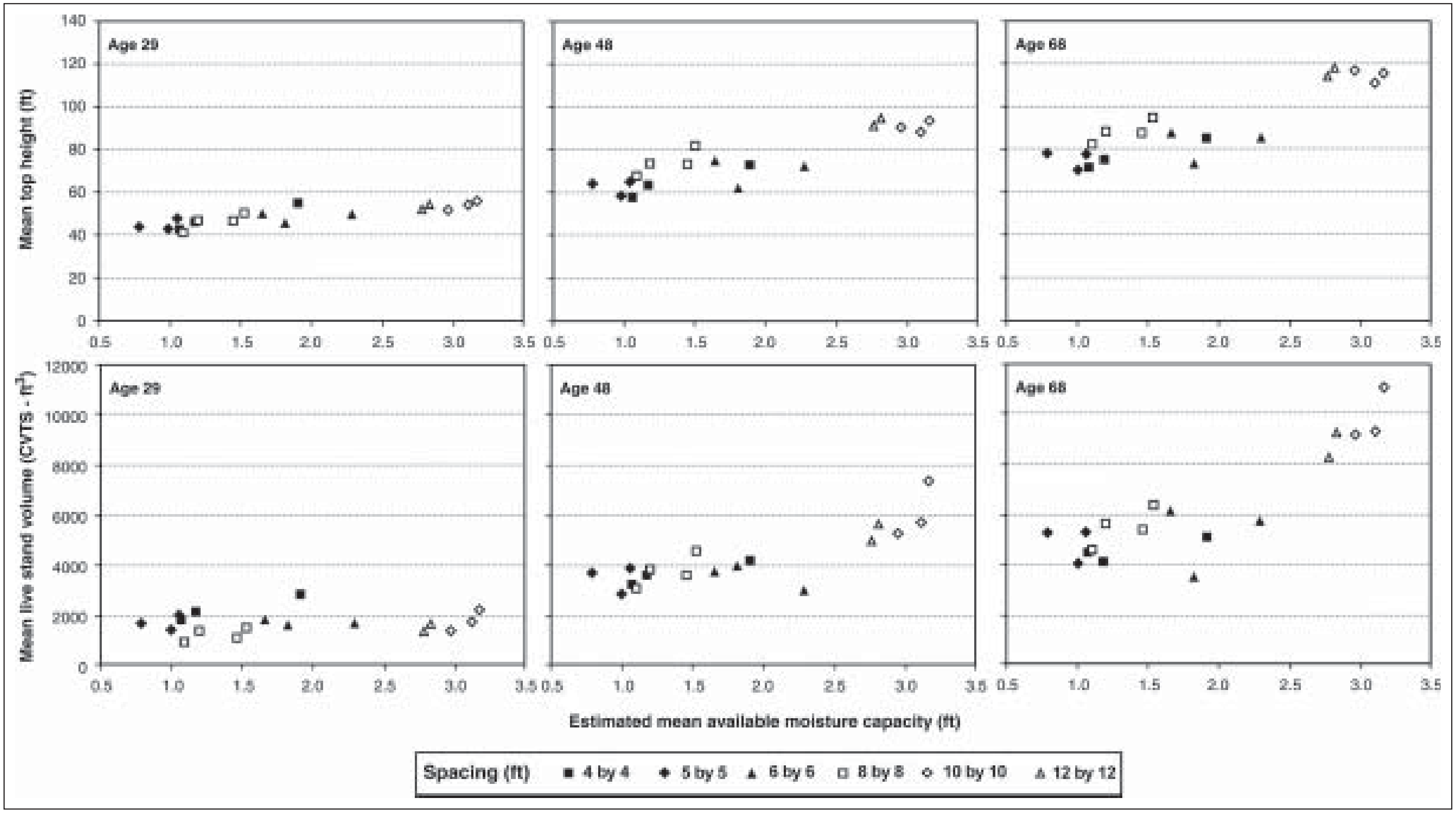

Figure 17—Mean top height (H40) and live stand volume (CVTS) related to estimated mean available water capacity at tree ages 29, 48, and 68 years.

The protracted increases in stand yields in the 10- and 12-ft spacings compared to closer spacings are mathematically related to parallel trends of continuing increases in mean tree size (d.b.h. and height) in these widest spacings and maintained, rather than decreased, numbers of live trees. Thus, the correlation between H40 and CVTS was 0.40 at age 23 years, progressing to 0.95 at age 68 (table 3).

Discussion

The purpose of our investigation was to assess the relative contribution of factors other than seedling spacing to tree performance. We initially assumed that differences among spacings in past growth and current yield at this location were influenced by the following factors and their interactions:

- Soil characteristics, both inherent (soil depth and texture) and as modified by logging and two wildfires
- Initial spacing of planted trees (4 by 4 ft through 12 by 12 ft)
- Replacement of early mortality with equal-aged or younger seedlings of different seed sources and nursery treatments
- Stand dynamics (e.g., competition, snow breakage, blowdown, mortality from suppression)

Several questions are pertinent:

1. What is the relative importance of these growth factors to tree height, d.b.h., and stand volume per acre at this location?

2. Does a gradient of soil quality exist in the study area? Does this gradient favor any spacing (block)?

3. What future research should be undertaken at this site, and at what intensity and with what potential benefits?

The Relative Importance of Individual Growth Factors

Soil characteristics in and near plots sampling this relatively level area differ more than expected. Between the soil surface and the underlying bedrock several sources of variation are potentially significant to tree growth.

Our soil pits and borings near some plots indicate that the surface of the underlying, nonweathered basalt is not smooth but can have at least 5 ft of vertical relief within 40 ft of horizontal distance. This localized variation affects soil depth, hence volume available for rooting. We usually found roots near the basalt bedrock, indicating the importance of soil depth to tree growth. Soil volume available for rooting is further reduced by volume of gravel and cobbles, which are more prevalent at the north end of the study area where the closer spacings are located.

Besides varying in total and effective depth, soil in the study area also differs in particle size: from clay to popcorn-size pumice, to gravel and cobbles of andesite and basalt near the dry channel that dissects the study area. Differences in AWC of these geologic materials and the soils developing from them influence tree growth. Clay content generally increases with increasing soil depth, and in some profiles, clay is 30 to 40 percent by weight of the <2-mm fraction immediately above either the underlying basalt or a thin layer of gravel that occasionally covers it. Even in the dry, late summer (1992), this deep, clay-rich layer at one pit (13 E in the 10-ft spacing) was wet, and Douglas-fir roots reached the bedrock. We infer that water locally accumulates atop the bedrock, which may further explain superior growth in some plots.

Spacing of the planted seedlings (both initial and replacement) is probably the stronger factor affecting tree performance in the study area. This opinion is supported by visual comparisons of tree size where no or minimal differences in soil quality are likely. For example, trees are much larger on the 10-ft spacing side of the east-west boundary between that spacing and the adjacent 4-ft spacing (fig. 18A). Earlier, Eversole (1995: 17) noted "an almost step-like break in the codominant crown level from the 4 x 4 spacing into the 10 x 10 spacing." Secondly, the outermost trees planted at the close spacings border more open conditions outside the plantation; these outermost trees are much larger than their planted counterparts in the interior of the same spacing (fig. 18B).

Finally, inconsistent seed source, planting stock, and planting dates and weather could also explain some variation in tree growth within and among spacings. For example, about 67 percent of the initial planting stock was replaced. The consequence of this could be significant but cannot be quantified because location and subsequent performance of replacement seedlings were not documented.

Is There a Gradient of Soil Quality in This Study Area?

Although initial spacing between trees is probably the most important single factor influencing tree growth and stand yields at this location, some of the exceptionally good tree and stand growth in the 10- and 12-ft spacings is explained by location in deeper, more clay-rich soil at southern portions of the study area. In contrast, soils in the northern portions, where the 4-, 5-, and 6-ft spacings are located, are more influenced by the former gravelly stream channel and are shallower to bedrock. Outcrops or surficial basalt are apparent only on the north and northeast boundary of the study area. Because soils in the closer spacings are generally shallower and have less AWC than do soils in the widest spacings, we conclude that a gradient of soil quality exists among spacings, and the superior tree growth attained in the 10- and 12-ft spacings is due in part to more favorable soil conditions (fig. 17). Note that the effect of more favorable soil quality on height and volume growth is most apparent after age 29.

What Future Research?

The 1925 Wind River spacing test has provided useful information about tree size and growth in the simplest of silvicultural regimes—planting but with no further silviculture. Considering the advanced age of the current stand and lack of true replication of any spacing, we surmise that further research on these plots would yield marginal benefits. We suggest three possibilities, however, if time and finances were available:

1. Focus future soil investigation on within-spacing relations between size of individual trees and soil factors. Our current investigation disclosed much variation in soil texture and in depth to roughly surfaced, nonfractured bedrock. The scale of our labor-intensive sampling, however, was too crude to describe this variation accurately or precisely and then relate it to individual tree performance. Sampling the soil at a finer (more intensive) scale, however, should be considered only when less labor-intensive methods are available.

   Our existing soil information and maps (figs. 15 and 16) suggest that areas of comparable soil exist among portions of some spacings, especially neighboring portions of the 10-, 8-, and 4-ft spacings. For example, temporary 0.05-acre plots could be established in portions of each spacing that sample similar AWC, and the dimensions of the two largest trees in each plot (H40, D40) could be measured. Potential plot locations that might contain gaps from past mortality or snow breakage should be avoided.

A

B

Figure 18—(A) Tree size and uniformity in November 2002 near the boundary between the 4 by 4 and 10 by 10 spacings. (B) Note differences in size of planted trees near the edge of the 5-ft spacing and the more open stand conditions outside that plantation.

2. Greater tree size in wider spacings could have several explanations: more moisture, nutrients, or both. The simpler of these factors to disprove as an explanation is nutrients because these can be added by fertilization. For example, to what extent is growth of dominant trees at two or more spacings increased after fertilization? Does the response differ among the spacings? Considering the parent material and the relatively short period for soil development at this location, we surmise that addition of 200 to 400 lb of nitrogen per acre would increase tree growth measurably. To hedge the possibility that other nutrients also may limit tree growth at this location, addition of other nutrients such as phosphorus, potassium, and sulphur generally known to limit growth in pumiceous soils should be considered.

   We expect that dominant trees in close spacings would respond more to added nutrients (or increased space from thinning) than trees at wider spacing. The trial could be conducted by fertilizing individual trees representing two crown classes (or classes of live-crown ratio) in two or more spacings. We suggest that trees with short crowns would respond slowest or least to added nutrients. Restricting test trees to those located on the more prevalent soils 1 and 2 (app., fig. 19) should reduce within-treatment variation in response. The proposed research question is: Does response in tree height and basal area growth differ (1) among spacings? (2) between crown class or live-crown ratios in each spacing?

3. Seedlings were uniformly planted in this spacing test. Existing stem maps for each plot display an initially uniform pattern and later a nonuniform pattern of surviving trees in each spacing. The paucity of tree mortality in the wider spacings at Wind River means that the trend to nonuniformity of tree-to-tree spacing is proceeding more slowly than at closer spacings, where irregular mortality (associated with snow breakage) as well as suppression mortality is more prevalent. Changing spatial patterns of surviving trees in these plantations could be analyzed and compared with those reported for naturally regenerated stands, which show the opposite trend: between-tree competition drives the natural forest patterns from clustering toward regularity (Moeur 1993).

Conclusions

Some of the differences among the plots in tree height, stand volume, and possibly stand density are explained by soil differences. Tree growth on shallower soils is less than that on deeper soils. Although differences in soil texture and localized perching of water on the basalt bedrock also contribute to differences in soil quality and growth at this spacing trial, their effects are more difficult to estimate.

Deeper soil and greater rooting volume contribute to the superior height and volume growth at the 10- and 12-ft spacings; however, the influence of spacing on growth is probably stronger than that of soil factors at this location.

Acknowledgments

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Metric and English Equivalents

When you know:	Multiply by:	To find:
Inches (in)	2.54	Centimeters
Inches	25.4	Millimeters
Feet (ft)	.3048	Meters
Square feet (ft^2)	.093	Square meters
Acres	.4047	Hectares
Trees per acre (TPA)	2.47	Trees per hectare
Square feet per acre (ft^2•acre)	.229	Square meter per hectare
Cubic feet (ft^3)	.0283	Cubic meters
Cubic ft/acre (ft^3•acre)	.6997	Cubic meter per hectare
Pounds per cubic foot (lb•ft^3)	.0160	Gram per cubic centimeter or megagram per cubic meter
Pounds per cubic foot (lb•ft)	1.12	Kilograms per hectare
Bar	100.0	Kilopascal
Millimeters (mm)	.04	Inches
Grams per cubic centimeter (g/cm^3)	2.	Pounds per cubic foot

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Appendix: Modal Soil Characteristics

***Analytical methods*—**Data in appendix table 4 are based on the following:

Property	Procedure
Physical:[a]	
Bulk density	3 to 50-cc cores per horizon (Blake
Texture	and Hartge 1986) hydrometer
Chemical:[b]	
Organic matter	Potassium dichromate (Grewilling and Peech 1960)
Total nitrogen	Bremner (1965)
Exchangeable cations (P, K, Ca, Na, Mg)[c]	Ammonium acetate with exhaustive extraction
Cation exchange capacity	U.S. Salinity Laboratory Staff (1954)
pH	1:1 water

[a] Analyzed by the Pacific Northwest Forest and Range Experiment Station, Wenatchee, Washington.

[b] Analyzed by the Department of Agronomy, Washington State University, Pullman, Washington.

[c] P = phosphorus, K = potassium, Ca = calcium, Na = sodium, and Mg = magnesium.

Inferences

We infer from laboratory data from modal profiles that tree growth should be favored most on soil 1 and favored least on the shallower and gravelly soil 3 (app. table 4). Although differences between modal profiles of soils 1 and 2 are subtle, we infer better growth conditions on soil 1. The narrower carbon-to-nitrogen (N) ratio in soil 1 indicates a more favorable rate of N cycling between the tree stand and the soil. Secondly, amounts of exchangeable cations in soil 1 are greater than those of soil 2 at all depths. Both characteristics should enhance tree growth on modal soil 1 compared to soil 2. Additionally, strong resistance at about 40 in in soil 2 limits root growth, reducing root frequency (see footnote 7). Meyer noted that compaction (resistance) was not related to greater bulk density, but was related to observed size and number of macropores. Finally, soil 1 has finer textures (silt + clay) below the 4-ft depth. This texture difference should increase plant-available moisture and cation-exchange capacity. Subsequently, we observed rooting to bedrock in the modal profiles of both soil 1 (7.1 ft) and soil 2 (11.6 ft, app., table 5). Total N was estimated at about 6,070 lbs·acre^{-1} for soil 1 and more than 7,000 lbs·acre^{-1} for soil 2 (app., table 4), surprisingly high for these juvenile soils that experienced recent and severe wildfires in 1920 and 1924.

Table 4—Modal soil characteristics of three soil phases as initially mapped in the Wind River spacing trial

Soil phase and modal pit	Depth[a]	Texture >2 mm	Texture Sand	Texture Silt	Texture Clay	Available water[b]	Nitrogen	Cation exchange[c]	Carbon/ nitrogen	Bulk density (<2 mm)	Resistance (firmness)
	Inches	*– – Percent use by weight – –*				*Inches*	*Lb/acre*	*Meq/100 g*		*G/cc*	
1	0-9	21	54	30	16	0.93	1,262	2.0	19	0.82	None
	9-26	17	53	31	16	4.08	1,976	3.8	18	.87	None
16 SW	26-37	4	66	24	10	2.59	847	2.0	8	.89	None
	37-50	5	53	32	15	3.03	787	4.6	9	.85	Weak
	50-85	9	32	43	25	7.86	1,200	18.5	8	.96	Weak-moderate
	All	—	—	—	—	18.5	6,070	—	—	—	—
2	0-8	18	54	30	16	.94	952	1.2	2	.80	None
	8-17	20	56	29	16	.94	1,023	1.1	23	.83	None
7 SW	17-33	5	58	31	11	3.10	1,398	1.3	10	.73	Weak
	33-41	4	68	22	9	1.43	573	1.3	10	.69	Moderate
	41-53	7	66	25	10	2.63	826	1.6	9	.71	Mod.-strong
	53-63	2	75	16	9	2.11	369	.8	10	.79	None
	63-110	0	56	30	15	14.31	1,852	1.7	12	.76	None
	110-139	0	22	46	33	12.79	?	—	—	—	None
	All	—	—	—	—	38.2	7,000	—	—	—	—
3	0-4	16	62	22	16	.63	677	2.1	23	.74	None
	4-12	13	63	22	15	1.22	1,117	1.7	21	.79	None
6 SW	12-22	12	67	19	14	1.10	1,218	1.7	19	.73	None
	22-46	56	74	13	13	.21	1,475	2.3	15	.78	None
	All	—	—	—	—	3.2	4,490	—	—	—	—

— = not applicable.

Source: Meyer 1971 (see footnote 7).

[a] Genetic horizons were not identified.

[b] Difference in percentage moisture (0.2- and 15.0-bar tension).

[c] Sum of exchangeable, potassium, sodium, calcium, and magnesium.

Table 5—Estimated soil depth, available water-holding capacity, and rooting depth at 36 pits in the spacing test[a]

PIT	Soil	Total depth	Effective depth	Available water	Rooting depth
		– – – – – – – – – – – – *Feet*	– – – – – – – – – – – – –		
1 NE	2	5.8	5.3	1.5	3.4
1 SE	2	8.4	8.1	2.2	6.0
3 NE	2	6.9	6.7	1.0	5.8
3 S	3	2.8	1.4	.3	1.8
5 NW	2	6.0	5.3	1.7	6.0
6 N	2	6.3	5.6	1.6	5.3
6 SW	3[b]	3.8	1.6	.3	3.5
6 NW	3	2.0	1.7	.4	2.0
7 SE	2	10.0	9.5	2.7	10.0
7 SW	2[b]	11.6	10.9	3.1	11.6
8 NE	2	4.6	4.0	1.3	4.6
8 W	2	6.6	6.0	1.6	6.6
9 NE	2	4.5	4.0	1.1	4.5
9 NW	2	7.7	6.9	2.0	7.7
10 SW-1	2	5.2	4.5	1.2	5.2
10 SW-2	2	2.7	2.4	.7	2.7
11 NW	2	7.3	7.0	1.9	7.3
13 E	1	10.9	10.8	3.7	9.7
13 NW	1	6.2	—	—	—
14 NE	2	13.7	13.3	3.5	12.8
15 SE	1	9.3	8.8	2.9	9.3
15 NW	1	13.6	13.2	4.0	13.6
16 E	1	4.7	4.4	1.4	4.7
16 SE	1	8.6	8.4	2.9	8.6
16 SW	1[b]	7.1	7.0	1.5	7.1
17 NE	2	5.5	5.0	1.4	3.0
17 NW	3	1.2	1.2	.3	1.3
S-4[c]	2	7.2	6.7	1.8	—
S-6[c]	2	8.7	8.3	2.4	7.0
S-8[C]	3	4.2	4.1	1.1	4.2
S-12[c]	1	14.3	14.2	3.5	14.3
T1 W	3	5.2	4.2	1.2	—
T1 E	3	4.0	2.4	.6	4.0
T3 E	3	4.0	3.9	1.3	4.0
T3 W	3	4.0	3.8	1.2	4.0
T5 W	3	6.0	2.7	.9	6.0

— = not available.

[a] See figure 21 for computer-derived, weighted mean values for each plot.

[b] Modal profile (Meyer 1971). See footnote 7.

[c] Described by Steinbrenner (1961). See footnote 1.

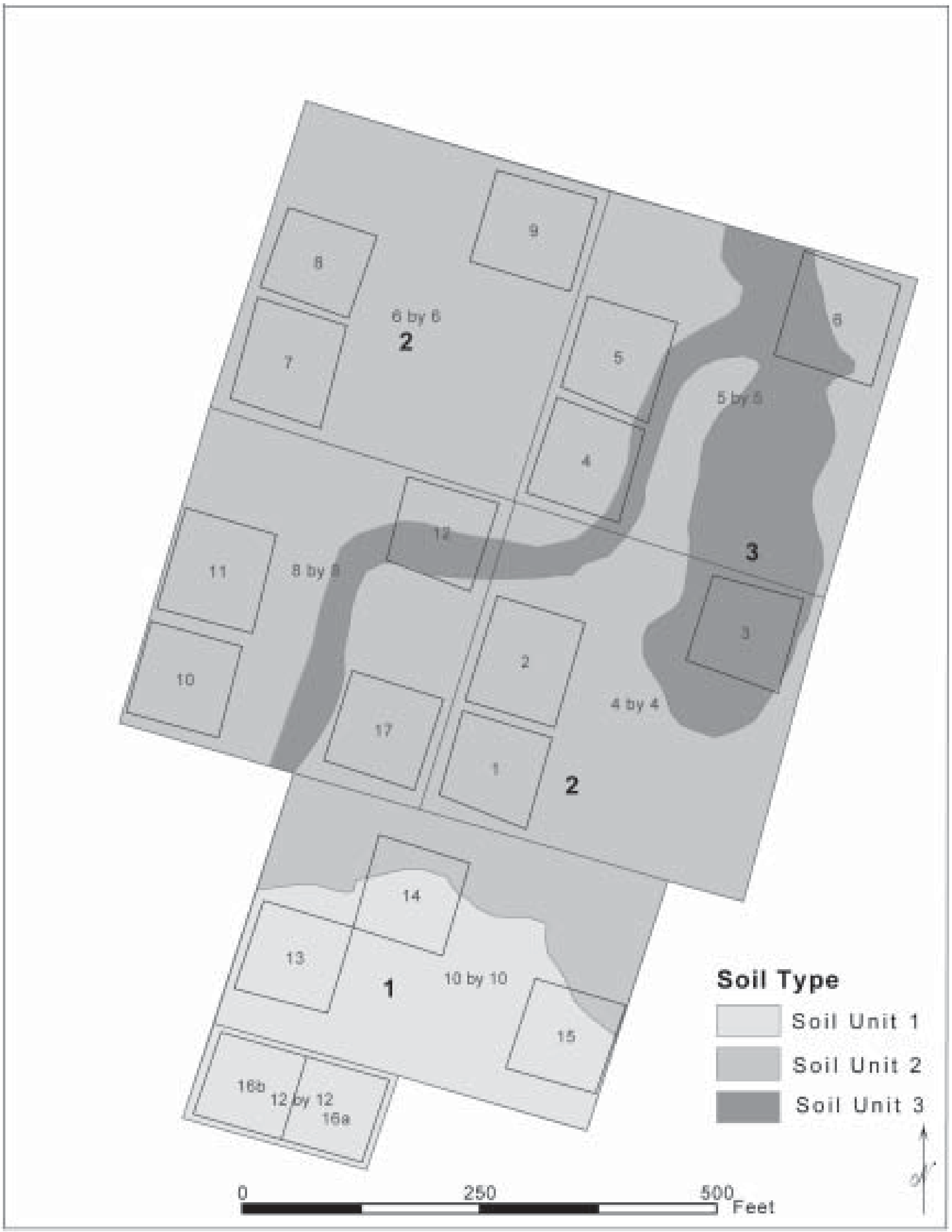

Figure 19—Soil survey map (Meyer 1971, see footnote 7).

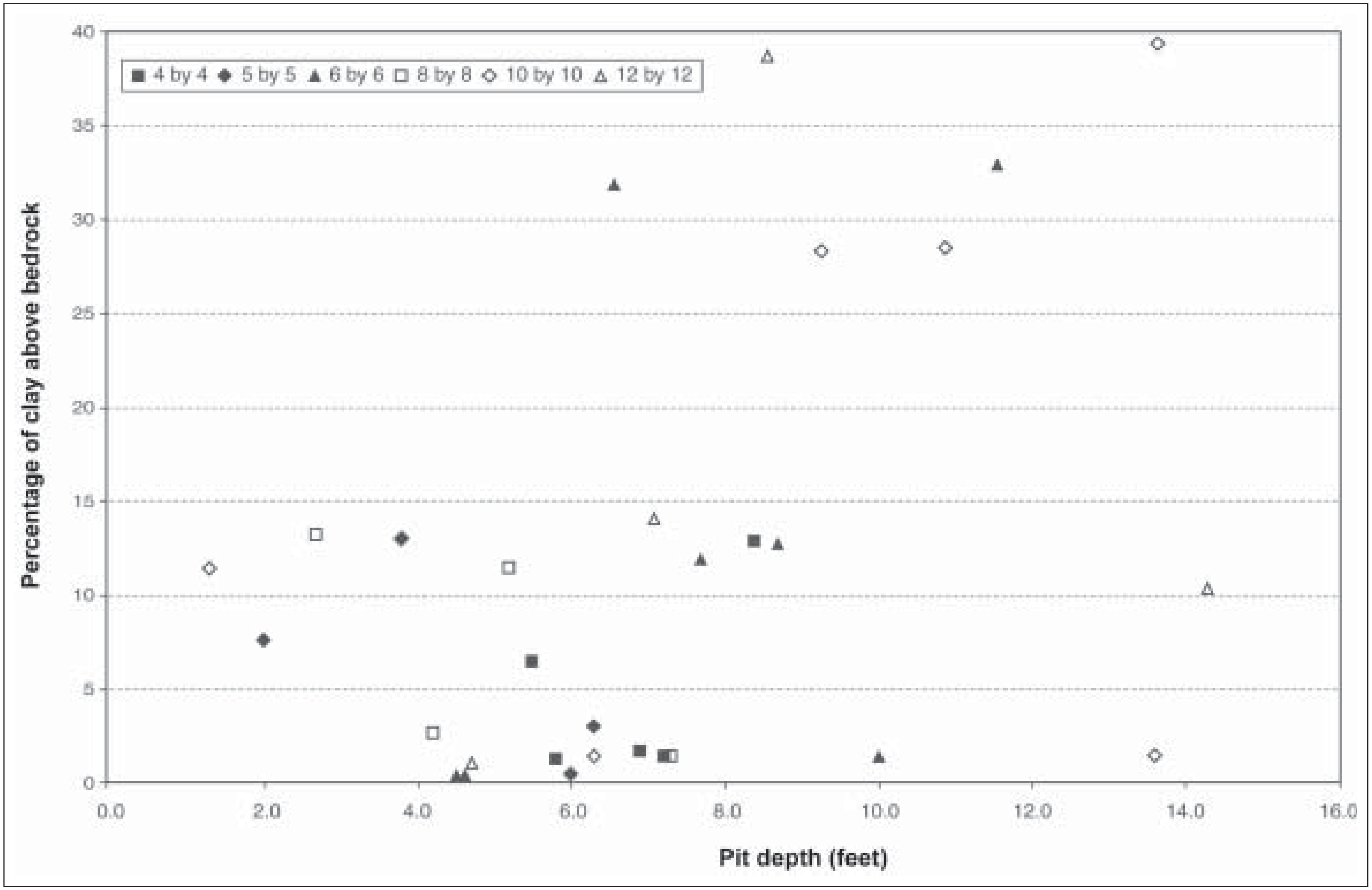

Figure 20—Percentage of clay within 6 in of bedrock versus depth to bedrock.

A

B

Figure 21—Depth to bedrock was determined by (A) excavation (pit 1 SE to 8.4 ft) or (B) partial excavation and boring (pit 17 NE).

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