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# Estimating DOUGLAS-FIR SITE QUALITY from AERIAL PHOTOGRAPHS

by

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# SUMMARY

This study investigated the feasibility of developing a technique for estimating site index of Douglas-fir in the Pacific Northwest, using aerial photos and topographic maps. Physiographic features were used as indicators of site index. Analysis showed that although most of the features were highly significant as criteria for predicting site index, they explained less than one-third of its variation. Equations, using the physiographic features as independent variables, were shown to be useful for estimating site index by a double-sampling procedure--particularly in relatively inaccessible places. As a pioneer study, this paper points the way for further productive research in this field.

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# INTRODUCTION

Increasing intensity of forest management in many areas has generated greater interest in the productivity of forest lands. In the Douglas-fir subregion of the Pacific Northwest, the current transition from an era of liquidation of old-growth timber to one of more intensive management of resources has brought demands for better estimates of growth and yield. This in turn has resulted in a need for more detailed information on site quality.

The site index system as presented by McArdle *et al.* (17) is generally used for judging site quality of Douglas-fir in the Pacific Northwest--limited in this paper to the States of Washington and Oregon. Site index is defined here as the average total height that has been or will be attained by the dominant and codominant trees at 100 years.

Determination of site index has always been based on field measurements of height and age; however, the cost of intensive field work to satisfy most present demands for site data would be prohibitive.

For this reason, research has been directed towards developing a less costly method of estimating site index. This research has been especially prompted by the need on the part of the nationwide Forest Survey[1] for more localized site data to supplement that obtained from its extensive field sampling procedure.

Aerial photographs have revolutionized inventory methods in many fields of resource management. Their value for site determination has been established by several studies and operational surveys (3, 12, 16, 18, 19). For various reasons, however, techniques which have been developed are not entirely suited to the Douglas-fir subregion. None of the methods is geared to the estimation of site index for a particular species. Furthermore, soil maps or a thorough knowledge of soil characteristics of the area are a requisite for these methods. In Washington and Oregon, only a very small amount of forest land has been included in the national Soil Survey which has been concentrated in the agricultural areas. As the Soil Survey is extended, a method of site estimation based, at least in part, on the use of soil maps will undoubtedly be feasible (6, 9, 11, 15).

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[1] Conducted by the U.S. Forest Service to determine the facts regarding present and prospective forest resource supplies and demands of the Nation, and to develop from such facts a sound basis for policy and program decisions on national, State, and local levels.

Several studies have shown significant correlations between site quality and certain topographic conditions which can be measured on photos or topographic maps (1, 2, 4, 7, 8, 15, 20). Aspect, slope gradient, position on slope, and slope configuration can all be evaluated on photos; elevation can be determined from topographic maps. Therefore, a promising approach appeared to lie in the use of aerial photographs and maps to study the effect of such conditions on site index.

## THE DOUGLAS-FIR SUBREGION

Development of a method applicable throughout the subregion is complicated by a great range in climatic and soil factors which affect tree growth. Annual precipitation, for example, varies from less than 20 inches a year in a few places on the lee side of the mountains to more than 120 inches in some areas on the west slope of the Coast Ranges. The frost-free growing season varies from more than 200 days along the coast to less than 90 days at some higher elevations in the Cascade Range. Similarly, soils vary in depth, texture, drainage, and parent material--characteristics which are important to tree growth.

It seemed evident that these broad differences in growing conditions would produce variations in site index which could not be accounted for by topographic features discernible on photos or maps. In an effort to isolate and remove this source of variation, it was decided to divide the subregion into individual study areas, each of which would be broadly homogeneous with respect to climate and soil.

The problem of how to make this subdivision was a difficult one. Climatological data were extremely complex, and information on soil conditions was meager. There was no clear-cut evidence to indicate which of the various climate or soil characteristics was best for defining the desired site strata.

Rather than theorize at the best guidelines, it was decided to use a set of existing site maps as an empirical expression of the effects of climate and soil on growth. These maps showed the distribution of Douglas-fir sites in terms of the five classes described in U. S. Department of Agriculture Technical Bulletin 201 (17). In this classification, site index is expressed as the average height in feet of the dominant and codominant trees at 100 years, with the midpoint of site class I at site index 200, and that of site class V at site index 80.

The site maps, at a scale of 12 miles to the inch, show broad differences in site quality from one part of the subregion to another. These differences reflect the combined effect of climate and soil on tree growth, and areas mapped as a uniform site class could be considered relatively homogeneous with respect to these two influences.

At the same time, the maps were of such a generalized nature that within any one site class there was plenty of local variation, usually including most if not all of the full range of the five site classes. This local variation within broad areas of uniform mapped site was important. It was hypothesized that a large part of it could be accounted for by measurements of physiographic features on photos and maps. Without such a variation there would be no study, for it was necessary to have a range of site values in order to determine the relation between site index and physiographic features.

Thus, the site maps provided a suitable basis for dividing the subregion into separate study areas. They were detailed enough to show broad differences due to the effects of soil and climate yet general enough to permit the needed local variation within these broad areas. Using the site maps, the subregion was tentatively divided into the 11 study areas shown in figure 1. In each of these areas one, or sometimes two, of the mapped site classes predominated.

This paper is based on a study of one of these areas, as shown in figure 1, to be referred to hereafter as the study area.

## THE STUDY AREA

The study was conducted on an area of about 4.2 million acres along the west slope of the Cascade Range. The area is roughly 235 miles long and varies from 10 to 50 miles in width.

The generalized site maps indicated that this area was predominately site class III. However, the site class distribution of the plots used in the study showed that all classes were sampled very nearly in proportion to the distribution of sites in the entire Douglas-fir subregion. The study area offered enough local site variation to make the study possible.

|  | Study plots (Percent) | Douglas-fir subregion (Percent) |
|---|---|---|
| Site class: |  |  |
| I | 4 | 2 |
| II | 19 | 29 |
| III | 39 | 44 |
| IV | 29 | 21 |
| V | 9 | 4 |
| Total | 100 | 100 |

In general, the study area slopes downward from east to west. The east boundary roughly coincides with the edge of the true fir–mountain hemlock type at approximately 3,000 feet elevation at the north end of the area and rises to about 4,000 feet at the south. A few areas with greater elevations occur further to the west and stand as islands within the study area.

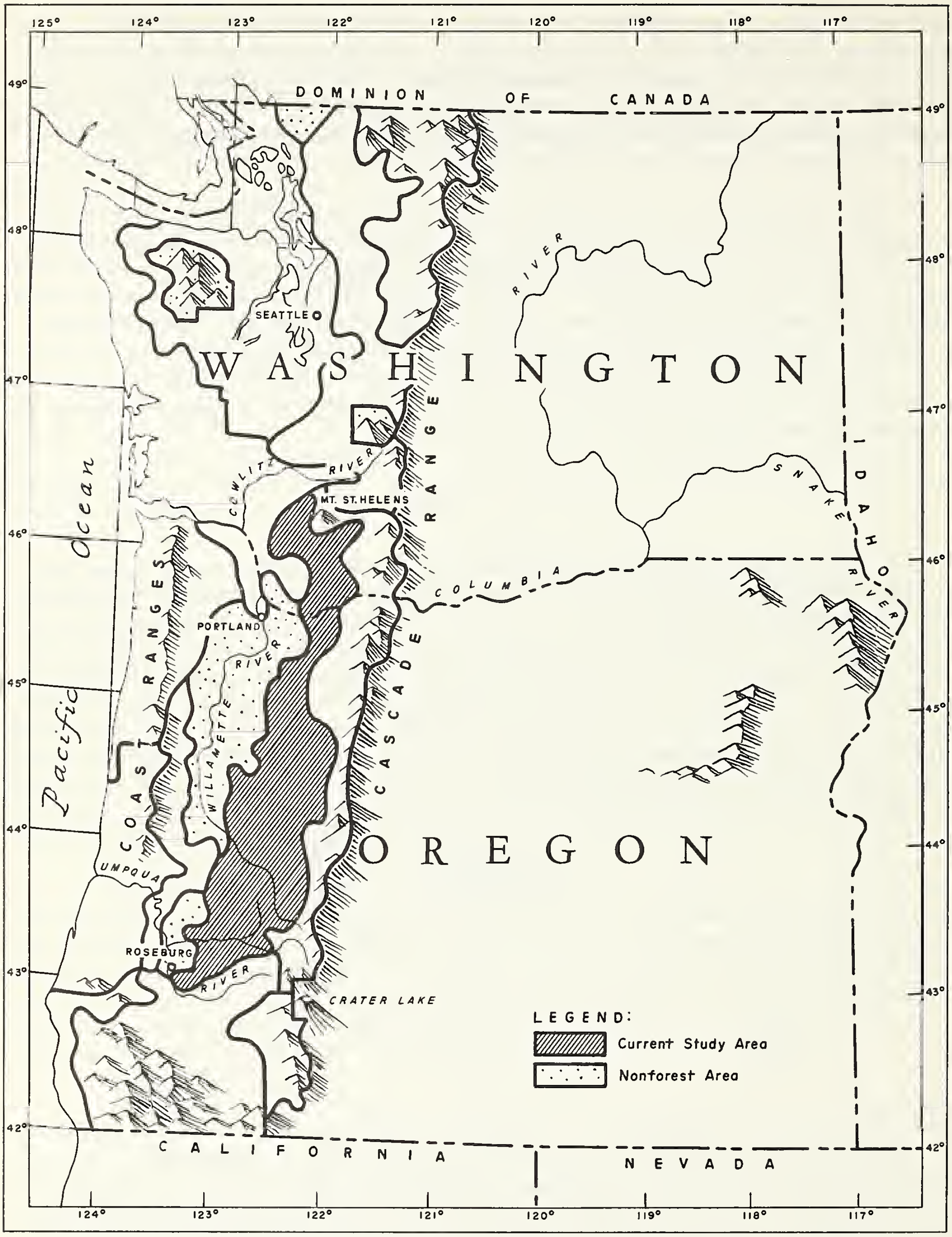

Figure 1.--Logical study areas within the Douglas-fir subregion.

The west boundary of the area is less clearly defined in some places. In Washington, it varies between 1,500 and 2,000 feet and follows the eastern edge of an area of better sites (site class II) which comprises part of a future study area. In Oregon the west boundary follows the edge of the farm and farm-forest lands which lie in the Willamette Valley and meanders southward to about latitude 43°.

The forest consists almost entirely of Douglas-fir with an intermingling of western hemlock, western redcedar, and true firs. Red alder, the principal broadleaf tree, occurs in small patches and stringers.

Extremes of climatic and soil conditions are considerably less than for the entire subregion. Except for a few minor areas, average annual precipitation ranges from 40 to 80 inches. Average length of periods without a killing frost varies from 120 to 190 days. Soils, while ranging greatly in depth, are in many other important respects less heterogeneous than those of the subregion as a whole.

## METHODS

The three principal steps in the study were: first, selection of independent variables having an important effect on site index (the dependent variable); second, collection of data--measurements of dependent and independent variables at locations throughout the study area; third, analysis of data by multiple regression. Methods are discussed here in terms of these three steps.

### Variables

In selecting independent variables, the best approach was to measure topographic and other features which might affect climate and soil and therefore provide a measure of site index.

The choice of specific independent variables rested on two considerations: first, preferably they were features which had been indicated experimentally or empirically as having an effect on tree growth; and second, they were consistently recognizable and susceptible of measurement or classification through the use of aerial photographs or maps. Based on these considerations, seven independent variables were selected for testing: elevation, latitude, aspect, slope percent, shape in profile, shape in contour, and soil depth.

Elevation.--Site index of Douglas-fir decreases generally from low to high elevations. Evidence even indicates that elevation-related differences in growing conditions have resulted in strains of Douglas-fir with inherently different growth rates (13 and 14). For this study area, which ranged from just above sea level to 4,000 feet, and in a few places to more than 5,000 feet, elevation appeared as an essential and promising variable.

Latitude.--Results of the investigative work referred to above (13 and 14), also showed that growth habits vary with latitude. Even within the 235-mile length of the study area, climatic data indicated a difference in length of the growing season sufficient to affect growth rate.

Another consideration in the use of latitude as a variable was the possibility that it might reflect the effect on growth of major soil differences which occur from south to north.

Aspect.--Aspect is universally considered as having an important effect on tree growth. In temperate latitudes the cool, moist, north slopes are more favorable for growth of many coniferous species than the hotter and drier south slopes. For Douglas-fir in the Pacific Northwest, McArdle *et al.* (17) observed that "The most rapid growth was found on slopes facing north, northeast, and east...".

The classifying or rating of aspect so that it could be used as a variable in a multiple regression analysis was one of the most difficult problems in the study. Literature provided no more than generalized information. Largely through rationalization based on scanty data, the decision was made to use three classifications which were assigned arbitrary ratings or values. The most favorable locations were considered as those facing north, northeast, and east (between 315 and 135 degrees azimuth) and the poorest as facing south, southwest, and west (135 to 315 degrees azimuth). The classification of level locations (less than 5-percent slope) as to aspect was not clearly indicated since a level location might be considered as representing either all or no aspect. The rational approach appeared to lie in classifying them as intermediate.

Slope percent.--This variable was considered important not only because of its obvious effect on drainage but also because it is a factor in determining various other soil characteristics and climatic conditions. As discussed later under "Analysis," it was decided that the interrelated effect of aspect and slope percent on site quality could be better expressed by combining these two variables.

Shape in profile.--Configuration of the land affects soil and climatic conditions which in turn affect site quality. In this study, land is classified on the basis of its shape in two planes--vertical (profile) and horizontal (contour).

Tarrant (20) studied the effect of curvature of the land in profile on site quality of Douglas-fir. He found that site index was significantly greater on the concave terrain characteristic of lower slopes, valleys, and basins than on the convex situations associated with upper slopes, hilltops, and ridges. Upper slopes lose moisture and soluble salts through drainage and are depleted of fine material and humus by erosion. Also, they are generally more exposed to winds and lose a greater amount of moisture by evaporation than do lower slopes. Conversely, sites on lower slopes benefit from deposition of fine material, soluble salts, and water.

Between these two extremes of topographic shape are the straight slopes of relatively uniform gradient, neither convex nor concave. These are generally intermediate in site quality.

As a result of these considerations, the following three classifications for shape in profile were used in this study.

Convex.--Relief is bulging or rounded in profile and includes, for the most part, upper slopes and ridgetops. For the purpose of this study it also includes level areas or plateaus which do not receive drainage from above.

Straight.--Slopes which are neither convex nor concave, i.e., of uniform gradient. These are usually midslopes which lose moisture through drainage at about the same rate as they receive it.

Concave.--Relief is hollowed in profile, and is represented most frequently by lower slopes, basins, and valley floors. For the purpose of this study, it also includes level areas in bottoms or benches which are primarily receivers rather than donors of runoff and underground drainage.

Figure 2 illustrates the situations normally encountered and the classifications used.

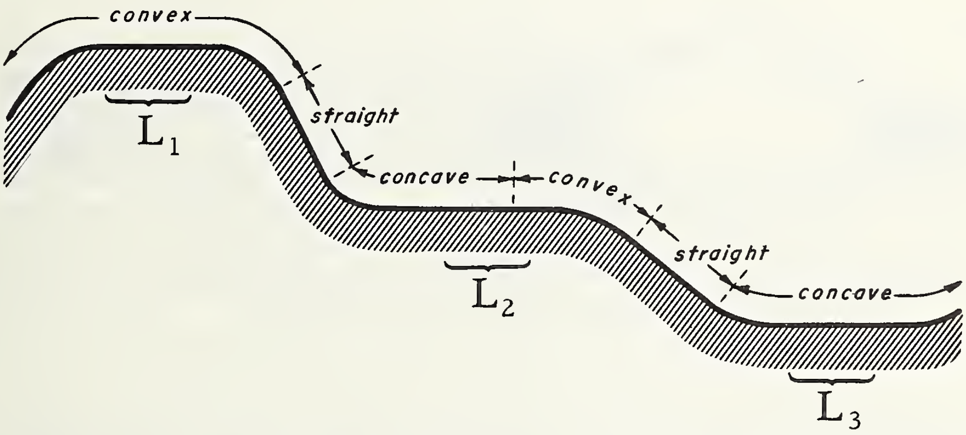

Figure 2.--Classification of shape in profile illustrated by a diagram of a vertical section through a hillside. Level locations ($L_1$, $L_2$, and $L_3$) are rated as concave or convex, depending on topographic location and consequent drainage characteristics. Note that the portion of $L_2$ which is judged primarily a receiver of drainage is rated concave, and that which is largely a donor of drainage as convex.

Shape in contour.--The terms "convex" and "concave" were also used to express the curvature of the land in a horizontal plane. Thus, the end of a ridge or a protuberance on a ridge was classified as convex, while an indentation such as a draw or a cove would be concave.

Horizontal or contourwise configuration is important because it affects the duration or frequency of exposure of the site to wind and sun, and also because it influences drainage. A site in a depression such as a draw is usually more moist than one on a spur or the end of a ridge. The former is more sheltered from the drying effects of wind and sun and, furthermore, is frequently the location of a stream or intermittent drainageway.

The three classifications used for this variable were:

Convex.--Relief is bulging in contour, such as ends or protuberances of ridges.

Straight.--Slopes without significant curvature in contour. This classification also includes level situations.

Concave.--Relief is hollowed in contour, such as draws or minor valleys on hillsides.

These classifications are illustrated diagrammatically in figure 3.

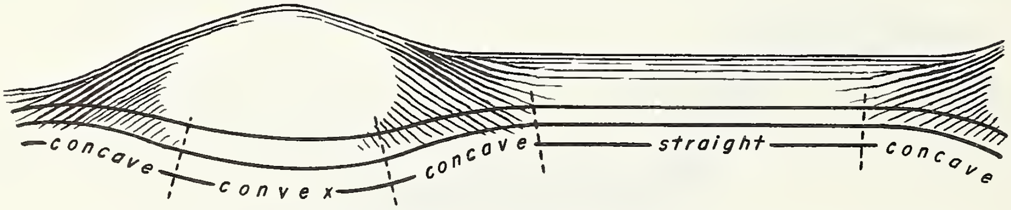

Figure 3.--Classification of shape in contour illustrated by the configuration of contour lines on a hillside.

Soil depth.--Depth of soil has been recognized as an important factor affecting the growth of Douglas-fir (4, 9, 15). While it was obvious that a photo interpreter could not measure soil depth, he could see on the photos certain features that were related to it.

Elevation, slope, and topographic shape are known to have an effect on soil depth, and these have already been taken care of as independent variables. Also, it was possible to distinguish on the photos broad areas where relatively shallow soils were indicated by visible rock outcrops and generally rugged terrain. When such evidence occurred over areas of several square miles or more, all soils within the area, except alluvial valley floors, were given the classification of "shallow." All other soils were simply classified as "deep."

## Collection of Data

Observations were made at 800 locations in the study area. For 662 of these, data were taken from Forest Survey plot records; for the other 138, new locations were visited in the field--principally in portions of the study area not covered by the survey. Data from both sources consisted of field measurements of tree height and age and aerial photos showing exact locations of field measurements.

The field measurements of tree height and age provided an estimate of site index for each plot. In the case of the Forest Survey plots, these were based on one dominant tree. On the new plots, however, two or three dominant trees were measured, and an average site index was computed.

Elevation and latitude for each point were determined from topographic maps--mostly at scales of 1:62,500 with 80-foot contour intervals.

The other independent variables were estimated from aerial photographs on which field locations had been pricked. Photo scales were from 1:12,000 to 1:24,000; focal lengths were 12 inches for the larger scales and 8-1/4 inches for the smaller.

For the purpose of determining aspect, slope, and topographic shape, a minimum area of 1 acre was arbitrarily adopted. Areas much smaller than this were too difficult to characterize on small-scale photos, and larger areas often became too complex to describe.

Aspect of each location was measured on photos by laying a straightedge in the direction that the slope faced and measuring the angle it made with some known bearing. Where photo flight lines ran in cardinal directions, an assumed orientation for the photo edge was considered accurate enough for this study.

Slope percent was measured on either photos or maps. When photos were used, parallax measurements were made at two points (usually less than 10 chains apart) which appeared to lie on the plane of the average gradient of the site location. Preferably they were chosen along the line of direction of aspect, one point being located uphill and one downhill from the location. Where heavy cover prevented observations at ground level, the canopy was used. The difference between the parallax readings of the two points, converted to feet, divided by the horizontal distance between the points (as measured in feet on the photos) gave a fraction which when multiplied by 100 equaled slope percent.

The use of topographic maps at a scale of 1:62,500 with 80-foot or closer contour intervals was found to be faster and almost as accurate as the parallax procedure. Analysis of the accuracy of the two methods on about 100 plots for which ground readings of slope percent were available showed that the parallax method gave only a slightly lower average error and an insignificantly higher correlation coefficient of ground and estimated values.

Shape in profile, shape in contour, and soil depth were all evaluated on the photos as previously described.

## Analysis

The variables previously discussed were used as independent variables in a multiple regression analysis to produce an equation for predicting site index.

This method requires that each variable have a numerical value for each of the plot observations. Elevation, latitude, and slope were quantitative variables, and the values were obtained directly from the plot measurements on maps and photos. To simplify the computations, measurements for these variables were grouped into classes, and code values were assigned as tabulated below.

| | Value |
|---|---|
| Elevation (above sea level): | |
| 0-100 feet | 1 |
| 101-200 " | 2 |
| 201-300 " | 3 |
| ↓ | ↓ |
| 5,901-6,000 " | 60 |
| Latitude: | |
| 42°00'-42°29'59" | 1 |
| 42°30'-42°59'59" | 2 |
| 43°00'-43°29'59" | 3 |
| 43°30'-43°59'59" | 4 |
| 44°00'-44°29'59" | 5 |
| 44°30'-44°59'59" | 6 |
| 45°00'-45°29'59" | 7 |
| 45°30'-45°59'59" | 8 |
| 46°00'-46°29'59" | 9 |
| 46°30'-46°59'59" | 10 |
| 47°00'-47°29'59" | 11 |
| 47°30'-47°59'59" | 12 |
| 48°00'-48°29'59" | 13 |
| 48°30'-48°59'59" | 14 |
| Aspect: | |
| Azimuth 315°-135° | 1 |
| Level (less than 5-percent slope) | 2 |
| Azimuth 135°-315° | 3 |

|  | Value |
|---|---|
| Slope percent: |  |
| 0-14.9 | 1 |
| 15-34.9 | 2 |
| 35-54.9 | 3 |
| 55-74.9 | 4 |
| 75+ | 5 |
| Soil depth: |  |
| Shallow | 1 |
| Deep | 2 |

|  | (Profile) | (Contour) |
|---|---|---|
| Shape: |  |  |
| Convex | 1 | 1 |
| Straight | 2 | 2 |
| Concave | 3 | 3 |

The remaining variables were qualitative rather than measured, and it was necessary to assign somewhat arbitrary values to the various classes recognized. A clear-cut explanation on the use of qualitative variables in a multiple regression analysis could not be found in the literature. However, this method has been previously used in a somewhat similar study (4).

Tentative values were assigned to each class of these qualitative variables, using logic and the best available information, in an effort to express their probable relation to site index. The basic data was then sorted into these classes, and average site index was plotted over the various independent variables to test the reasonableness of the assigned values.

For example, the poorest sites were known to be associated with convex land forms, the best with concave shapes, while straight slopes were intermediate. A logical approach was to rate such shapes respectively 1, 3, and 2; a plotting of the basic data indicated that this approach was reasonable. It also showed that shape in profile and in contour had equal influence on site index, and hence should be given the same ratings. Using this same procedure, the ratings shown above were assigned to the remaining qualitative variables.

The sorting and plotting of site index values over various independent variables served the additional purpose of indicating any tendency toward curvilinear relations or interaction between independent variables. Where curvilinearity was suggested, the square of the variable was added as an additional independent variable. Where sorting simultaneously by two variables produced a family of curves that fanned out, the product of these variables was added to take care of the interaction.

In the process of sorting and plotting the basic data, variables were also combined several different ways to see if any of the resulting combinations appeared to be more closely related to site index than were the individual variables. Two instances were found where pairs of variables worked best when added together rather than treated separately. Combined variables were therefore made and assigned values obtained by simply adding the values of the individual variables.

As a result of this preliminary analysis, the following appeared to be the most promising variables for estimating site index:

Elevation
Elevation$^2$
Latitude
Latitude$^2$
Aspect + slope
(Aspect + slope)$^2$
Shape in profile + shape in contour
Soil depth
Elevation X latitude

The multiple regression analysis was performed on an IBM 704 electronic data processing machine, using the Southern Forest Experiment Station's 704 regression program (10). This recently developed program permitted an infinitely more comprehensive analysis than would otherwise have been feasible. It provided the solution to 511 regression equations for predicting site index. This was every possible equation involving one or more of the nine independent variables. The program furnished the equation constant and the regression coefficients for each variable in each of these equations. It also showed how much of the total variation in site index was accounted for by each equation, thereby indicating which equations were best.

Another form of analysis, covariance, would have been appropriate for this kind of data containing some qualitative variables. It was rejected because of the problems created by the large number of groups into which the data would have to be sorted. The three categories each for aspect, shape in profile, and shape in contour, plus two for soil depth, would have resulted in a total of 54 groups for the covariance analysis. Not only would some of these groups have been too weak for a satisfactory analysis, but the large number of prediction equations would have been unwieldy to apply.

## RESULTS

The 511 equations were screened to select those which appeared most efficient from the standpoint of statistical significance and ease (cost) of use. The initial screening consisted of selecting nine equations--one from each of the nine groups (1-variable group, 2-variable group, etc.). The equation selected in each case was the best one; that is, the one which accounted for the greatest amount of variation in the dependent variable, site index. A test was then made of the reduction in variation in going from the best of the 1-variable equations to the best of the 2-variable, the best of the 2-variable to the best of the 3-variable, and so on. Significance was found at the 1-percent level in going from the 1-variable to the 2-variable, from the 2 to the 3, the 3 to the 4, the 4 to the 5, and at the 5-percent level going from the 5 to the 6, the 6 to the 7, and the 7 to the 8; nonsignificance was encountered between the 8 and the 9 variables.

Eight equations from the initial screening are shown as equations 1 to 8 in table 1. The 9-variable equation was omitted from the table since it was not significantly better than equation 8. The variable $x_6$, (aspect + slope)$^2$, has also been omitted inasmuch as it only appeared in the 9-variable equation. The ninth equation in the table was added for reasons which are discussed below. Table 1 also shows for each equation the variation in site index accounted for and the multiple correlation coefficient.

In selecting the "best" equation for practical application, cost of measurement of each of the variables must be considered, as well as the variation accounted for by the equations. Of the nine independent variables, the aspect + slope combination ($x_5$) is by far the most expensive to measure; also it is in general the poorest contributor to a satisfactory estimate of site index, as shown by the standard partial regression coefficients in table 2. The magnitude of these coefficients (without regard to sign) is indicative of the relative effectiveness of the variables within an equation. For these reasons it appeared desirable to select, as an efficient equation, the one which did not include either $x_5$ or $x_6$. This is shown as number 9 in table 1. This equation, while slightly less precise than 7 and 8, is probably the most efficient for general use.

The poor showing of aspect + slope is surprising, and difficult to explain. Possibly these factors actually have more bearing on site quality than has been shown by this study but were not effectively evaluated or rated. Or they really may not significantly affect growth in this portion of the midlatitudes where climatic factors are more moderate than those prevailing further north or south or beyond the mountains to the east.

Interesting effects of latitude and elevation on site index are shown in figure 4. As stated previously, consideration of latitude was intended to account for the effect of the differences in length of growing season between north and south. At higher elevations, results are much as expected--a decrease in site index from south to north. At lower elevations, the relationship is reversed, with other factors such as precipitation and soil fertility apparently overriding and resulting in better sites to the north.

Table 1.--Values for selected regressions of site index on one to eight independent variables

| Equation number | Constant | Partial regression coefficients for independent variables, including standard errors for these coefficients in equations 8 and 9 | | | | | | | | Variation accounted for | Multiple correlation coefficient |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Elevation | Elevation$^2$ | Latitude | Latitude$^2$ | Aspect + slope | Shape in profile + shape in contour | Soil depth | Elevation X latitude | | |
| | (a) | ($x_1$) | ($x_2$) | ($x_3$) | ($x_4$) | ($x_5$) | ($x_7$) | ($x_8$) | ($x_9$) | | |
| | | | | | | | | | | Percent | |
| 1 | 100.319 | -- | -- | -- | -- | -- | -- | 21.9623 | -- | 14.42 | 0.380 |
| 2 | 128.708 | -0.698504 | -- | -- | -- | -- | -- | 15.8268 | -- | 19.24 | 0.439 |
| 3 | 104.744 | -0.668522 | -- | -- | -- | -- | 6.09781 | 15.4478 | -- | 22.95 | 0.479 |
| 4 | 79.4151 | -- | -- | 5.11886 | -- | -- | 6.16029 | 13.6257 | -0.124242 | 25.70 | 0.507 |
| 5 | 47.1654 | -- | -- | 18.0847 | -1.10547 | -- | 6.00265 | 13.4524 | -0.127078 | 27.14 | 0.521 |
| 6 | 57.8028 | -- | -- | 17.6783 | -1.08051 | -1.46587 | 5.78870 | 12.2024 | -0.126915 | 27.62 | 0.526 |
| 7 | 37.4848 | 0.613757 | -- | 21.7618 | -1.19082 | -1.42965 | 5.76121 | 12.5407 | -0.237048 | 28.05 | 0.530 |
| 8 | 17.5713 | 1.67562<br>±0.5782 | -0.014071<br>±0.0067 | 24.1676<br>±3.9656 | -1.27436<br>±0.2846 | -1.43768<br>±0.6370 | 5.85921<br>±0.9608 | 12.6291<br>±2.0298 | -0.293665<br>±0.0602 | 28.45 | 0.533 |
| 9 | 6.7313 | 1.68517<br>±0.5796 | -0.0139802<br>±0.0067 | 24.6595<br>±3.9699 | -1.30123<br>±0.2851 | -- | 6.06752<br>±0.9589 | 13.8627<br>±1.9599 | -0.296403<br>±0.0603 | 27.99 | 0.529 |

Table 2.--Standard partial regression coefficients for independent variables in equations 8 and 9

| Equation number | Elevation ($x_1$) | Elevation$^2$ ($x_2$) | Latitude ($x_3$) | Latitude$^2$ ($x_4$) | Aspect + slope ($x_5$) | Shape in profile + shape in contour ($x_7$) | Soil depth ($x_8$) | Elevation X latitude ($x_9$) |
|---|---|---|---|---|---|---|---|---|
| 8 | 0.5850 | -0.2804 | 1.5598 | -0.9706 | 0.0726 | 0.1854 | 0.2184 | -0.5727 |
| 9 | 0.5883 | -0.2785 | 1.5916 | -0.9911 | -- | 0.1920 | 0.2397 | -0.5780 |

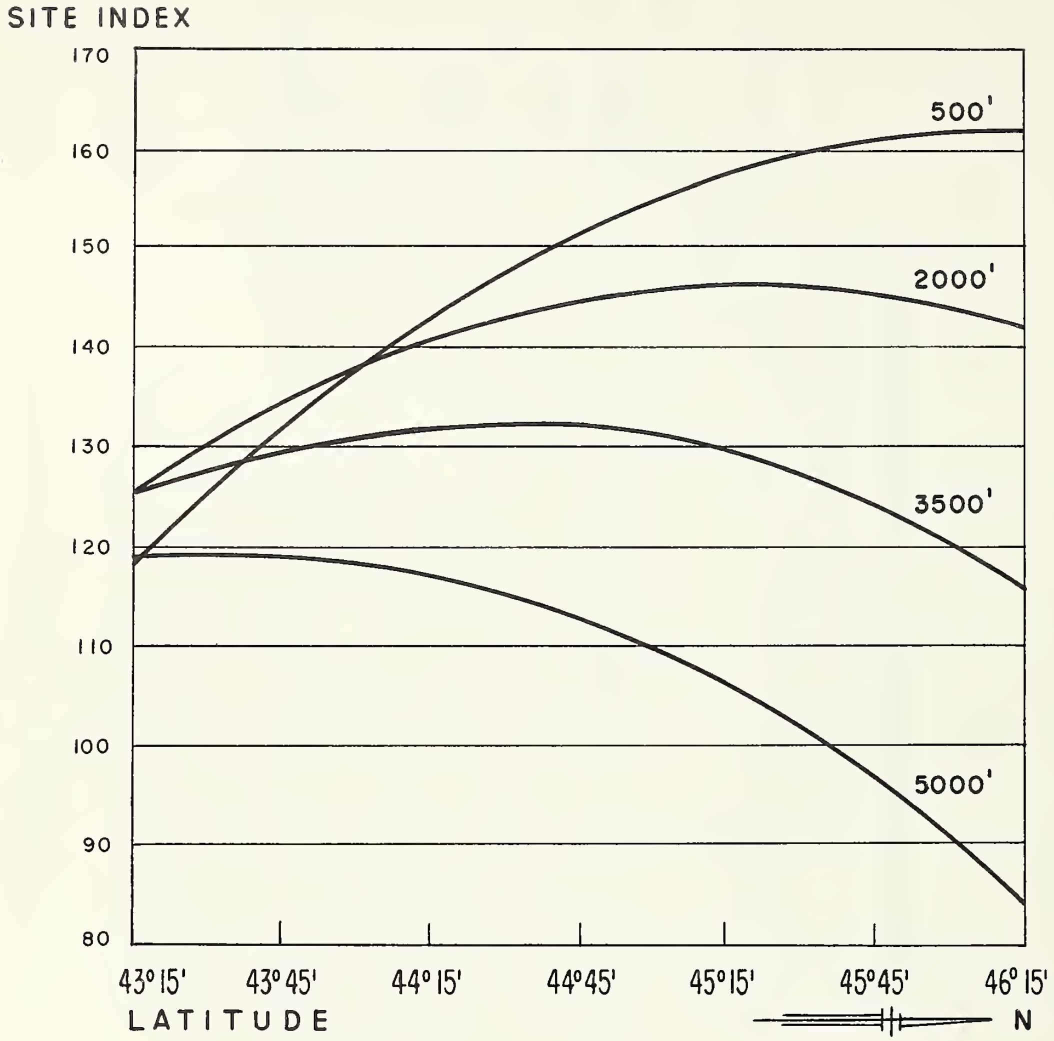

Figure 4.--Site index as affected by latitude at certain elevations. Relationships were computed by equation 8, with variables $x_5$, $x_7$, and $x_8$ held at their means.

## TEST FOR SUBJECTIVITY

Since all measurements for the study were made by one interpreter, it was desirable to test the technique with other interpreters. If significant differences were found among interpreters in their evaluation of the independent variables, applicability of the equations in table 1 for estimating site index might be questioned.

The test was based on measurement of three variables by each of three interpreters. Measurements of the variables were made for 100 locations selected at random from the original 800. The three variables--aspect + slope ($x_5$), profile + contour ($x_7$), and soil depth ($x_8$)--were selected as the only ones for which interpreter bias might result in significant differences in measurements. Since the other variables were based on map readings of elevation and latitude, identical values could be expected for all interpreters.

The three interpreters (the one who conducted the study and two others) varied considerably in their experience in measuring and evaluating terrain features on aerial photos. The interpreter who conducted the study and trained the other two (for about 2 days) in the techniques and standards used for evaluating the variables had almost 15 years' experience; the second interpreter had 10 years' experience; and the third about 3 years'.

A statistical test of significance showed that all interpreters got essentially the same values for profile + contour and soil depth but not for aspect + slope. The test was based on analysis of variance which recognized three sources of variation--plot, interpreter, and the plot-interpreter interaction. Except for aspect + slope, the interpreter effect was not significantly greater than the interaction effects.

A test was also made to determine whether interpreter subjectivity materially affected estimation of site index. For this test the site index at each location was estimated by each interpreter using equation 8 (all variables). For $x_5$, $x_7$, and $x_8$, the interpreter's estimates were used; for other variables, values were held constant for all three interpreters at each location. Analysis of variance of these data showed no significant differences among interpreters in their estimation of site index.

In summary, results of the test indicate no significant differences among trained interpreters in their estimation of average site index. Even when the aspect + slope variable is used this is the case. However, the significantly different results among interpreters in their measurements of aspect + slope provide further reason for discarding this variable; it contributes little to the total estimate and is difficult and time consuming to measure.

## APPLICATIONS

Of the total amount of variation in site index, only 28 percent is accounted for by the best of the prediction equations. The remaining 72 percent is not associated with the independent variables used, resulting in a substantial sampling error for any estimates of site index made by using the equations. Under these conditions, site index estimates for specific points or small areas would not be feasible. However, the best prediction equations could be efficiently used to estimate the average site index for relatively large and inaccessible areas.

The effect of basing a site index estimate on a single observation can be seen when the sampling error is computed. Under conditions where each of the independent variables has an average value, the predicted site index and its standard error are 137.7 ± 24.6. At the 95-percent confidence level, the sampling error becomes ±48.3 site index points. In other words, the true site index should lie within ±48.3 points of the estimated site index (137.7), unless a 1-in-20 chance has occurred. If observation values for the independent variables differ considerably from their mean values, then the sampling error for the predicted site index increases slightly. With sampling errors of this size, it is clear that little confidence can be placed in a site index estimate based on a single observation.

On the other hand, photo observations may be quite useful for predicting average site index of areas within a survey unit such as watersheds, working circles, or ownership classes. For rough estimates, photo observations alone may be sufficient, but for a more precise estimate a combination of photo and ground estimates will be needed.

Use of photo estimates alone will usually be limited to determining relative site quality of several areas rather than accurate (unbiased) estimates for each area. The occasional demands for rough but quick comparisons of site quality of two or more areas can, in many instances, be fulfilled much more economically by photo estimates than by field work. An estimate of relative site quality for various portions of a deforested area is another instance where the physiographic criteria used in the study might be particularly valuable. In such cases ground estimates of site index may be impossible for lack of trees on which to measure height and age.

A combination of photo and ground plots will be necessary whenever unbiased estimates for individual areas are important. The best principal application in this respect might be double sampling with regression.

This method requires a relatively large number of inexpensive photo estimates (based on one of the equations developed in the study) together with a few far more costly field measurements. The latter are taken on a portion of the locations used for photo estimates. Regression is used to adjust the large photo sample by means of the small field sample. This correlation between ground and photo estimates results in a more precise estimate than that which could be obtained for the same cost with ground plots alone. As shown in table 2, a correlation coefficient somewhat greater than 0.5 may be expected.

The two sets of estimates--photo and field--provide the necessary data for computing average site index using the following formula (5):

$$\bar{y}_D = \bar{y} + b\,(\bar{x}_L - \bar{x})$$

where $\bar{y}_D$ = estimate of average site index from the double sample

$\bar{y}$ = average of all field observations of site index

$b$ = regression coefficient (regression of field on photo for locations at which both measurements were taken)

$\bar{x}_L$ = average of all photo observations of site index

$\bar{x}$ = average of photo observations of site index at locations for which field observations were also taken.

A double sampling survey can only be considered more efficient than a conventional field survey if it results in a lower cost for the same standard error, or a lower standard error for the same cost. In obtaining maximum efficiency from double sampling, the number of photo plots in relation to the number of field plots is critical. The optimum ratio of photo plots to field plots is the one that will give the minimum standard error of the double sample for a given cost. The formula[2] for computing this standard error is:

$$s_{\bar{y}_D} = \sqrt{\frac{V_{y(x)}}{n} + \frac{V_{y(x)}(\bar{x}_L-\bar{x})^2}{\Sigma(x_i-\bar{x})^2} + \frac{b^2 s^2 x_L}{N}}$$

where $s_{\bar{y}_D}$ = standard error of the double sample estimate of site index

$V_{y(x)}$ = variance about regression =

$$\frac{\Sigma(y_i-\bar{y})^2 - \dfrac{\left[\Sigma(y_i-\bar{y})(x_i-\bar{x})\right]^2}{\Sigma(x_i-\bar{x})^2}}{n-2}$$

$y_i$ = individual field observation of site index

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[2] Cochran (5, p. 145) considers the case where the average from the large sample is without error. For this case the third term on the right side of the equation goes out.

$x_i$ = individual photo observation of site index (at locations for which field observations were also taken)

$s_{x_L}$ = standard deviation of all photo observations of site index

n = number of field observations

N = number of photo observations

The optimum ratio of $\frac{N}{n}$ that will reduce $s_{\bar{y}_D}$ to a minimum for a given cost can never be exactly predicted for a proposed survey. The ratio is affected by two sets of values which cannot be accurately determined until the survey has been completed. One set of values are those in the ratio $\frac{\text{cost of a field observation}}{\text{cost of a photo observation}}$ and second, the values for $V_{y(x)}$, b, $s_{x_L}$, $\bar{x}$ and $\bar{x}_L$ in the formula for $s_{\bar{y}_D}$. Although neither of these sets of values can be accurately forecast, reasonably close estimates can be made on the basis of past experience.

The cost of a photo observation is practically constant from one area to another. This cost includes not only time spent in making photo and map readings but also other expenses which are not encountered in a field survey. Such expenses might include additional expense for photos, training of photo interpreters, and more time-consuming computations.

The cost of a field observation, on the other hand, varies from area to area since it depends largely on accessibility. Personnel familiar with the area of a proposed survey can usually estimate this cost quite closely.

Although the ratio of plot costs can generally be estimated closely, obtaining the second set of values--those for other factors in the formula for $s_{\bar{y}_D}$--is more difficult. Until some surveys have been made and experience data are available, interim use may be made of figures 5 and 6 as developed from this study.

To illustrate the use of figures 5 and 6, in making a choice between a double sample survey and a straight field survey, one would need to know if the former was more efficient and if so how much. If accessibility is such that 40 photo observations cost the same as 1 field observation ($\frac{40}{1}$ cost ratio), an optimum ratio of photo plots to field plots is indicated by figure 5 to be $\frac{3.6}{1}$, and a corresponding gain in efficiency of about 16 percent is shown in figure 6.

A brief explanation of methods used in preparing these curves may be helpful for those wishing to calculate similar relationships from experience data.

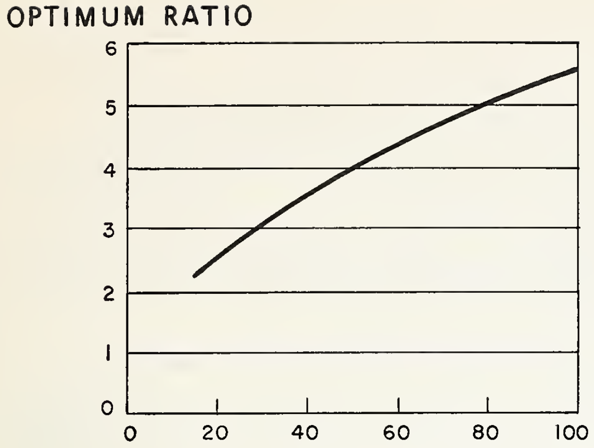

Figure 5.--Optimum ratio in relation to cost ratio.

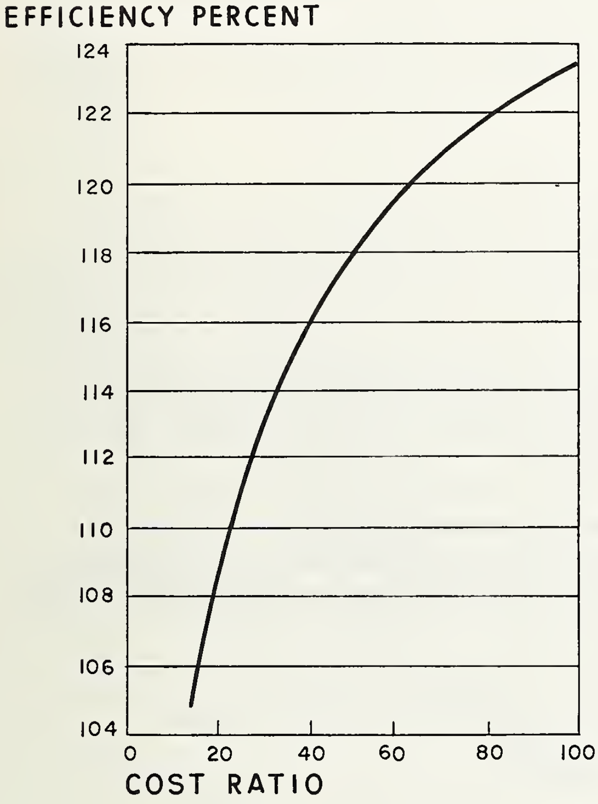

Figure 6.--Efficiency percent in relation to cost ratio.

Optimum ratios were calculated for selected cost ratios by determining the combination of N and n that minimized standard error of a double sample ($s_{\overline{y}_D}$) when total survey cost was kept constant. In the formula for $s_{\overline{y}_D}$ it was assumed that $\overline{x}_L = \overline{x}$ which resulted in wiping out the middle element $\frac{V_{y(x)}(\overline{x}_L-\overline{x})^2}{(x_i-\overline{x})^2}$.

Then $s^2_{\bar{y}_D} = \frac{V_{y(x)}}{n} + \frac{b^2 s^2_{x_L}}{N}$. If the cost equation is

$$C_T = nC_n + NC_N$$

where $C_T$ = total cost of double sampling survey

$C_n$ = cost to get an observation of "n" (field plot)

$C_N$ = cost to get an observation of "N" (photo plot)

Then for a set total cost, values of n and N can be found that give a minimum value of $s^2_{\bar{y}_D}$.

Substituting $n = \frac{C_T - NC_N}{C_n}$ (from the cost equation) in the formula $s^2_{\bar{y}_D} = \frac{V_{y(x)}}{n} + \frac{b^2 s^2_{x_L}}{N}$ and setting the first derivative with respect to N equal to zero, we have

$$P = \sqrt{\frac{b^2 s^2_{x_L} R}{V_{y(x)}}}$$

where P = optimum ratio of $\frac{N}{n}$

R = cost ratio $\left(\frac{C_n}{C_N}\right)$

The value for $V_{y(x)}$ was taken as 606, which analysis had shown as the mean square error for equation 9. The value of 191 was used for $b^2 s^2_{x_L}$ based on values of 0.878 for b and 15.748 for $s_{x_L}$, both of which were indicated by the test for subjectivity.

Efficiency percent, which expresses the cost advantage of a double sampling survey as compared to a field survey having the same standard error, was then calculated for each cost ratio and corresponding optimum ratio, using the following equation:

$$E = \frac{PVR\ 100}{(R+P)\left[b^2 s^2_{x_L} + V_{y(x)}P\right]}$$

where E = efficiency percent

P = optimum ratio

V = variance of site index from field observations

Other symbols are as before.

The value of V was taken as 834 (variance in actual field site index on the 800 plots).

On an actual survey, the efficiency indicated by figure 6 may not be attained, even though the cost ratio might be accurately predicted. This could occur because values for $V_{y(x)}$, b, and $s_{x_L}$ differed from those obtained in the study. Furthermore, even though the optimum ratio might be accurately predicted, the estimated efficiency percent still might not be attained because of a different variance in site index from field observations (V).

In one sense the efficiencies shown in figure 6 are overstated. This bias results from the assumption used in the efficiency analysis that $\overline{x}_L = \overline{x}$. Any difference in these averages--and there will almost always be some--will tend to increase $s_{\overline{y}_D}$ and therefore reduce efficiency. A further reduction in the apparent advantage of double sampling may occur because of unfavorable values of $V_{y(x)}$, b, $s_{x_L}$, and V. There is less likelihood of a complete loss of efficiency in the case of inaccessible areas (high cost ratio). Conversely, the use of photo techniques in a double sampling survey may not be justified for accessible areas.

## CONCLUSIONS

Results of this study on "Estimating Douglas-fir Site Quality from Aerial Photographs" lead to a number of conclusions about relationships of physiographic features encountered and their usefulness for estimating site index within the study area.

1. Photo and map evaluations of elevation, latitude, topographic shape, and soil depth are highly significant as indicators of site index.

2. The combined variable, aspect + slope, was significant at the 5-percent confidence level but was rejected because its contribution to the prediction of site index was minor, and it was the most expensive of the variables to measure. The poor showing could be due to aspect and slope within the study area not being closely related to site index, or to the somewhat arbitrary ratings assigned to this partly qualitative combined variable. It could be that the ratings did not reflect the variable's true relation to site index.

3. Equations, although based on highly significant relationships, are limited in usefulness to certain types of extensive surveys. The maximum variation in site index accounted for--about 28 percent--in general renders the equations of little value for a single observation. They hold greatest promise for use in a double sampling procedure, especially in situations where field work is relatively expensive.

4. Photo interpreters with general experience can be readily trained to the point where subjectivity will not significantly affect their estimates of site index.

5. More research is needed to step up the "accountable variation." Results of this study, while providing a substantial step towards improving the efficiency of site determinations, are probably more important as indicators of the direction of future research. Such research might investigate new criteria as well as improve the evaluation schemes for some of those used in this study. Research should be particularly fruitful in areas where soils have been or are being mapped. Then, consideration of detailed soil classifications, in conjunction with criteria and techniques such as used in this study, may explain much more of the variation in productivity of forest lands.

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